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Enhanced strength analysis method for composite open-hole plates ensuring design office requirements

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ABSTRACT

The use of unidirectional carbon fibre-reinforced composites in the design of primary structures, such as the centre wing box, has spread increasingly over the past few years. However, composite structures can be weakened by the introduction of geometrical singularities, such as holes or notches. The semi-empirical aspect of the current open-hole failure approaches requires the allowables to be systematically fitted against specific test results. This point constitutes a strong limitation for optimum design. A simplified strength analysis method for perforated plates is presented, ensuring design office requirements in terms of precision and computational time. The predictions of the proposed approach are compared successfully with a large experimental database, with different configurations of perforations, different stacking sequences and in different Carbon/Epoxy materials.

1. Introduction

Due to their high specific properties, the use of fibre-reinforced composites has spread increasingly, during the past few years, for the design of primary structures, such as the centre wing box, the wings or the fuselage. Composite materials allow to answer to the request of aeronautical companies for lighter, safer and less polluting civil aircrafts. It is well known that composite structures can be weakened by the introduction of geometrical singularities [15], such as holes, notches or cut-outs. Consequently, the strength analysis of high stress gradient parts of the structures still remains a key problem in the design of engineering structures.

From an academic point of view, many advanced strength analysis methods for perforated composite plates can be found in the literature. Some methods are based on (i) damage modeling to predict the intralaminar damage (transverse cracks) and (ii) cohesive zone modeling to predict interlaminar damage (delamination) [2,3,9]. Some methods use only cohesive zone elements to model the most probable cracks [4,20] (both intra and interlaminar damage), whereas other authors explicitly mesh all the possible cracks [17] and manage crack nucleation and propagation through linear fracture mechanics. These recent damage and failure approaches, physically based, offer a fine description of the different damage and failure mechanisms observed in a laminated open-hole plate subjected to tensile loading and present interesting predictive capabilities. However, these advanced failure approaches are currently too complex in order to be used in a design office, and the associated computational times remain prohibitive to design aeronautical structures.

From an industrial point of view, some simplified strength analysis methods, specific for the prediction of failure for perforated plates such as the point stress method [19,18] or the average stress method [14], are widely used. However, the semi-empirical aspect of these current open-hole failure approaches requires the allowables to be systematically fitted against large test campaigns. Consequently, it is necessary to propose an alternative strength analysis method for perforated plates manufactured with aeronautical stacking sequences, based on physical considerations, but inducing a short computational time. Some authors have proposed recently a method based on a coupled criterion to predict the failure of open-hole plates subjected to tensile loadings [1,13]. This method permits to obtain quite good results but necessitates the identification of the toughness that could not be performed using the existing industrial standards. Moreover, this method has been applied in the only case of a few loadings and necessitates the *a priori* knowledge of the crack direction.

The aim of the present study is to propose an alternative fast computational method matching the different requirements of design offices, *i.e.* a fast computational method easy to identify,

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to be used by stress engineers and available for a large number of configurations.

The proposed simplified method for the strength analysis of perforated plates is first presented and can be decomposed into three main steps: (i) the estimation of the membrane loadings within the perforated structures, (ii) the determination of the fracture behaviour of the different plies constituting the laminate and, finally, (iii) the prediction of the ultimate rupture of the composite structure. Then, the predictive capabilities of the present approach are evaluated through comparisons with many test cases representative of the aeronautical industries.

2. Strength analysis method for open-hole plates

2.1. Estimation of the membrane loadings within the perforated plates

The estimation of the membrane loadings at each point of an open-hole plate is performed using the analytical approach proposed by Tan [16]. This modeling, initially developed for metallic materials, leads to the exact solution for a circular hole perforated infinite plate subjected to multiaxial membrane loadings, the macroscopic material behaviour being assumed as orthotropic linear elastic. Then, an empirical correction factor, expressed in Eq. (1), is applied to the estimated membrane loadings in order to take into account the effect of the finite dimensions, especially the plate width (w) and the hole diameter (d).

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{bmatrix} = C_{w/d}\left(\frac{d}{w}\right)\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{bmatrix}_{w=\infty} \quad \text{with } C_{w/d}\left(\frac{d}{w}\right) = \frac{2+\left(1-\frac{d}{w}\right)^3}{3\left(1-\frac{d}{w}\right)} \tag{1}$$

Then, the predicted membrane loadings within the open-hole plate have been compared with those obtained through finite element (FE) simulations performed with the commercial Samcef© finite element (FE) code with different meshes (different sizes or different types of shell elements). As reported in Fig. 1, the stress gradients in the vicinity of the perforation, predicted with the analytical method, are in very good agreement with those obtained through FE simulations for a w/d ratio (plate width to hole diameter) equal to 5.

However, the predictions of the analytical approach overestimate the membrane loadings near the free edges of the plates because the edge effect is not taken into account, contrary to the FE simulations. Therefore, it has been demonstrated that the validity domain of this analytical approach is limited to perforated plates in which the effect of the edges on the stress gradient around the hole is negligible. The analytical approach can thus be used only for perforated plates presenting a w/d ratio superior or equal to 3. Otherwise, the estimation of the membrane loadings within the perforated plate should be performed using FE simulations (in the present case, with the Samcef© FE code).

2.2. Determination of the non-linear mesoscopic behaviour

Then, as a post-treatment at each point of the open-hole plate, the behaviour of the laminate up to failure is re-analysed considering the different sources of non-linearity (thermal residual stresses, viscosity, elastic non linearity, intra-ply damage) at the ply scale using a laminate theory extended to non-linear behaviour [10] and the previously determined membrane loadings. The prediction of the local non-linear mesoscopic behaviour up to the specimen failure is performed with the progressive failure approach proposed in [10] which is briefly summarized in this section. The present multiscale failure approach considers the unidirectional (UD) ply as the elementary entity of modeling and is predictive for different stacking sequences. It could be decomposed into four main steps.

Firstly, in order to predict accurately the failure of a ply in a laminate, it is necessary to estimate correctly the mesoscopic stresses and strains. A non-linear thermo-viscoelastic behaviour is proposed in Eq. (2).

$$\underline{\sigma} = \underline{\underline{\widetilde{C}}} : (\underline{\varepsilon} - \underline{\varepsilon_{th}} - \underline{\varepsilon_{ve}} - \underline{\varepsilon_{nl}}) \tag{2}$$

where $\underline{\sigma}$ is the mesoscopic stress, $\underline{\underline{\widetilde{C}}}$ the effective rigidity, $\underline{\varepsilon}$ the total strain, $\underline{\varepsilon_{th}}$ the thermal strain (in order to take into account the thermal residual stresses, which are essential to predict accurately the first ply failure), $\underline{\varepsilon_{nl}}$ the non-linear elastic strain [7] (in order to describe the hardening observed experimentally [8] in UD plies subjected to longitudinal tensile loadings and especially in new generations of composite materials such as T700GC/M21 [7] reported in Fig. 2a), and $\underline{\varepsilon_{ve}}$ the viscoelastic strain [10] (in order to consider the non-linearity observed in UD plies subjected to shear loading which is essential to predict accurately the behaviour and final failure of $[\pm 45°]_s$ laminates subjected to tensile loading as reported in Fig. 2b, or highly disoriented laminates containing many ±45° plies).

Secondly, the prediction of the ply failure within the laminate is performed with a failure criterion, based on Hashin's hypotheses [5], distinguishing the fibre (Eq. (3)) and in-plane interfibre (Eq.

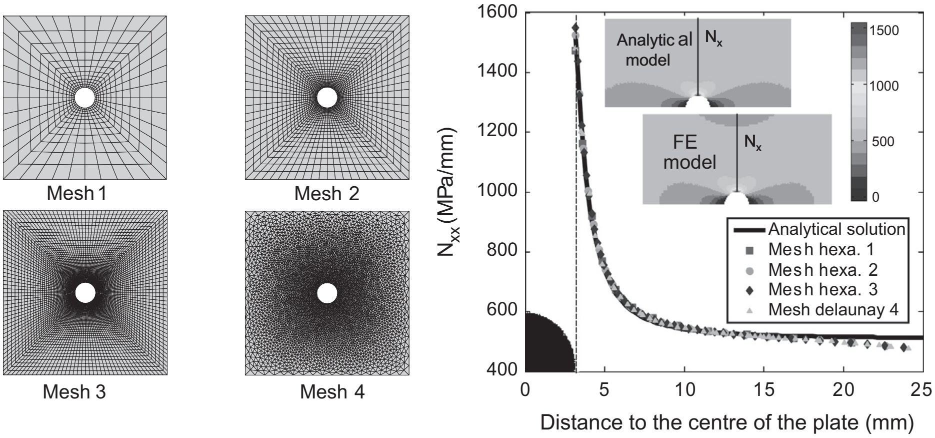

Fig. 1. Comparison of the stress gradient in the vicinity of the perforation in a T700GC/M21 quasi-isotropic open-hole plate subjected to the uniaxial tensile loading predicted using FE simulation and an analytical model.