European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS 2000
Barcelona, 11-14 September 2000

FINITE ELEMENT MODELING OF DAMAGE ACCUMULATION IN BOLTED COMPOSITE JOINTS UNDER INCREMENTAL TENSILE LOADING

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Key words: composite laminates, bolted joints, progressive modeling, damage accumulation, finite element modeling

Abstract. *A three-dimensional progressive damage model was developed in order to simulate the damage accumulation of bolted single-lap composite joints under in-plane tensile loading. This model is capable of predicting the residual strength and residual stiffness of laminates with arbitrary lay-ups, geometries and bolt positions. The parametric study includes stress analysis, failure analysis and material property degradation. Stress analysis of the three-dimensional geometry was performed using the ANSYS FE code. Failure analysis and degradation of material properties were implemented using a progressive damage model, which is incorporated in an ANSYS macro-routine. The progressive model utilizes a set of stress-based Hashin-type criteria and a set of appropriate degradation rules. A parametric study was performed to examine the effect of bolt position and friction upon residual strength and damage accumulation.*

1 INTRODUCTION

Mechanically fastened joints are critical parts in composite aircraft structures. The material combination in the joined parts along with the stress concentration around the holes makes the joint a very complex element to design. Predicting strength of these parts is of great practical interest, since improper design may cause structural problems of the aircraft fuselage. The technology for optimum joint design in composite structures is still evolving because of the involvement of complex phenomena and many parameters in their behavior. Such parameters include geometry stiffness properties, joint configuration, friction, clamping force and loading conditions. Their various combinations result in various joint configurations, which are very difficult to be analyzed with certainty. This complexity is the main reason for the simplicity of the majority of models used in the literature to simulate the behavior of bolted composite joints.

Failure in fiber-reinforced laminated composite structures containing stress concentration areas, such as bolt-loaded holes, has been one of the technological issues studied by many researchers during the last decades. Most of the analyses used to predict failure of composite laminates are numerical[1,2,5,6,7,9,10] because it is very difficult to model the complicated failure mechanisms by analytical methods. The majority of the previously proposed numerical analyses were semi-empirical and required data from experiments or information on some empirical parameters. Moreover, these analyses could not provide information on the extension and type of damage from the first ply failure to final failure. Thus, in recent years most efforts are concentrated on the development of progressive failure analyses tools, which give the ability to model the damage accumulation by accounting for the initiation, evolution and type of damage.

Chang and Chang[1] developed a two-dimensional progressive damage model for notched laminate plates subjected to tensile loading, which was latter modified to predict net-tension and shear-out failure of loaded holes[2]. Both, geometric and material non-linearity was considered. Failure analysis was performed using the Yamada-Sun[3] and the Hashin criteria[4]. Application was made for simple laminate configurations and geometries. Calculated strengths agreed with experimental results within 20%. Yet, as the model is two-dimensional it cannot account for all damage modes associated to through-the-thickness stresses, delamination, failure at interfaces e.t.c. This study was latter modified by Chang and Lessard[5] and Chang *et. al.*[6] to predict the strength of unloaded holes both in compression and tension. The effect of ply clustering on the reduction of ply transverse and shear strength was studied extensively, and comparisons were made with experimental results, X-radiographs and photographs of damaged specimens.

Based on the assumption that the stiffness degradation of a ply does not depend on how the damage is caused, Tan[7] developed a two-dimensional progressive model for laminates with unloaded holes subjected to tensile loading. Fiber failure was calculated by a self-proposed quadratic criterion and matrix cracking by the Tsai-Wu criterion[8]. The stiffness degradation was simulated by factors reducing the material properties. The progression of damage agreed with experimental results from X-radiographic examination of the specimens at several load cases, but the results were very sensitive to the values of the degradation factors. The consideration of substantial matrix failure as final failure criterion has been proved insufficient for the accurate prediction of the experimentally derived final failure load. In addition, all limitations and drawbacks discussed above for the Chang *et. al*[6]. model, regarding its two-dimensional character, are valid for the same reasons for the Tan model as well.

A more realistic simulation of bolted joints has been proposed by Lessard and Shokrieh[9]. They considered plates including pin-loaded holes. For the analysis, they developed two-dimensional linear and non-linear models. The proposed models involve an oversimplification, as it is exactly the through-the-thickness pin-load induced pressure, which causes significant failure modes, such as edge delaminations. In a recent work[10] of the same authors, advancement on the development of a three-dimensional fatigue progressive damage model has been reported.

Despite the progress made on progressive damage modeling of composite laminates containing pin/bolt-loaded holes, the problem is far from being understood and even less resolved. Basic aspects such as failure criteria and material property degradation are still open issues for research. In addition, the development of reliable and computing efficient models is recognized by the industry as an urgent need in order to face design problems of bolted composite joints[11,12]. This work is concentrated on the detailed three-dimensional finite element modeling of the joint and the examination of the effect of critical parameters such as friction and geometry.

2 PROGRESSIVE DAMAGE MODEL

The proposed progressive damage model involves the steps of stress analysis, failure analysis and material properties degradation. These steps, which operate in an iterative procedure following the mentioned order have been incorporated into a parametric ANSYS macro/routine and will be described separately in the following. An overview is given in the flowchart of Figure 1.

Stress analysis was performed numerically using the commercial Finite Element code ANSYS which can provide the ply-by-ply calculated stresses to be used as input to the progressive model. This part will be described in detail in a next section of this paper.

Failure analysis of laminates with bolted joints is very complex due to the large number of failure mechanisms in composite materials. As a result the existing methods use numerous, mostly empirical failure criteria. In the present investigation failure analysis was performed by implementing the commonly used Hashin polynomial failure criteria, as they were modified from Shokrieh *et. al*[10]. These criteria were selected because they can distinguish between different failure modes and may be applied with ease in a finite element formulation. Evaluation of the efficiency of today used failure criteria is beyond the scope of this work. A set of seven stress-based criteria applicable in the ply-by-ply approach was used to predict the failure modes. They include matrix tensile and compressive failure, fiber tensile and compressive failure, fiber-matrix shear-out and delamination in tension and compression. The seven failure criteria as they reported from Shokrieh *et. al.*[10] are as follows:

Matrix tensile failure, for $(s_y > 0)$:

$$\left(\frac{s_y}{Y_T}\right)^2 + \left(\frac{s_{xy}}{S_{xy}}\right)^2 + \left(\frac{s_{yz}}{S_{yz}}\right)^2 \geq 1 \tag{1}$$

Matrix compressive failure, for $(s_y < 0)$:

$$\left(\frac{s_y}{Y_C}\right)^2 + \left(\frac{s_{xy}}{S_{xy}}\right)^2 + \left(\frac{s_{yz}}{S_{yz}}\right)^2 \geq 1 \tag{2}$$

Fiber tensile failure, for $(s_x > 0)$:

$$\left(\frac{s_x}{X_T}\right)^2 + \left(\frac{s_{xy}}{S_{xy}}\right)^2 + \left(\frac{s_{xz}}{S_{xz}}\right)^2 \geq 1 \tag{3}$$

Fiber compressive failure, for $(s_x < 0)$:

$$\left(\frac{s_x}{X_C}\right)^2 \geq 1 \tag{4}$$

Fiber-matrix shear-out, for $(s_x < 0)$:

$$\left(\frac{s_x}{X_T}\right)^2 + \left(\frac{s_{xy}}{S_{xy}}\right)^2 + \left(\frac{s_{xz}}{S_{xz}}\right)^2 \geq 1 \tag{5}$$

Delamination in tension, for $(s_z > 0)$:

$$\left(\frac{s_z}{Z_T}\right)^2 + \left(\frac{s_{xz}}{S_{xz}}\right)^2 + \left(\frac{s_{yz}}{S_{yz}}\right)^2 \geq 1 \tag{6}$$

Delamination in compression, for $(s_z < 0)$:

$$\left(\frac{s_z}{Z_C}\right)^2 + \left(\frac{s_{xz}}{S_{xz}}\right)^2 + \left(\frac{s_{yz}}{S_{yz}}\right)^2 \geq 1 \tag{7}$$

where s_{ij} are the layer-stress components in the ij direction and the denominators are the strengths in the corresponding directions.

Once failure is detected in a ply the material properties of the ply are degraded by implementing a sudden degradation rule. The scope of using degradation rules is to disable the ply from carrying a certain load. Thus, for each mode of failure there exists a corresponding degradation rule. The available ply-by-ply material property degradation rules are empirical and include assumptions resulting from engineering constraints in the properties of composite materials. Their physical background is not always obvious. For the purpose of the present work the sudden material property degradation rules have been taken from [10] as they fit well to the failure criteria used.

Matrix tensile and compressive failure: When this type of failure is detected in a ply, it is assumed that the matrix cannot carry any load. The material properties of the failed ply that are reduced are:

$$E_y = n_{xy} = 0 \tag{8}$$

Fiber tensile and compressive failure: When these types of failure are detected in a ply, it is assumed that the material cannot carry any load in the failed region. All the material properties of the failed ply are reduced as follows:

$$E_x = E_y = E_z = G_{xy} = G_{yz} = G_{xz} = n_{xy} = n_{yz} = n_{xz} = 0 \tag{9}$$

Fiber-matrix shear-out: When this type of failure is detected in a ply, it is assumed that the material can carry load only in the fiber and transverse to fiber directions. It cannot carry shear load. The material properties of the failed ply that are reduced are:

$$G_{xy} = n_{xy} = 0 \tag{10}$$

Delamination in tension and compression: Delamination failure affects the properties in the z-direction of the delaminated area. When delamination failure is detected it is assumed that the material looses its ability to carry load in the z-direction as well as shear loads. The material properties of the failed ply that are reduced are:

$$E_z = G_{yz} = G_{xz} = n_{yz} = n_{xz} = 0 \tag{11}$$

The previously described steps of the progressive model have been programmed into an ANSYS parametric macro-routine, which works iteratively. The macro-routine is explained by means of the flowchart shown in Figure 1 and involves the following steps.

1. Generation of the 3-D model of the joint by giving as input the initial material properties, the specimen geometry, boundary conditions, initial load and load step.

2. Performing non-linear stress analysis and calculation of the on-axis stresses for each ply.

3. Performing failure analysis by applying the failure criteria.

4. Check for ply failures.

- **4.1** If no failure is calculated, the applied load P^n is increased by an increment ΔP according to equation $P^n = P^{n-1} + \Delta P$. Then, the program returns back to step 2.
- **4.2** If any mode of failure is detected the program continues to the next step.

5. Application of the appropriate material property degradation rule on the failed ply.

6. Check for final failure of the component.

- **6.1** Stop if final failure is reached.
- **6.2** If not, the program returns to step 2. Non-linear stress analysis with the same load is performed again in order to calculate the redistributed stresses. Convergence at a load step is assumed when no additional failures are detected.

7. This procedure is repeated until final failure occurs.

The progressive damage model, described above has been implemented for the case of a bolted single-lap composite joint in order to evaluate its residual strength under an incremental in-plane tensile loading.

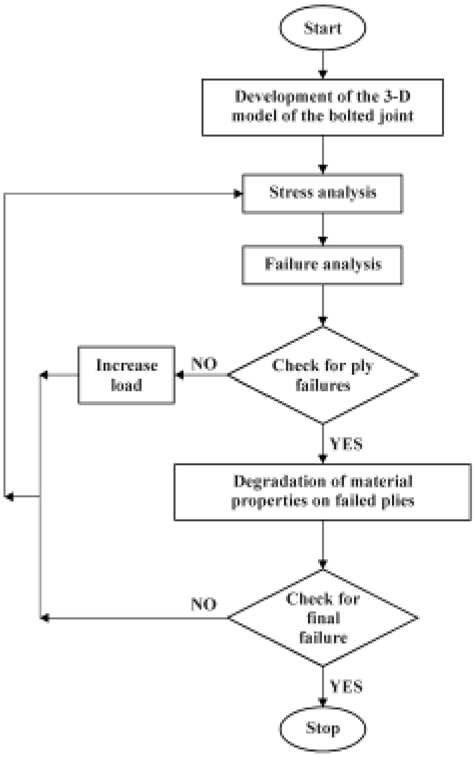


Figure 1. Flowchart of the progressive damage model

3 FINITE ELEMENT MODELING

The lap geometry was taken as for the work in [13] in order to enable comparison. It is shown in Figure 2 and consists of an upper plate made of composite laminate, a lower plate made of aluminum and a bolt with protruding head. The composite laminate is made of fibrous unidirectional layers. The ply orientation was selected to be $[90/0/-45/45]_{S8}$ The geometry of the two plates and bolt are depicted in Figure 3 and the geometry input dimensions in Table 1.

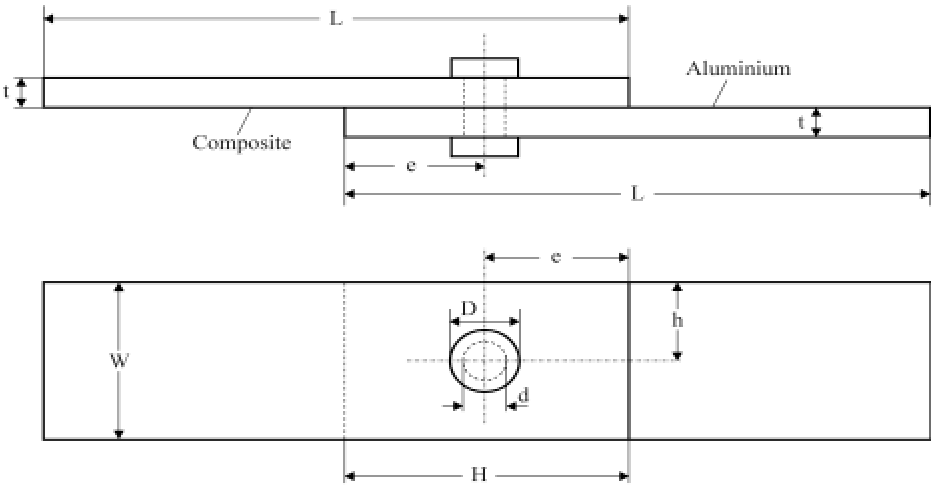


Figure 2. Geometry of the bolted single-lap joint

For the creation of the three-dimensional modeling of the above-described geometry, a parametric input file has been developed in the ANSYS code. A typical mesh is shown in Figure 3. For the modeling of the composite plate the 8-noded SOLID46 3-D ANSYS layered element with three displacement DOF’s per node was used. This element is defined by layer thicknesses, layer material direction angles and orthotropic material properties. The metallic plate and the bolt were modeled using the SOLID45 3-D ANSYS element with three displacement DOF’s per node. The contact between the two plates, the bolt head and the plates and between the bolt and the surface of the hole was modeled using the node-to-surface 3-D CONTAC49 ANSYS element, which implements a penalty-Lagrange multiplier contact algorithm.

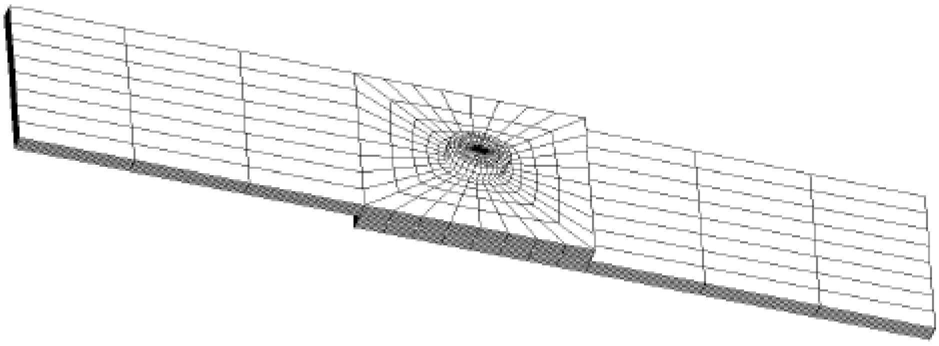
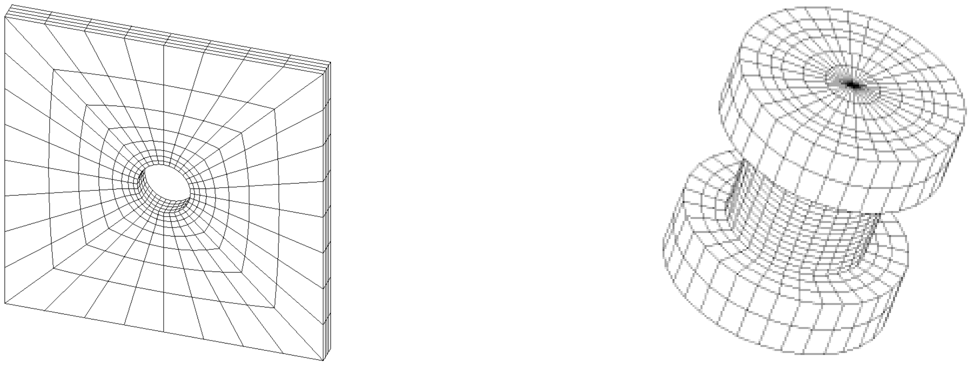


Figure 3. Finite element model of the bolted single-lap joint

The 3-D type of analysis aims to an accurate representation of the 3-D stress field developed around the bolt due to bending effects and to clamping force of the fastener. It allows addressing all three-dimensional damage types, such as delamination and out-of-plane buckling, as well as stacking sequence effects and secondary moment in the area close to the bolt.

The mesh of the plates is divided into two main regions. A square corresponding to the overlap area with detailed mesh around the bolt, shown in Figure 4(a), and a region with a coarser mesh away from the bolt as indicated in Figure 3. Figure 4(b) shows the geometry and the finite element mesh of the bolt. To achieve high accuracy in the calculations of the interlaminar stresses for the composite laminate eight layered elements stacked together were used in the thickness direction. The bolt, washer and nut were considered as one unit to limit the number of contact elements in the model.



(a) (b)

Figure 4. (a) Detailed mesh of the area around the bolt
(b) Finite element model of the protruding head bolt

The composite plate is loaded with an in-plane uniform tensile pressure at its end, while the aluminium plate is fully built in. As a first load step, pre-tension load in the fastener was applied, by giving first thermal expansion properties in the axial direction of the fastener and then decrease the temperature to create thermal stresses. Secondary bending of the joint was prevented by applying lateral support (zero displacement in the z-direction) in the model. Friction was considered in the model by giving different friction coefficients for the different contact surfaces. Their significance in the calculated stresses has been studied. More attention was given to the friction between the two plates, which was found[13] to affect significantly the results.

4 RESULTS AND DISCUSSION

In order to check the model, an application was made for the case that the lap joint of Figure 2 was loaded with a constant tensile load of 8kN. Computed strain distributions of the present model are given in Figure 5. The strains have been calculated for the xy-plane at $z=t$ at the angles of 0, 22.5 and 45^o with respect to the x-axis of the global coordinate system. Comparison was made with experimental and numerical results from [13]. The experimental values of strain were measured[13] using different sets of strain gauges arranged circumferentially around the hole at angles of 0, 22.5 and 45^o. The comparison with experimental results indicates a sufficient accuracy of the present model. The coincidence of the computed strains for the 0, 22.5 and 45^o angles with present model seems more realistic than the respective curves calculated with the model in [13] with regard to the considered pseudo-isotropic material.

Implementation of the progressive model was made for the case that the bolted single-lap joint was subjected to incrementally increasing tensile load. The initial applied load was 2.0kN, as it was found that the first failure (matrix compressive failure) occurs in the value of 1.5kN. The load increment was 1.2kN. Due to symmetry of the configuration only the half of the finite element model shown in Figure 3 was solved. Material properties and strengths of the laminated material HTA/6376 used for progressive modeling are shown in Tables 2[11] and 3[11], respectively.

Figure 6 illustrates the prediction of progressive damage in the composite laminate for different load steps. In this figure the shaded area denotes the areas that have suffered from fiber breakage, which represents the most important failure mode for the current configuration. A friction coefficient of 0.3 was considered only for the contacts between the two plates and between the bolt washers and plates. In the early stages of loading the composite behaves elastically with no indication of damage in the material. As the load increases the first ply fiber failure load is computed at a load of 3kN and damage begins to appear near the stress concentration at the hole boundary. Damage initiates at about 45^o with respect to the loading direction and propagates through the bottom side of the laminate, mainly due to the pressure from the bolt. Further loading is causing damage growth (Figure 6(b)) leading to a situation indicated in Figure 6(c) where the composite cannot handle more load, i.e. where the point of ultimate failure has been reached. The ultimate load of 20.2kN is predicted. For component final failure it has been selected the point where damage has spread to the outer edge of the specimen. This choice is not obvious and is still a matter for additional investigation. At the point of final failure, analysis showed that substantial matrix failure has occurred in the entire laminate. Delamination failure was calculated in the hole edges and in a big area around the hole due to high free-edge interlaminar and shear stresses. In Figure 7 the analysis results for the lower surface of the laminate, are presented. Observation of the computed damage indicates that damage propagates in a faster way than in the upper surface, due to higher stress values observed between the two plates as a result of friction.

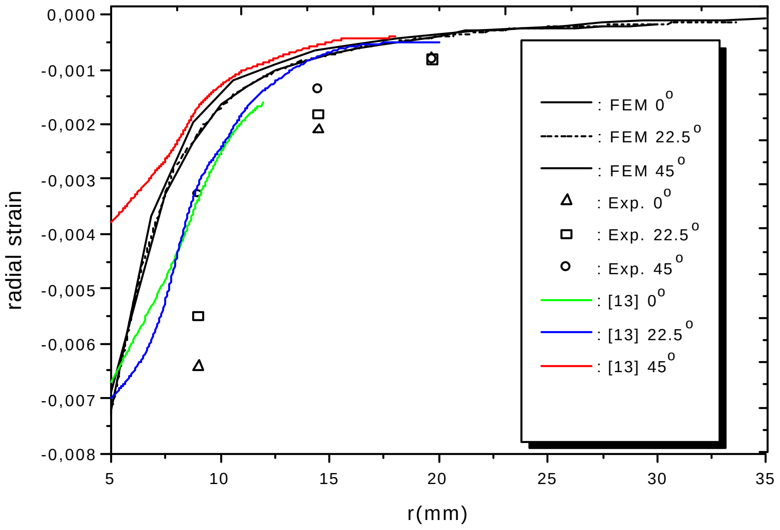


Figure 5. Comparison of calculated strains with experimental and numerical results from [13]:

L (mm)	*W* (mm)	*D* (mm)	*d* (mm)	*e* (mm)	*h* (mm)	*t* (mm)
240	60	16	10	30	30	4.16

Table 1. Geometrical data for the investigated geometry

E_X (GPa)	E_Y (GPa)	E_Z (GPa)	G_{XY} (GPa)	G_{XZ} (GPa)	G_{YZ} (GPa)	n_{XY} (GPa)	n_{XZ} (GPa)	n_{YZ} (GPa)
145	10.3	12.1	5.3	5.275	3.95	0.301	0.5	0.495

Table 2. Elastic properties of HTA/6376 material.

X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S_C (MPa)
2250	1600	64	290	98

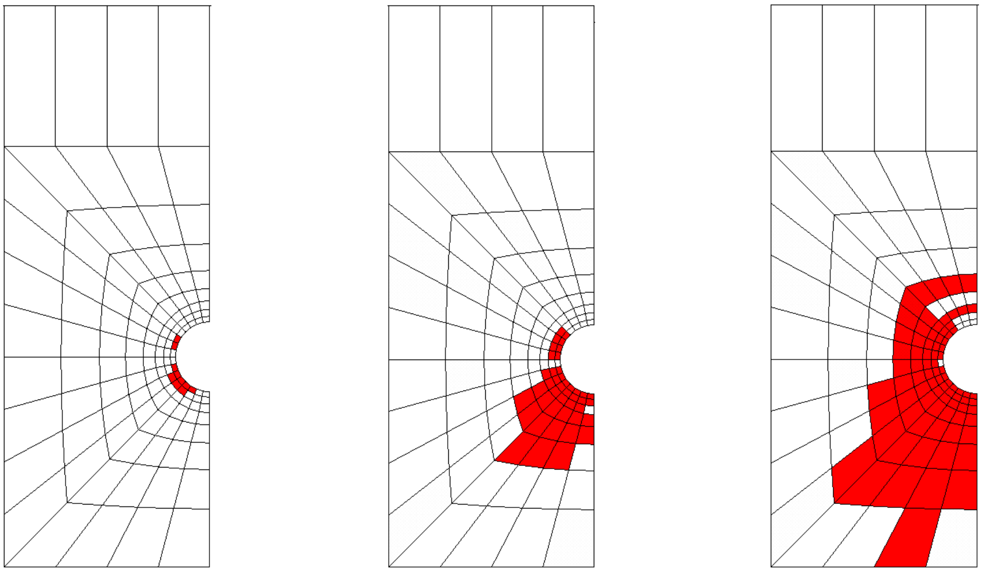
Table 3. Strengths of HTA/6376 material.

In order to account for the effect of two important geometrical parameters, which are the width *w* of the plate and the vertical distance *e* of the hole to the free-edge on the damage initiation and propagation, an extended parametric study was carried out. The damage accumulation predicted for the cases of *w*=40mm, *h*=20mm and *e*=15mm are shown in Figures 8(a) and 8(b), respectively. It is clear that as the hole is placed closer to the boundary of the specimen, damage initiates at a lower loading (1.0kN for case (a) and 1.25kN for case (b)) and propagates faster towards the free-edge. The final failure predicted is at 14.7kN and 17.2kN, repectively. Further investigation is currently conducted in order to examine the effect of ply orientation on the strength and damage accumulation as well as to examine the appropriateness of the used failure criteria and degradation rules.

5 CONCLUSIONS

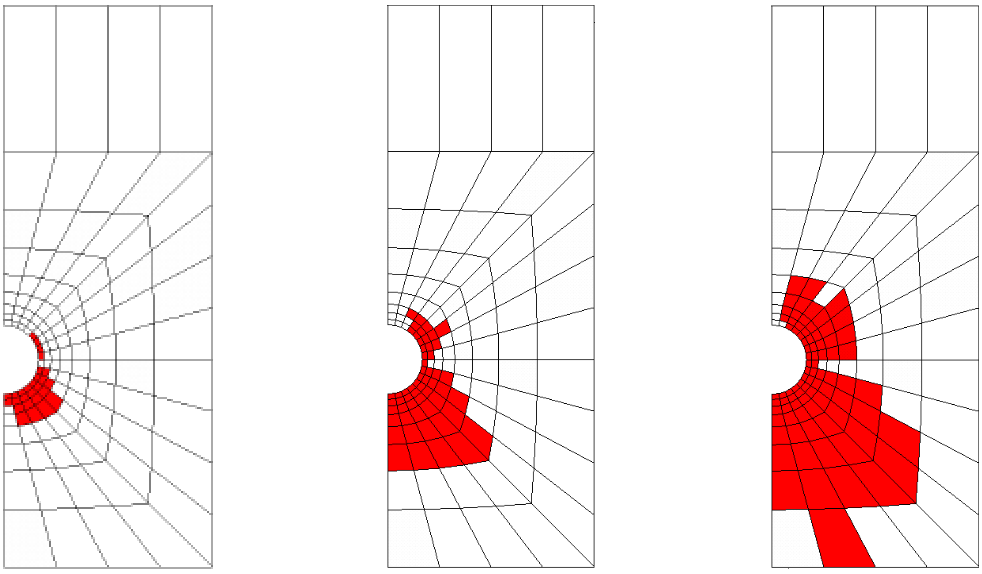
A three-dimensional progressive damage model was developed in order to predict the ultimate strength of bolted single-lap composite joints under in-plane tensile loading. The parametric model involves stress analysis, failure analysis and material property degradation. Stress analysis was performed using the FE code ANSYS. Failure analysis and material property degradation were implemented using a set of stress based Hashin type failure criteria and a set of appropriate degradation rules.

Preliminary validation of the model was done for the case of a constant pressure by comparing the radial strain distribution in different angles around the laminate hole with analytical and experimental values. For the case of progressive loading, the analysis showed that after a certain load value damage initiates near the stress concentration of the hole and propagates at 45^o with respect to the loading direction towards the lower specimen edge. The load value where damage has reached the outer specimen edge was selected for a final failure criterion. The results show that the geometry of the bolted hole configuration can dramatically influence both the initiation of damage and the residual strength.



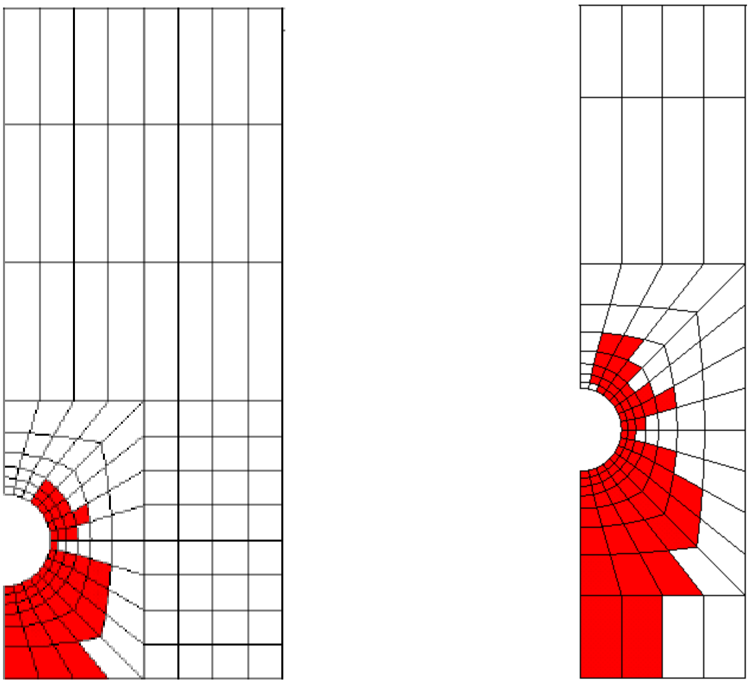
(a) 3kN (b) 12kN (c) 20.2kN

Figure 6. Illustration of damage propagation predicted by the present model at different load steps Upper surface of the $[90/0/-45/45]_{S8}$ laminate



(a) 3kN (b) 12kN (c) 20.2kN

Figure 7. Illustration of damage propagation predicted by the present model at different load steps. Lower surface of the $[90/0/-45/45]_{S8}$ laminate.



(a) 14.7kN (e=15mm) (b) 17.2kN (w=40,mm h=20mm)

Figure 8. Illustration of damage propagation predicted by the present model at different load steps. Lower surface of the $[90/0/-45/45]_{S8}$ laminate.

ACKNOWLEDGEMENTS

This work was conducted in the frame of the programme “Efficient Design and Verification of Composite Structures” (EDAVCOS). The financial support provided by the European Community Commision under Contract BRPR-CT98-0611 is gratefully acknowledged.

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