INFLUENCE OF OUT-OF-PLANE STRESSES ON FAILURE PREDICTION OF COMPOSITE BOLTED JOINTS

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Abstract

In this work a failure criterion was used to analyze the failure of a single-lap bolted-joint on two laminate plates. The proposed failure criterion is a modified version of the Chang-Lessard criterion, including out-of-plane shear stresses and a non-linear shear stress-strain relationship. The failure criteria were implemented in a finite element model and validated through comparison with experimental results from literature. The model showed an excellent agreement with experimental results. Moreover, results were compared with those reported in literature using Hashin failure criteria.

1 Introduction

Composite materials have a wide application area in aircraft industry due to their high mechanical properties and low weights. Joining by mechanical fasteners is a common technology for assembling composite structural components in aircraft. Due to anisotropy and inhomogeneity of composites, failure and strength of composite bolted joints can be considerably different from the failure and strength of metallic joints. Damage in composite can initiate at an early loading stage and accumulate inside the laminates as the load increases. As a consequence, the strength and failure of the joints are significantly influenced by the damage accumulated inside the composites [1].

There are four basic failure modes related to composite failure in mechanical fastened joints: net-tension, shear-out and bolt-failure can be considered catastrophic failure modes; while bearing damage produces a progressive failure. Thus, composite bolted joints are designed to fail by bearing damage [2]. Bearing failure is a local compressive failure mode due to contact and frictional forces acting on the surfaces of the hole. As literature survey indicates, damage phenomena of bearing failure in a composite bolted joint are very complex. Compressive in-plane stresses can produce the failure of the composite plate due to contact forces. But also out-of-plane stresses produces by torque bolt and frictional forces in the vicinity of the hole can influence on bearing failure.

Literature review shows that many authors use numerical models based on Finite Elements Method to predict bearing failure in composite bolted joints. The use of failure criteria has proved to be accurate for estimating failure under both static and dynamic conditions.

Nevertheless these models do not consider the influence of out-of-plane stresses on bearing failure [3] including only in-plane stresses in the failure criteria, as in the criteria of Chang-Chang [4] and Chang-Lessard [5]. However, several works have shown that out-of-plane stresses play a major role in bolted joints [2,6-10], thus there is a lack of studies about the influence of out-of-plane stresses on bearing failure. Also, several studies has demonstrated that non-linear shear stress-strain relationship must be considered to predict pin-joints bearing strength [6,11-13].

In this work, a single-lap, single-bolt metal-composite joint is investigated using three-dimensional FE model including out-of-plane stresses in the failure criteria used to predict bearing failure. FE model was validated with experimental data obtained from literature [10]. Progressive damage and failure criteria were implemented through a user subroutine USDFLD in ABAQUS/Standard. The validated model was used to analyze the influence of out-of-plane stresses on bearing damage on composite bolted joints. The results were also compared with those obtained by Riccio using 3D Hashin failure criteria [14].

2 Failure criteria

In this work a modified version of Chang-Lessard criteria [5] was developed. Chang-Lessard developed the criteria to predict the failure of laminate composites subjected to compressive load. Since in bolted composite joints composite laminates out-of-plane stresses appear due to tightening torque and secondary bending effect, the failure criteria proposed in this work includes the effect of both normal and shear out-of-plane stresses.

Chang-Lessard criteria consider four failure modes: matrix crushing, matrix cracking, fibre-matrix shearing failure, and fiber failure. The proposed model incorporates the out-of-plane shear stresses in the formulations of the four failure criteria of the Chang-Lessard criteria, and includes two new failure modes: out-of-plane matrix crushing and delamination, Table 1.

A tape lamina has a non-linear behavior when is subjected to in-plane shear stress. In this work the nonlinear shear stress-strain relationship proposed by Hahn and Tsai [30] was applied, Eq.1:

$$\gamma_{12} = \frac{1}{G_{12}}\tau_{12} + \alpha\tau_{12}^3 \tag{1}$$

where G12, τ12, and γ12 are, respectively, the in-plane shear modulus, shear stress, and shear strain. α is a constant parameter which is determined experimentally.

The non-linear shear behavior of a laminate due to out-of-plane shear stresses (τ_{13} and τ_{23}) is difficult to test experimentally. However, since non-linear response of composite is mainly dominated by matrix behavior, in this work the Eq.1 is also used to model the out-of-plane shear deformations (γ_{13} and γ_{23}). This non-linear behavior was included in the six failure modes, table 1:

Failure mode	Equation
In plane matrix crushing	$\left(\frac{\sigma_2}{Y_C}\right)^2+\frac{\frac{\tau_{12}^2}{2G_{12}}+\frac{3}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{2G_{12}}+\frac{3}{4}\alpha S_{12}^4}+\frac{\frac{\tau_{23}^2}{2G_{23}}+\frac{3}{4}\alpha\tau_{23}^4}{\frac{S_{23}^2}{2G_{23}}+\frac{3}{4}\alpha S_{23}^4}=e_{mc2}^2$
Out-of-plane matrix crushing	$\left(\frac{\sigma_3}{Z_C}\right)^2+\frac{\frac{\tau_{13}^2}{2G_{13}}+\frac{3}{4}\alpha\tau_{13}^4}{\frac{S_{13}^2}{2G_{13}}+\frac{3}{4}\alpha S_{13}^4}+\frac{\frac{\tau_{23}^2}{2G_{23}}+\frac{3}{4}\alpha\tau_{23}^4}{\frac{S_{23}^2}{2G_{23}}+\frac{3}{4}\alpha S_{23}^4}=e_{mc3}^2$
In-plane matrix cracking	$\left(\frac{\sigma_2}{Y_T}\right)^2+\frac{\frac{\tau_{12}^2}{2G_{12}}+\frac{3}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{2G_{12}}+\frac{3}{4}\alpha S_{12}^4}+\frac{\frac{\tau_{23}^2}{2G_{23}}+\frac{3}{4}\alpha\tau_{23}^4}{\frac{S_{23}^2}{2G_{23}}+\frac{3}{4}\alpha S_{23}^4}=e_{mt2}^2$
Out-of-plane matrix cracking	$\left(\frac{\sigma_3}{Z_T}\right)^2+\frac{\frac{\tau_{13}^2}{2G_{13}}+\frac{3}{4}\alpha\tau_{13}^4}{\frac{S_{13}^2}{2G_{13}}+\frac{3}{4}\alpha S_{13}^4}+\frac{\frac{\tau_{23}^2}{2G_{23}}+\frac{3}{4}\alpha\tau_{23}^4}{\frac{S_{23}^2}{2G_{23}}+\frac{3}{4}\alpha S_{23}^4}=e_{mt3}^2$
Fiber-matrix shearing failure	$\left(\frac{\sigma_1}{X_C}\right)^2+\frac{\frac{\tau_{12}^2}{2G_{12}}+\frac{3}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{2G_{12}}+\frac{3}{4}\alpha S_{12}^4}+\frac{\frac{\tau_{13}^2}{2G_{13}}+\frac{3}{4}\alpha\tau_{13}^4}{\frac{S_{13}^2}{2G_{13}}+\frac{3}{4}\alpha S_{13}^4}=e_s^2$
Fiber failure	$\left(\frac{\sigma_1}{X_T}\right)^2+\frac{\frac{\tau_{12}^2}{2G_{12}}+\frac{3}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{2G_{12}}+\frac{3}{4}\alpha S_{12}^4}+\frac{\frac{\tau_{13}^2}{2G_{13}}+\frac{3}{4}\alpha\tau_{13}^4}{\frac{S_{13}^2}{2G_{13}}+\frac{3}{4}\alpha S_{13}^4}=e_{ft}^2$

Table 1. Equations for the failure criteria

The present failure criterion includes in the expression proposed by Chang-Lessard for the matrix crushing and matrix cracking failure, the contributions of out-of-plane shear stress and the non-lineal shear stress-strain relationship described previously. Additionally, a matrix crushing and matrix cracking failure criterion is added to consider out-of-plane normal stresses (compressive and tensile, respectively). The out-of-plane matrix crushing failure criterion can take into account the damage produced by tightening torque. The out-of-plane matrix cracking failure criterion can be used to predict delamination onset.

The same modification was included in the shearing failure criterion. Chang-Lessard criterion considers only the effect of normal stress in fiber direction and in-plane shear stress; in the proposed criterion the contribution of out-of-plane shear stresses and the non-linear stress-strain relationship was added.

Chang-Lessard fiber failure criterion considers only compressive loads. The proposed criterion includes a tensile fiber failure mechanism, using the equation proposed by Chang-Chang [4], including the non-linear shear behavior.

3. Numerical model

Non-linear analysis was carried out using ABAQUS/Standard due to the large displacements and non-linear composite behavior. The model reproduces the geometry and materials of single-lap joint tests carried out by Riccio and Murciano [14]

Single-lap composite-to-aluminum joints made from HTA 7/6376 carbon/epoxy and AA7475-T76 aluminum were analyzed. The composite lay-up was $[(0/\pm45/90)2]_S$. Titanium 6Al114VSTA were used for bolts and nuts. The geometry of the model is showed in Fig.1

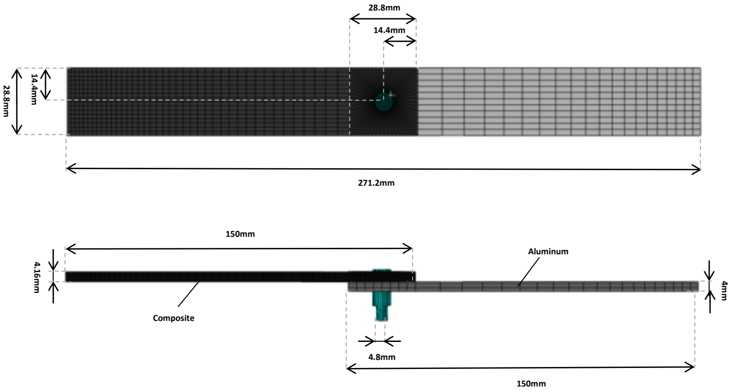


Figure 1. Geometry of the join and model mesh

Loading path was divided into two steps. In the first step, tightening torque was applied while the free ends of aluminium and composite plates were clamped. A bolt load, introducing a pre-tension condition, was implemented in the FE model to apply the tightening torque. The value of the normal pressure exerted by the washer was obtained using the relationship between the applied torque and the normal pressure proposed by Collings [15]. In the second step, the bolt length was fixed simulating the conservation of tightening torque and the free end of aluminum plate remained clamped, while the tension load was applied at the free end of composite plate. The load was applied by imposing only a longitudinal displacement, thus plates were free to rotate leading to secondary bending phenomenon.

The contact interactions between the different components of the joint were modeled using surface-based contact considering the linear penalty method. A constant value of friction coefficient equal to 0.114 was used. This friction coefficient was obtained from the work of Herrington and Sabbaghian [16].

The plastic behavior of the metallic components was reproduced using isotropic hardening model. The failure of composite plate was predicted using the proposed failure criteria. A progressive damage model was implemented using a USDFLD subroutine in Abaqus/Standard to reproduce the mechanical properties degradation after failure. Stresses are called into the subroutine at the start of the current increment and used to evaluate failure criteria. Once the failure criteria are met, the field variables are updated and used to reduce the elastic properties according to the corresponding failure mode, table 2.

Failure mode	**E_1**	**E_2**	**E_3**	**G_{12}**	**G_{13}**	**G_{23}**	**ν_{12}**	**ν_{13}**	**ν_{23}**
Fiber tension	0.14	0.4	0.4	0.25	0.25	0.2	0	0	0
Fiber compression	0.14	0.4	0.4	0.25	0.25	0.2	0	0	0
Fiber -Matrix shear				0.25	0.25		0	0	
Matrix tension		0.4	0.4			0.2	0	0	0
Matrix compression		0.4	0.4			0.2	0	0	0

Table 2. Material properties degraded according to each failure criterion.

When material properties are degraded at an element, the load re-distributes to other elements, which could then fail themselves. It is therefore necessary to iterate at the same load level when material properties change to determine if other material points undergo failure. The accuracy of the results when using USDFLD depends on the size of the time increment. Thus, in this analysis very small load steps were used.

In addition, Riccio [17] developed a FE model of these tests including a progressive damage model based on Hashin failure criteria. Therefore, the results predicted by the proposed model could be compared with those predicted by classical 3D failure criteria such as Hashin.

4. Results

To validate the proposed failure criteria numerical results were compared with the experimental data obtained from scientific literature [10]. Moreover, the numerical predictions were compared with those of Riccio [14] who implemented a 3D progressive damage FE model, based on the Hashin failure criteria. Fig. 2 shows the comparison between experimental and numerical load-displacement curves. An excellent agreement between numerical prediction and experimental data was found in both stiffness and bearing strength. The proposed failure criteria predicted bearing failure for a load of 11,601 N, similar to the experimental results: 11,230 N. Moreover the present model can reproduce the non-linearity of the load-displacement curve and the progressive failure of the joint.

The predictions of the present failure criteria are closer to experimental results than those obtained by Riccio using Hashin failure criteria. Riccio progressive damage model showed a non-linear load-displacement relationship due to the degradation of mechanical properties. However, Hashin failure criteria overestimated the stiffness and the bearing strength of the joint. The maximum load predicted by the present model was lower than that predicted by Riccio because Hashin failure criteria does not consider non-linear shear stress-strain relationship. There are also other reasons that can contribute to these discrepancies as the different degradation procedure and the plastic model for metallic elements.

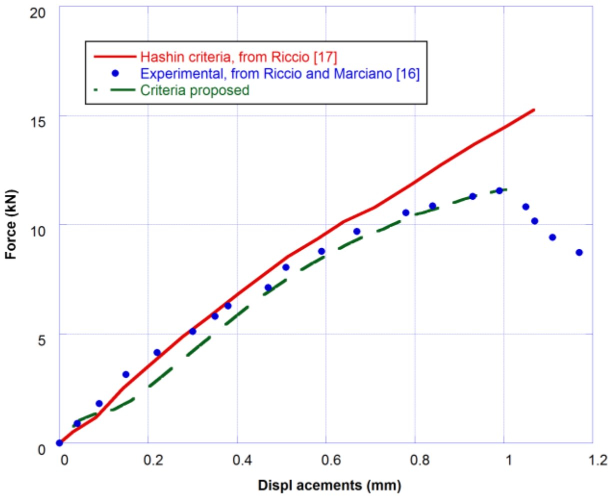
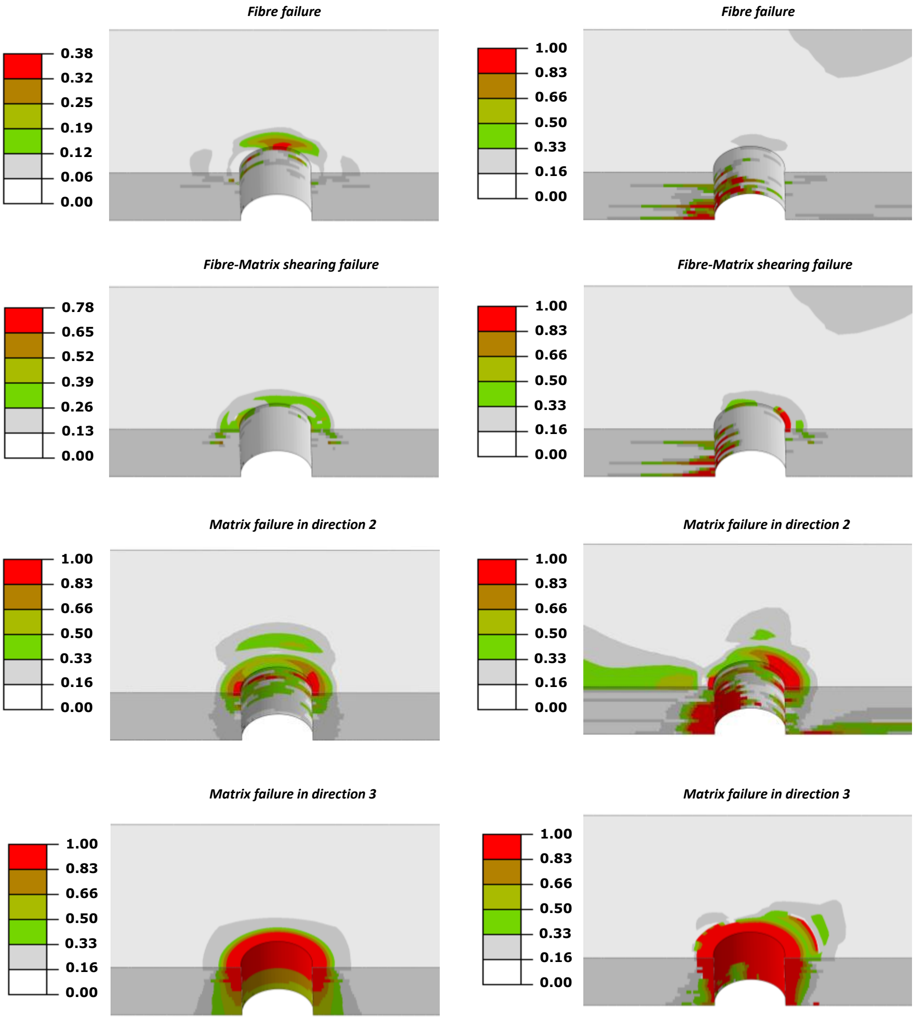


Figure 2. Force versus joint displacement; numerical and experimental results

In addition, FE model was used to analyse the damage mechanisms that produced the failure of the composite plate. The values of the failure criteria in the surroundings of the hole after tightening torque is applied are shown in Fig. 3a, while Fig. 3b shows the failure criteria values when bearing failure occurs. Matrix failure was mainly produced by compressive stresses thus, for sake of simplicity, only matrix crushing failure criterion is plotted. The through-the-thickness distribution of the failure criteria reveals that the single-lap composite joint is a 3D problem in nature.



a) b)

Figure 3. Failure criteria, a) Damage after the tightening torque is applied ,b) Damage when bearing failure occurs

The field of the matrix failure criterion in direction 3 revealed the weight of the tightening torque. In the surroundings of the hole, the matrix was damage due to the compressive load applied by the bolt head. Tightening torque produced matrix crushing in the composite plate and a degradation of the mechanical properties. Thus the consideration of the damage induced by the out-of-plane stresses is required to get an accurate prediction of the progressive bearing failure in bolted single-lap composite joints.

The distribution of the matrix failure criterion in transverse direction when the tension load was applied was dominated by secondary bending. The compressive load exerted by the bolt shank was concentrated on the lower plies. On the other hand, the top ply was damaged due to the compressive load applied by the bolt head. This pressure applied by the bolt head was non-uniform due to secondary bending.

The maximum values of fiber failure criterion were located at the lower plies of the laminate. Due to the secondary bending effect, the compressive load exerted by the bolt shank was concentrated on lower plies, thus the through-the-thickness distribution of the fiber failure criterion was non-uniform. Moreover, plies oriented in the longitudinal direction presented higher values of fiber failure criterion.

The maximum values of fiber-matrix shearing failure criterion were also located mainly at the lower plies due to secondary bending. For the same reason high values of fiber-matrix shearing failure also appeared in the top ply due to the compressive load exerted by the bolt head.

Conclusions

The main contribution of this work is the use of a new set of failure criteria to predict composite failure in bolted joints. The present failure criteria are an extension of Chang-Lessard criteria, including out-of-plane shear stresses in the formulations of the four failure criteria proposed by Chang-Lessard and the consideration of two new failure modes: out-of-plane matrix cracking and delamination. The main advantage with respect to others 3D failure criteria as Hashin is the inclusion of non-linear shear stress-strain relationship. The present model can take into account the out-of-plane stresses produced by torque tightening and the 3D stress field induced by secondary bending.

The accuracy of failure criteria was validated through comparison with experiments in literature [10].. The agreement was excellent in terms of joint stiffness and bearing strength. Moreover, the results were also compared with those obtained by Riccio [14] using classical 3D failure criteria as Hashin. The maximum load predicted by the present failure criteria was closer to experimental data than that predicted by Hashin because of the consideration of non-linear shear stress-strain relationship. Hashin criteria overestimated the stiffness and the bearing strength of the joint.

The analysis of failure mechanisms showed that secondary bending effect leads to a non-uniform through-the-thickness distribution. Maximum values of failure criteria were located at the lower plies producing a progressive failure of the joint. Therefore the consideration of 3D stress field including out-of-plane stresses is necessary to predict bearing failure in bolted single-lap composite joints.

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