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Modelling bearing failure in countersunk composite joints under quasi-static loading using 3D explicit finite element analysis

B. Egan, M.A. McCarthy, R.M. Frizzell [1], P.J. Gray [2], C.T. McCarthy *

Irish Centre for Composites Research (IComp), Materials and Surface Science Institute (MSSI), Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Ireland

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ABSTRACT

Three-dimensional explicit finite element modelling is used to predict the quasi-static bearing response of typical countersunk composite fuselage skin joints. In order to accurately simulate bearing failure, a user-defined 3D composite damage model was formulated for Abaqus/Explicit and included Puck failure criteria, a nonlinear shear law and a crack band model to mitigate mesh sensitivity. A novel approach was developed to employ characteristic element lengths which account for the orientation of composite ply cracks in the Abaqus/Explicit solver. Resulting models accurately predicted initial joint sticking behaviour and the elastic loading response of single-bolt and three-bolt joints, but preliminary predictions of bearing failure onset were overly-conservative. Improved failure predictions were obtained by utilising a fracture energy for compressive fibre failure which was considered more relevant for simulating bearing damage. The explicit models were exceptionally robust, showing capability to predict extensive hole crushing. Methods of dramatically improving joint model efficiency were highlighted.

1. Introduction

Inadequate failure prediction can lead to conservatively-designed composite bolted joints, which amount to severe weight penalties in aircraft structures [1]. Countersunk fasteners promote aerodynamic efficiency and are used in composite fuselage skin joints on next-generation aircraft such as the Airbus A350 XWB. Conservative joint design increases panel thicknesses across the fuselage, so improved modelling of countersunk composite bolted joints is a key priority for airframe manufacturers. A current EU FP7 project, MAAXIMUS (*M*ore *A*ffordable *A*ircraft through e*X*tended, *I*ntegrated and *M*ature n*U*merical *S*izing) [2], is aimed at extending the virtual testing platform for the development of highly efficient composite fuselage structures. The present work, carried out as part of MAAXIMUS, aims to develop an accurate and robust high-fidelity 3D modelling strategy for composite bolted joints.

Explicit solvers have already been used for highly-efficient simplified finite element (FE) modelling of bolted joint failure [3,4]. In [3], a hybrid shell/solid modelling approach was used to simulate fastener pull-through, while Pearce et al. [4] developed user-defined elements to create global joint models in PAM-CRASH. Explicit finite element analysis (FEA) offers several benefits over implicit FEA and should play an increasingly important role in simulating aircraft structural failures [5]. The explicit method offers more robust contact modelling, efficient solution of large problems, and avoidance of convergence issues which plague implicit analyses of composite failure. There have been several detailed 3D FE studies on the mechanical behaviour of composite bolted joints [6–12], the majority of which employ *implicit* FEA and feature protruding-head or pin-loaded joints, rather than countersunk configurations. Although implicit solvers *have* been used for 3D countersunk joint modelling [10,11], the complex countersunk surface interactions have been found to exacerbate contact convergence problems. Strain-softening composite damage models pose a further challenge in implicit FEA. McCarthy et al. [12] simulated multi-bolt joint failure but noted that the implicit solutions failed to converge to ultimate failure, and the predicted response depended somewhat on the choice of material degradation parameters. In 3D countersunk joint modelling, Hühne et al. [10] demonstrated better predictions with gradual stiffness reductions compared to a constant degradation model.

The use of explicit solvers has recently been extended to detailed modelling of countersunk composite joints [13–15]. A study of elastic joint behaviour by Egan et al. [13] compared results of a 3D explicit solution to those from an implicit solver. The explicit solver accurately predicted elastic joint behaviour, without the convergence issues highlighted in [10,11]. Abaqus/Explicit

* Corresponding author. Tel.: +353 61 234334; fax: +353 61 202944.
E-mail address: conor.mccarthy@ul.ie (C.T. McCarthy).

[1] Present address: Bell Labs Ireland, Blanchardstown Business & Technology Park, Dublin 15, Ireland.

[2] Present address: Airbus Operations S.A.S., 316 Route de Bayonne, 31060 Toulouse Cedex 9, France.

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simulations presented in [14,15] featured continuum shell elements rather than solid elements, but included the prediction of damage progression using the built-in Abaqus damage model. Cohesive elements were used to model delamination, though their inclusion only had a minimal effect on the predicted response. Predictions of ultimate strengths in single-lap countersunk joints were good but offset bearing strengths were less reliable. The calculated offset bearing strength was highly dependent on the initial model response which was somewhat unreliable due to poor simulation of clamping conditions in the shell element models. The presence of multiple plies through the element thickness along with the 2D nature of the continuum shell elements and built-in damage model caused further limitations. Nonetheless, overall predictions were reasonably good and the study represented a step change in composite bolted joint modelling as it was the first to feature a progressive damage analysis in a detailed *explicit* solution. Pearce et al. [16] recently used a similar stacked shell approach in PAM-CRASH to simulate bearing failure in a countersunk composite joint loaded at 10 m/s. A full 3D explicit analysis was avoided due to computational expense and numerical challenges, including hourglassing associated with reduced integration elements which are generally used in 3D explicit analyses. Good predictions of failure load and damage progression were obtained in the initial loading phase but the predicted response diverged from the experimental result after extensive damage development. Improved modelling of debris was proposed to improve predictions, while significant limitations were highlighted in simulating through-thickness damage using the essentially-2D shell elements. Stress distributions at bolt-hole interactions are highly three-dimensional, particularly in the case of countersunk fasteners [7,11]. The explicit modelling of this paper builds on the work in [15] and [16] by utilising *3D* solid elements, in a one-element-per-ply configuration, for analysing failure of countersunk composite joints.

A 3D damage model, developed specifically for these analyses, includes recent developments in failure criteria and continuum damage mechanics. The World-Wide Failure Exercise (WWFE) [17] scored leading composite failure criteria on their predictive capabilities, and found *Puck's criteria* [18] to contain a sophisticated treatment of matrix cracking which captured most features of experimental results [19]. These criteria must be checked on multiple potential fracture planes, but accurately predict increased longitudinal shear strength under moderate transverse compressive loadings [18,20,21], which many other criteria fail to do. As well as the need for such sophisticated ply failure criteria, the inherent mesh sensitivity of composite damage models pose a challenge for FE analysts. The *crack band model* [22] regulates fracture energy in a failing element and is currently the foremost solution to this issue. Pinho et al. [23–25] developed a physically-based damage model in an *explicit* solver (LS-DYNA), which included the Puck criteria, a fibre-kinking compressive failure model and a crack band model combined with a heuristic approach to calculating characteristic element lengths. Experiments were developed separately to determine ply fracture energies, for which no standard tests currently exist [23,26]. An explicit damage model for high velocity applications was developed by Raimondo et al. [27,28], while Donadon et al. [29,30] formulated a nonlinear shear law including gradual stiffness reduction and used an objectivity algorithm to obtain characteristic lengths in non-structured meshes. The explicit damage model developed here incorporates physically-based failure criteria, a nonlinear shear law and a crack band model to mitigate mesh sensitivity. The nonlinear shear law features an innovative treatment of load reversal and a novel approach was also developed to utilise characteristic element lengths which accurately account for the orientation of ply cracking in the Abaqus/Explicit solver.

2. Composite damage model

2.1. 3D elastic behaviour and nonlinear shear law

The composite damage model has been implemented in an Abaqus/Explicit (VUMAT) subroutine to update integration point stresses ($\sigma_i^{t+\Delta t}$) based on the total strains at the current time increment ($\varepsilon_i^{t+\Delta t}$). Vectorised notation used in this model outline, employs shorthand convention (i = 1(≡11), 2(≡22), 3(≡33), 4(≡12), 5(≡23), 6(≡31)), where the indices *1*, *2* and *3*, refer to the fibre, in-plane transverse and through-thickness directions respectively. The total stress vector is computed according to Eq. (1):

$$\begin{bmatrix}\sigma_{11}^{t+\Delta t}\\ \sigma_{22}^{t+\Delta t}\\ \sigma_{33}^{t+\Delta t}\\ \tau_{12}^{t+\Delta t}\\ \tau_{23}^{t+\Delta t}\\ \tau_{31}^{t+\Delta t}\end{bmatrix} = \begin{bmatrix} E_{11}A(1-\nu_{23}\nu_{32}) & E_{11}A(\nu_{21}-\nu_{23}\nu_{31}) & E_{11}A(\nu_{31}-\nu_{21}\nu_{32}) & 0 & 0 & 0\\ & E_{22}A(1-\nu_{13}\nu_{31}) & E_{22}A(\nu_{32}-\nu_{12}\nu_{31}) & 0 & 0 & 0\\ & & E_{33}A(1-\nu_{12}\nu_{21}) & 0 & 0 & 0\\ & \mathit{Symmetric} & & Eq.8 & 0 & 0\\ & & & & G_{23} & 0\\ & & & & & G_{31}\end{bmatrix} \times \begin{bmatrix}\varepsilon_{11}^{t+\Delta t}\\ \varepsilon_{22}^{t+\Delta t}\\ \varepsilon_{33}^{t+\Delta t}\\ \gamma_{12}^{t+\Delta t}\\ \gamma_{23}^{t+\Delta t}\\ \gamma_{31}^{t+\Delta t}\end{bmatrix} \quad (1)$$

where

$$A = 1/(1-\nu_{12}\nu_{21}-\nu_{23}\nu_{32}-\nu_{13}\nu_{31}-2\nu_{13}\nu_{21}\nu_{32}) \quad (2)$$

To define stiffness reductions for the in-plane shear response, maximum shear strain over time ($\bar{\gamma}_{12}$) is monitored via Eq. (3), and as in [24,29], it is decomposed into elastic (γ^e), elastic-damage (γ^{ed}) and inelastic (γ^{in}) parts:

$$\bar{\gamma}_{12} = \max_{t' \leqslant t+\Delta t}\{|\gamma_{12}(t')|\} \quad (3)$$

$$\bar{\gamma}_{12} = \gamma_{12}^e + \gamma_{12}^{ed} + \gamma_{12}^{in} \quad (4)$$

$$\text{where } \gamma_{12}^e = \frac{f_{\tau_{12}}}{G_{12}^0};\ \gamma_{12}^{ed} = \frac{f_{\tau_{12}} d_{12}}{G_{12}^0(1-d_{12})} \quad (f_{\tau_{12}} \text{ defines the shape of the nonlinear response (see Eq.(9))}) \quad (5)$$

The damage variable (d_{12}) reduces the virgin shear modulus (G_{12}^0) due to progressive matrix damage incurred in shear loading (see Fig. 1(a)). This is driven by $\bar{\gamma}_{12}$ using the slope ("*a*") of the experimentally-determined gradual shear stiffness reduction curve (GSRC) shown in the inset to Fig. 1(a):

$$d_{12} = -a\bar{\gamma}_{12} \quad (6)$$

Inelastic shear strain (γ_{12}^{in}) is determined from Eq. (7) and in-plane shear stress (τ_{12}) is updated in Eq. (8).

$$\gamma_{12}^{in} = \bar{\gamma}_{12} - \gamma_{12}^e - \gamma_{12}^{ed} \quad (7)$$

$$\tau_{12} = \begin{cases} if|\gamma_{12}| = \bar{\gamma}_{12} \rightarrow \frac{\gamma_{12}}{|\gamma_{12}|} f_{\tau_{12}} \\ if|\gamma_{12}| < \bar{\gamma}_{12} \rightarrow \frac{\gamma_{12}}{|\gamma_{12}|} G_{12}^0(1-d_{12})(\gamma_{12}-\gamma_{12}^{in}) \end{cases} \quad (8)$$

$f_{\tau_{12}}$, which defines the shape of the nonlinear shear law is given by:

$$f_{\tau_{12}} = \begin{cases} if\bar{\gamma}_{12} \leqslant \gamma_{P1,\max} \rightarrow c_1\bar{\gamma}_{12}^3 + c_2\bar{\gamma}_{12}^2 + c_3\bar{\gamma}_{12} \\ if\bar{\gamma}_{12} > \gamma_{P1,\max} \rightarrow d_1\bar{\gamma}_{12}^3 + d_2\bar{\gamma}_{12}^2 + d_3\bar{\gamma}_{12} + f_{\tau_{12}@\gamma_{P1,\max}} \end{cases} \quad (9)$$