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Numerical Simulation of Bolted Joints Pull Through Failure

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Abstract. Finite Element Analysis numerical models were generated to simulate and investigate the pull-through damage of bolted joints on composite laminates. Three-dimensional elements were used along with a user material subroutine incorporating the material failure criterion in Abaqus® software. Simplified Discrete Ply Modelling (DPM) and Cohesive Zone Modelling (CZM) were also employed. The numerical model predictive capability was assessed and the parameters influencing the pull-through failure process were investigated. The residual bearing strength of bolted joints following pull-through damage suggested a qualitative agreement between the numerical model and the experimental testing results.

1 INTRODUCTION

The application of fibre reinforced plastic composite materials in the aeronautical industry has been increasing rapidly due to the material excellent structural performance [1]. For relatively thin laminates commonly used in composite air vehicle structures, the secondary bending induced on single lap joints under tensile loading which can lead to pull though failure in the joint, is essential to be considered for predicting failure. The characteristics of pull-through damage are very similar to the damage from low velocity impact [2][3]. The pull-through failure material response is governed mainly by interlaminar delamination and through-thickness shear failure. The Discrete Ply Model (DPM) is a compacting modelling method, where cohesive elements were employed to simulate the inter-ply delamination and shear failure [4] at specific layer locations. The factors related pull-through performance include bolt hole clearance fit and friction, washer diameter, layup stacking sequence, interfacial strength of cohesive elements to name a few. Giannopoulos *et al.* analysed the residual bearing strength of bolted joints with various pull-through loading via experiments [5]. The scope and objective of this work was to generate numerical models of bolted joints in composite laminates for pull-through failure and residual bearing strength investigation.

2 METHODS

To accurately predict the pull-through failure, the out-plate stresses introduced along the thickness direction loading were considered. Thus, 3D elements were selected for the finite element modelling, with a user material failure criterion. The material used was Hexcel AS7/8552 and the specimen were designed with a stacking sequence of $[45/0/-45/90]_{3S}$, having a total thickness of 3.312mm. The specimen design is shown in
Figure **1**. Eight-node linear brick elements (C3D8) with full integration without hourglass effect were utilized. The simulation was divided in two steps; Firstly, the pull-through loading was applied on the bolt damage for investigating the damage extents. Then, the laminate with the imprinted pull though damage was subjected to bearing loading.

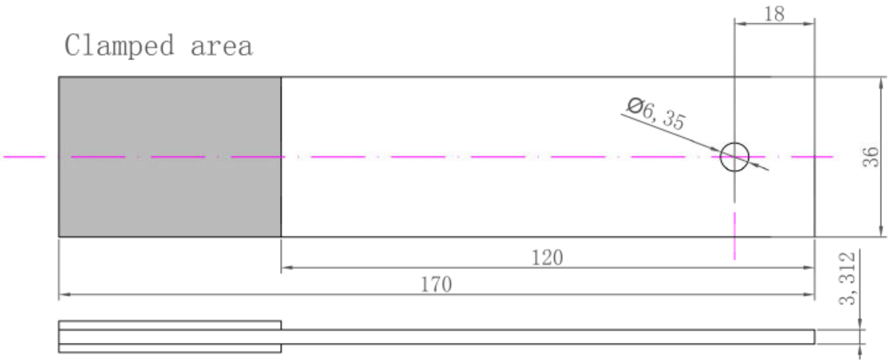

Figure 1. Dimensions of specimen

In the DMP modelling, the cohesive elements were placed at the interfaces of solid elements to represent the inter-ply delamination. To simplify the modelling, the cohesive boundaries were inserted between every four plies as shown in Figure 2. The critical parameters for numerical simulation of cohesive behaviour are the interfacial strength, penalty stiffness, energy release rate and the meshing size.

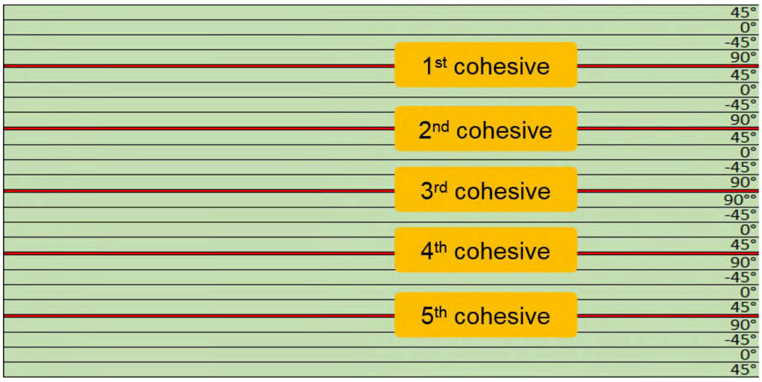

Figure 2 Cohesive behaviour in laminate

The material properties of AS7/8552 used in UMAT are listed in Table 1. The properties of cohesive interaction were shown in Table 2.

AS7/8552 properties							
E_{11}/GPa	145	E_{22}/GPa	12	G_{12}/MPa	4800	G_{13}/MPa	4800
G_{23}/MPa	3980	ν_{12}	0.32	ν_{13}	0.23	ν_{23}	0.43
X_t/MPa	250	Y_t/MPa	62.3	X_C/MPa	1862	Y_C/MPa	268
S_{12}/MPa	128	St/MPa	101	S_L/MPa	128	G_{IC}(N/mm)	0.25
G_{IIC}(N/mm)	0.69						

Table 1. Material Properties of AS7/8552

Cohesive interaction properties							
σ_{1max}/MPa	60	σ_{2max}/MPa	90	σ_{3max}/MPa	90	G_{IC}(N/mm)	0.25
G_{IIC}(N/mm)	0.69	K_{NN}(N/mm^3)	800000				

Table 2. Cohesive interaction properties

3 FINDINGS

Numerical FE simulation and experimental results of the pull through test are shown in Figure 3. The simulation curve showed two loading peak points, the first peak at (0.57mm, 11.77KN) and the second peak at (1.96mm, 18.87KN). The FE model prediction vs testing error for the first load peak was 8%. The error for the second load peak was 18%. The loading vs displacement curve slopes before the first and second loading peak values were almost identical between simulation and testing.

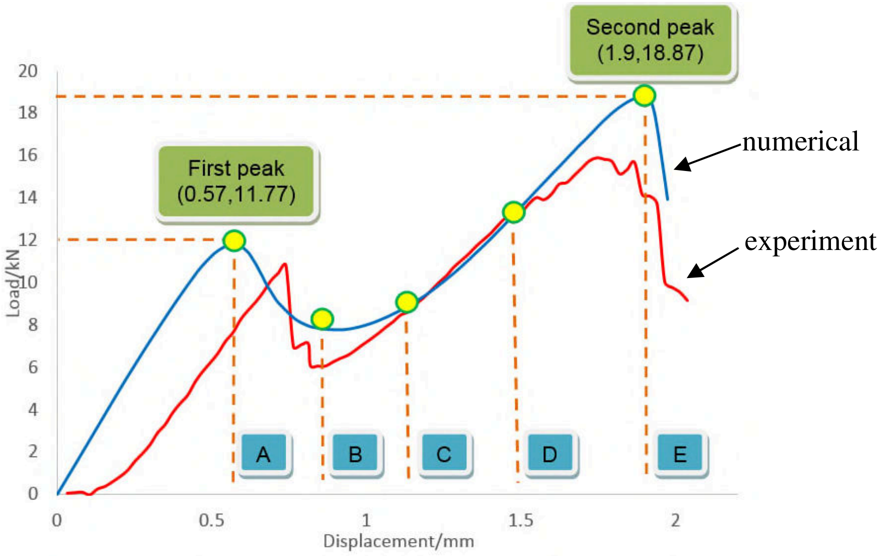

Figure 3. Numerical result and test data

The initial stage of loading exhibited non-linear behaviour during testing while it was linear during numerical simulation. The loading of numerical modelling dropped less abruptly.

The delamination of the laminate under pull-through is illustrated in Figure 4. The blue zone denotes the delamination area. Three loading points were selected, point A corresponding to first peak of the pull through curve, point B corresponding to first drop and point E corresponding to the second load peak, as shown on Figure 3. These are also reported for the first cohesive layer and the fifth, the first being the top side where there is contact with the bolt head.

It was concluded that the delamination through the whole laminates was caused by the crack under the bolt head that propagated through the thickness from the top laminates to the bottom laminates. The delamination played an important role in the amplitude of the first peak.

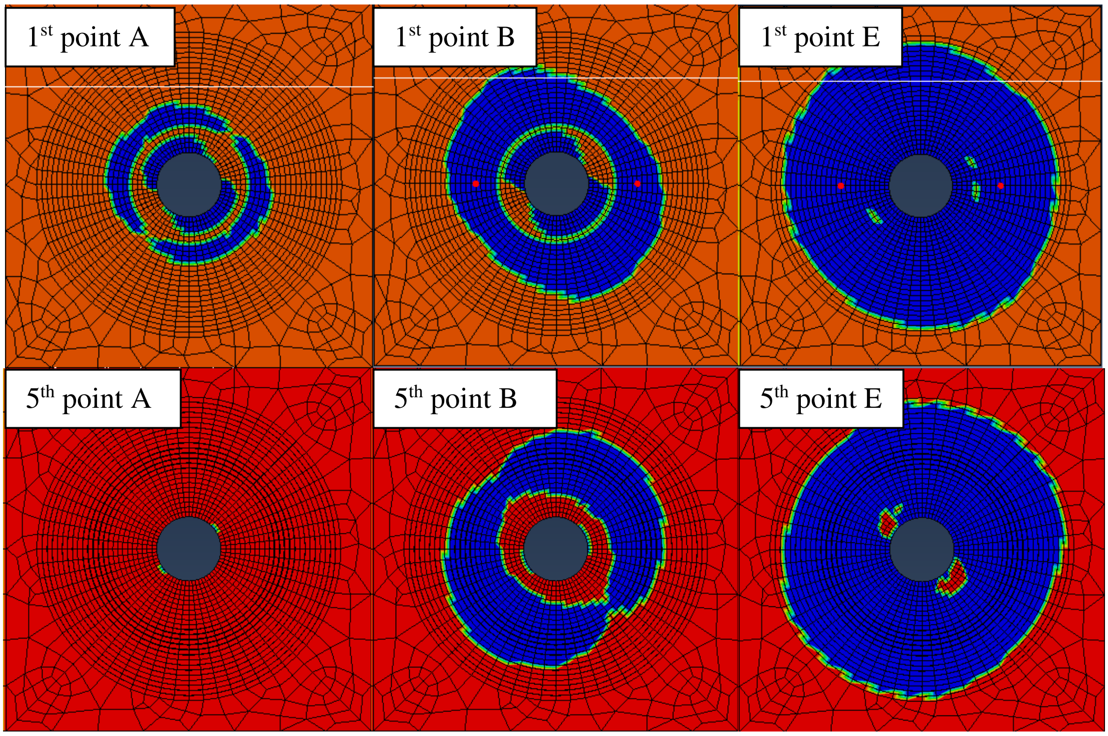

Figure 4. Delamination of cohesive

Figure 5 depicts the matrix failure. The failure started from the top surface and bottom surface under the bolt head. At the point A of first peak of the pull though phase according to figure 3, the matrix cracking propagated through thickness away the bolt hole. At the final damage, the matrix cracking occupied the regions near the bolt hole through the thickness direction with an envelop of a “staircase". The matrix cracking coincided with the interlaminar shear stress distribution.

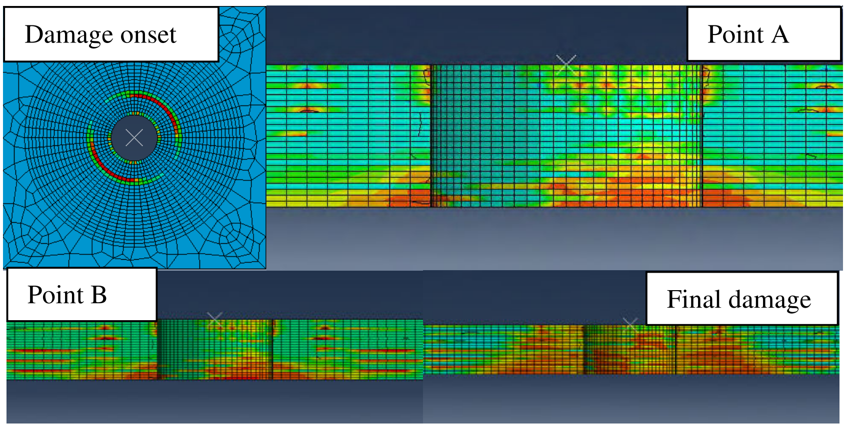

Figure 5 Failure of matrix

The failure of fibres under pull-through loading are shown in Figure 6 . It was found that the initial damage of fibre occurred at the point of first peak in the lower 90°ply. However, the fibre damage did not expand significantly until the second load peak. On the contrary, the matrix cracking propagated quickly after the first peak. It was concluded that fibres bore the pull-through loading after the first load drop, resulting a the second increasing of loading.

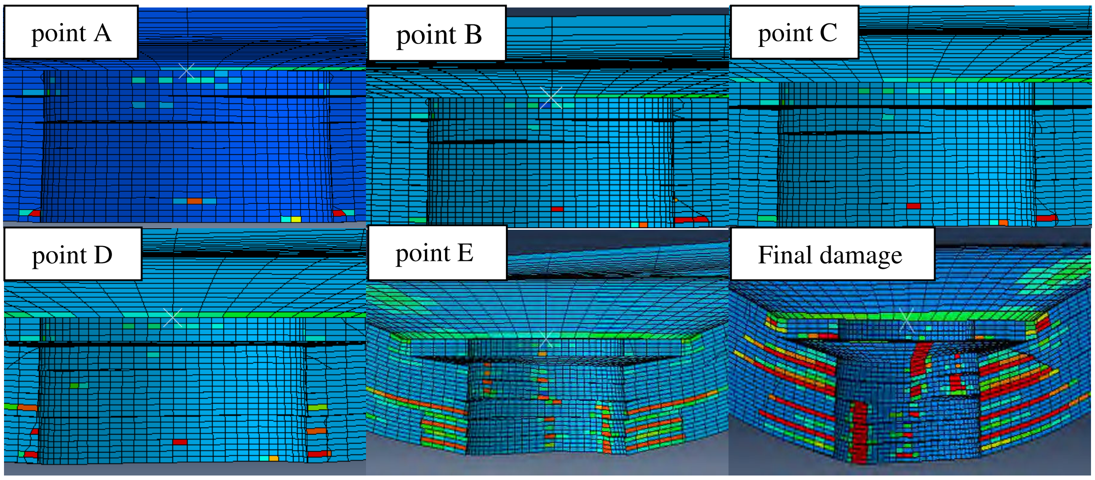

Figure 6 Failure of fibres

The parameters of the specimen of test, employed as benchmark for the numerical modelling. The parameters of testing specimen and standard numerical modelling were illustrated in Table 3.

Parameters	Values
Normal interfacial strength	60 MPa
Shear interfacial strength	90 MPa
Clearance of bolted joint	0 mm
Boundary diameter	26 mm
Stacking sequence	$[45/0/-45/90]_{3S}$
Washer diameter	12 mm

Table 3. Parameters of test

Factors influencing pull-through loading were investigated such as bolt hole to bolt shank clearance, washer diameter, boundary support diameter for pull through and interfacial strength of the composite laminates. The effects of interfacial strength and boundary support diameter for pull through are shown in Figure 7.

For the test and standard numerical modelling, the normal strength σ_{1max} of cohesive interaction and shear strength σ_{2max} were 60Mpa and 90Mpa respectively. To investigate the effect of interfacial strength on the pull-through loading, lower interfacial strengths were employed: 28MPa(σ_{1max})/47MPa(σ_{2max}), 40MPa(σ_{1max})/66MPa(σ_{2max}). It can be observed on figure 7 that the first peak loading was determined by the interfacial strength of the cohesive layers. The onset and propagation of delamination determined the magnitude of first peak of the loading curve.

The boundary diameter was the diameter of support fixture for the pull through test, which was of no influence on the pull-through loading. The diameter from the test was 26mm, but simulations were run with boundary diameters of 22mm and 30mm. From figure 7 it can be observed that the elastic stiffness of laminate under pull-through loading was affected but not the first drop failure load.

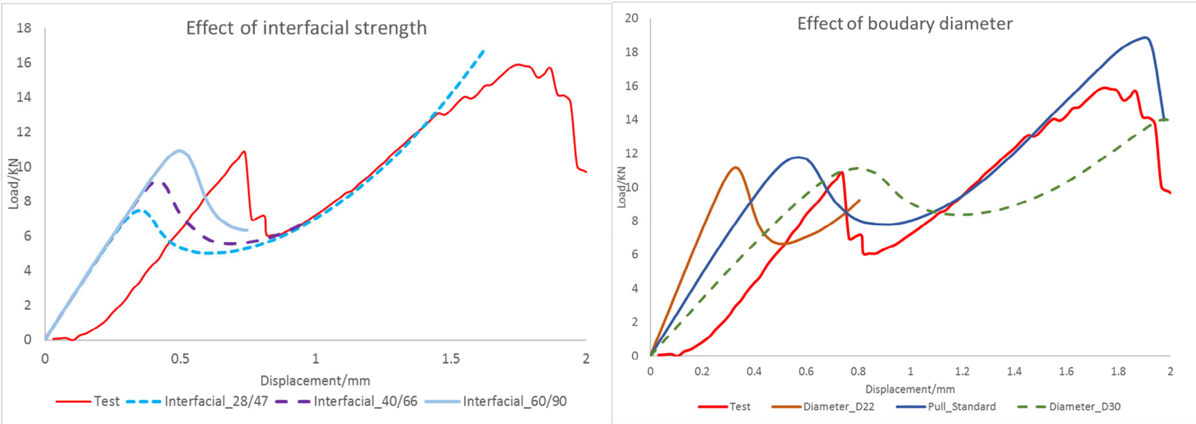

Figure 7 Effects of interfacial strength and boundary diameter

The influence of the washer and the bolt clearance of bolted joint were analysed with the results shown in Figure 8. The diameter of washer of the test was 12mm and a larger washer diameter of 15mm was employed to observe the influence. It was seen that the loading of first peak, final loading and elastic stiffness increased. The rise of first peak and elastic stiffness was 47%. However, the increase of final loading was larger, about 73.5% higher than smaller washer. The enlarged washer reduced the pressure on the laminate with the same pull-through loading, resulting enhanced loading capacity.

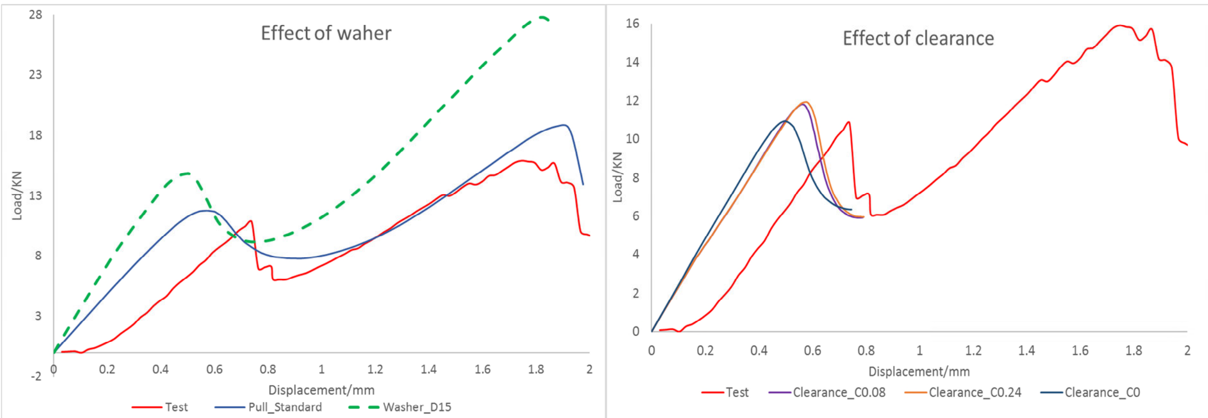

Figure 8 Effects of washer and clearance

Clearance had a different effect on pull-through loading versus that on bearing strength of bolted joint. It was concluded that the bearing strength reduces with the increased clearance [6]. The first peak loading increased slightly with a clearance of 0.08mm, however the rise of first peak was negligible when the clearance was further enlarged from 0.08mm to 0.24mm.

The residual bearing strength of bolted joints following pull-through damage was analysed via experimental testing [5][7]. It was indicated that the residual bearing strength reduced with bigger pull-through damage in place. The numerical modelling for residual bearing strength was created with inherent delamination and the results were illustrated in Figure 9.

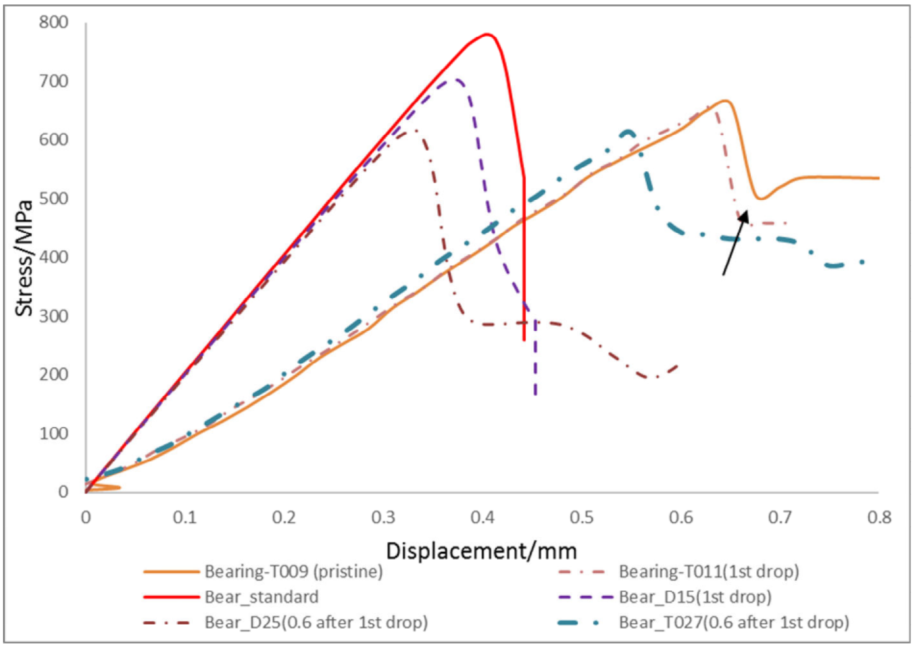

Figure 9 Residual bearing strength

It was found that the residual bearing strength was influenced by the inherent damage resulting from pull-through loading. For test data, the bearing strength decreased by 1.5% at the 1st drop and 7.6% at 0.6mm passing 1st drop. The results of FE model had the similar trend with test data; however, the ratio of reduction was bigger at the point of 0.6mm after 1st drop. The numerical modelling predicted the residual bearing strength of bolted joint qualitatively which captured the decrease trend of residual strength after pull-through damage. However, the strength predicted was not accurate enough versus test data due to the simplification of the inherent damage.

4 CONCLUSIONS

The numerical modelling including cohesive interaction was create to mimic pull-through failure of bolted joints. The numerical results were compared to those of experiment indicating that numerical modelling captured the typical points of pull-through failure and agreed with test data well. The mechanics of pull-through was analyzed thanks to stress distribution and delamination which was corresponding to conclusions in [3]. The residual bearing strength was investigated by a separate numerical modelling. The damage caused by pull-through damage was represented by inter-ply delamination. The numerical modelling predicted the residual bearing strength qualitatively well versus experiment data. Due to simplification and assumption in the numerical modelling for residual bearing strength, the numerical modelling had error and needed to be improved in the next stage.

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