PREDICTION OF OUT-OF-PLANE FAILURE MODES IN CFRP

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Keywords: Pull-through, CFRP failure, Bolted joints, Out-of-plane,

Abstract

The design of composite structures used in jet-engines in the presence of stress concentrations, such as bolted or riveted joints, is a critical step for the effective use of composite materials and for the reduction of structural weight. Recent developments on analysis methods did not account for the relevant out-of-plane failure modes of bolted joints (pull-through).

An experimental and numerical study is presented on the pull-through failure modes in carbon fibre reinforced plastic (CFRP). Assuming bolted joint failure at the first damage event, when the sub-critical failure load is reached, a numerical three-dimensional finite element model is proposed to predict the onset of damage. Numerical analysis models show good agreement between the experimental data and initial sub-critical predicted load.

1. Introduction

There are several parameters that influence the performance of a composite material when subject to out-of-plane load solicitations. Geometry of the fastener, laminate thickness, stacking sequence, material system, and specimen size are among the studied aspects on composite pull-through failure modes [1, 2, 3].

CFRP pull-through failure can be characterized by substantial internal damage that usually initiates at low levels (20 - 30% of the failure load) in the sub-surface plies. Failure mode is characterized by matrix cracking followed by delaminations distributed conically through the thickness of the laminate and moving away from the fastener axis [1, 2]. Laminate stacking sequence and resin system are pointed as the cause for the type of damage and the ultimate failure mode [2].

There are two options to predict out-of-plane failure modes. One is a simplified formulae such as equation (1) [4]:

$$\gamma_f C_m \sigma_{xz,s} \geq \frac{\sigma_{xz,k}}{\gamma_m} \tag{1}$$

where C_m is the coefficient of model uncertainty (taken as 2), γ_f, γ_m are actions and material properties factors of safety respectively, $\sigma_{xz,k}$ is the through-the-thickness shear strength and $\sigma_{xz,s}$ is the action stress defined as:

$$\sigma_{xz,s} = \frac{F_{bolt}}{\pi D t} \tag{2}$$

where D is the diameter of the fastener head or of the washer.

The second option to predict out-of-plane failure modes is by performing detailed three dimensional FEM together with CDM [5].

2. Experimental work

2.1. Material

The composite material used in this study was IM7/8552 from HEXCEL®. The test envelopes were manufactured using hot-press with quasi-isotropic $[90/0/\pm45]_{3S}$ ply lay-up. The UD mechanical properties of these laminates are reported in table 1 where: E_i is the Young's modulus in i direction, ν_{ij} is the Poisson's ratio in the i-j direction, G_{ij} is the shear modulus in i-j direction, X_T is the longitudinal tensile strength, X_C is the longitudinal compressive strength, Y_T is the transverse tensile strength, Y_C is the transverse compressive strength, S_T is the transverse shear strength, S_L is the longitudinal shear strength, and ρ is the density.

2.2. Pull-through tests

Tests were conducted using an INSTRON-4208 test machine and following ASTM standard D7332 - *Standard Test Method for Measuring the Fastener Pull-Through Resistance of a Fiber-Reinforced Polymer Matrix Composite* [6]. This norm is composed of two procedures. For the tests reported herein, procedure B was used. The procedure uses square flat test specimens with a circular hole in the center where the fastener is installed. Load is applied to the specimen by use of a steel fixture. Figure 1 shows the experimental set-up used.

Squared specimens with 84 mm in length and 3 mm thickness and with a center hole of 6 mm in diameter (Figure 2) were tightened with a torque of 2.2 N·m (finger-tight) and then tested until catastrophic failure. The test machine was equipped with a 100 kN load cell and the speed used for all tests was 0.2 mm/min (displacement controlled test). Load and displacement were recorded with a frequency of 5 Hz. The room temperature was 23°C with 50% relative humidity for the duration of all tests.

2.3. Experimental results

Figure 3 shows the load vs displacement curves for all tested specimens. The derived properties are reported in table 2 where the initial sub-critical load is taken as the point where there is a drop in the load or a change in the loading curve. The failure load is the maximum load obtained in the test. The damage process begins with matrix cracking immediately followed by delaminations at a relatively low load (initial sub-critical failure) on the bottom side (compression). As load increases the intralaminar fracture of the material starts and the fastener head begins to penetrate the test sample as catastrophic failure occurs. The effect of these damage mechanisms can be observed in Figure 4 which shows both sides of a specimen after testing.

3. Numerical model

A numerical model based on the Finite Element Method was developed to predict the onset of damage (initial sub-critical failure) using ABAQUS 6.11 [7] software package. The meshed model can be seen in Figure 5 where the specimen, bolt, washers and nut where modeled as deformable bodies, the steel plate (fixture apparatus) was modeled as an analytical rigid surface. A rough no-separation friction formulation was applied to all elements, after contact is established no slip will occur. The test specimen, in Figure 5, was modeled using an 8-node linear brick, reduced integration, hourglass control (C3D8R) with 0.6 mm element size for the refined part of the mesh.

Vogler et al. [8] plasticity model was implemented as the failure criteria using an ABAQUS user's subroutine (UVARM) to predict delamination, detailed definition of the invariant based model can be found in [8].

3.1. Numerical results

Figure 6 shows the predicted load (1,908 N) by the numerical model, and the experimental load values for delamination onset. As can be observed, the predicted values are in good agreement with the experimental data.

4. Concluding remarks

In this study an experimental and a numerical investigation was conducted on the off-axis damage mechanism in graphite/epoxy laminates. IM7/8552 squared plates with a hole in the center were used to conduct experimental pull-through tests. A three-dimensional numerical model was developed to predict the onset of damage on this particular type of load solicitation. Looking at the results, it can be concluded that:

- the interlaminar damage is the predominant initial damage mechanism.
- the numerical model accurately captures the initial sub-critical damage load.

5. Acknowledgments

The authors gratefully acknowledge the support of the European Union Seventh Framework Programme (FP7) Grant Agreement No. FP7-AAT-2012-RTD 4.1-6 314307 and all the SHEFAE program partners.

6. Tables and figures

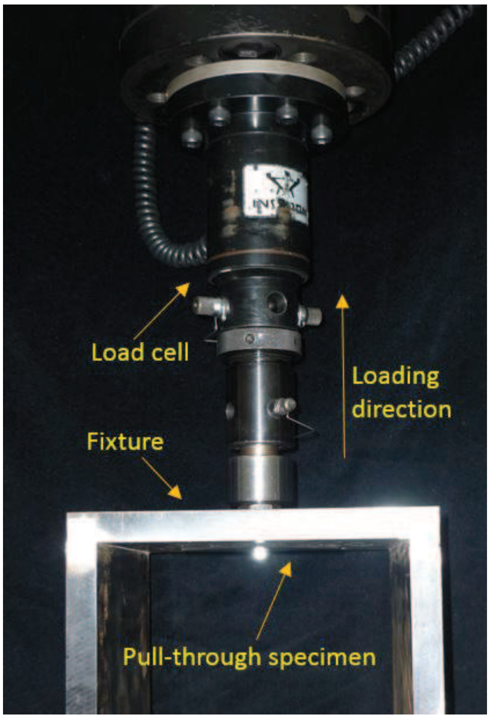

Figure 1. Experimental set-up used to perform the pull-through tests.

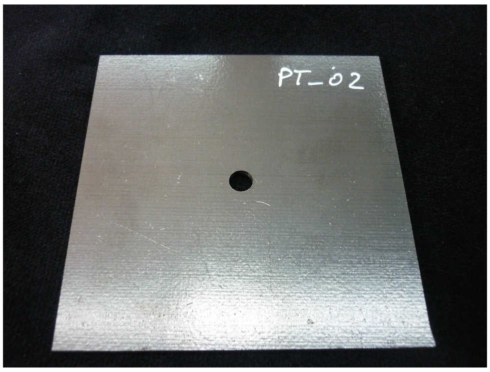

Figure 2. Photograph of a pull-through specimen prior to testing.

Property		**Units**
E_1	171.4	GPa
$E_2 = E_3$	9.1	GPa
ν_{12}	0.32	
$\nu_{13} = \nu_{23}$	0.52	
G_{12}	5290	MPa
$G_{13} = G_{23}$	4200	MPa
X_T	2323.5	MPa
X_C	1201	MPa
Y_T	160.2	MPa
Y_C	199.8	MPa
S_T	88.2	MPa
S_L	126.9	MPa
ρ	1590	kg/m^3

Table 1. Mechanical properties of the IM7/8552 UD laminate.

Specimen	**Initial sub-critical failure load (N)**	**Failure load (N)**
PT_01	3,524	7,308
PT_01_SG	2,396	6,880
PT_02	2,404	7,364
PT_02_FT	2,432	4,900
PT_03	1,968	6,660
Mean	2,545	6,622

Table 2. Pull-through test results.

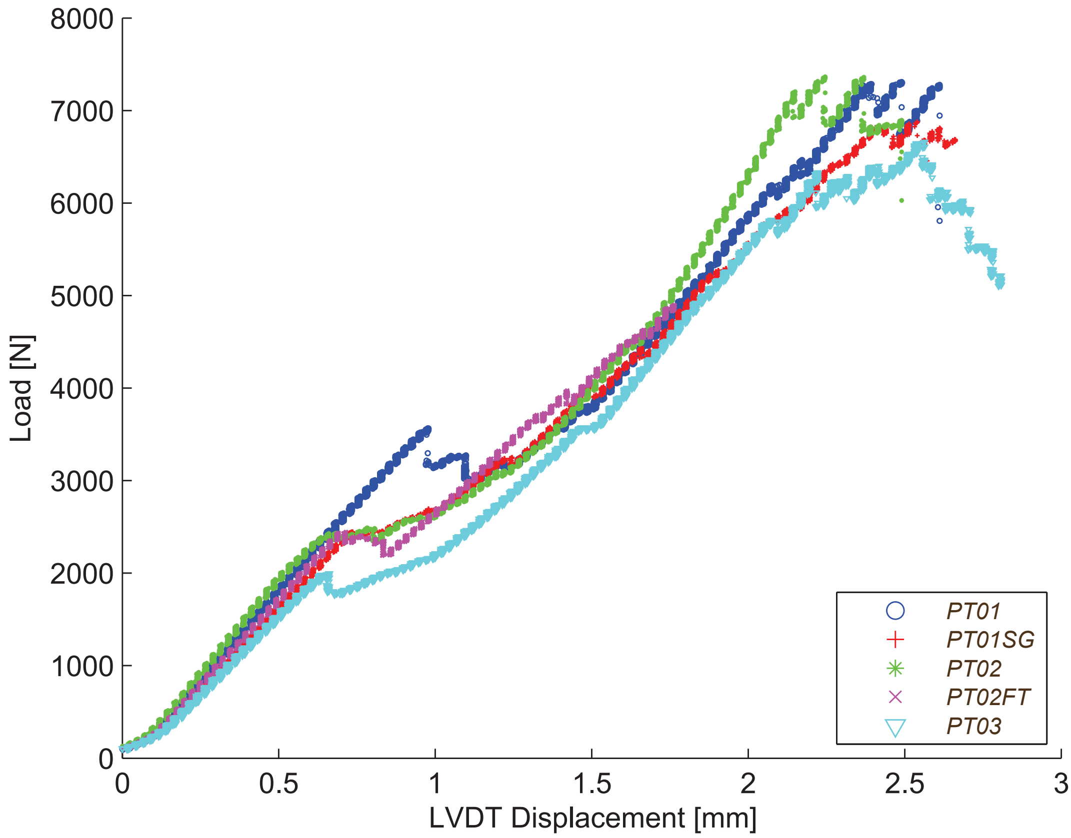

Figure 3. Test fixture used in Pull-through tests.

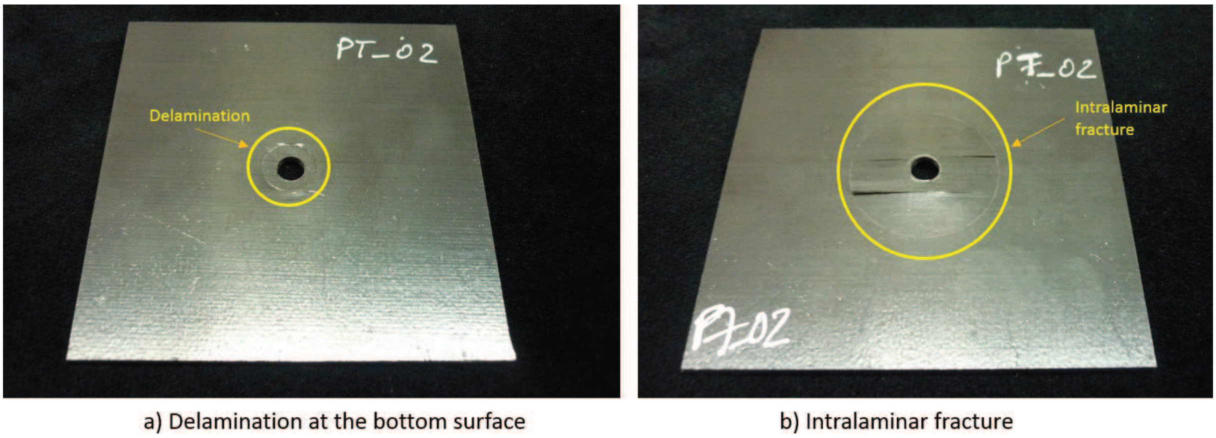

Figure 4. Pull-through specimen after experimental test.

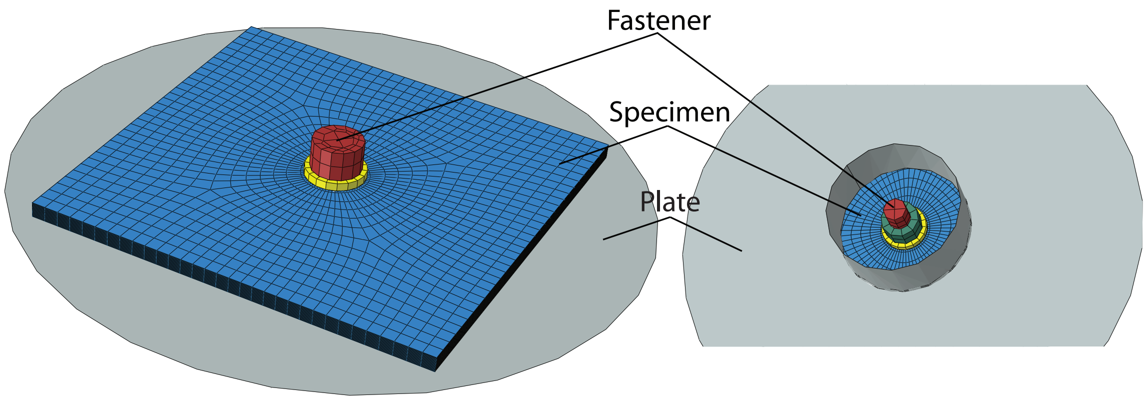

Figure 5. FE meshed model for the pull-through test showing bottom (left) and top (right) sides.

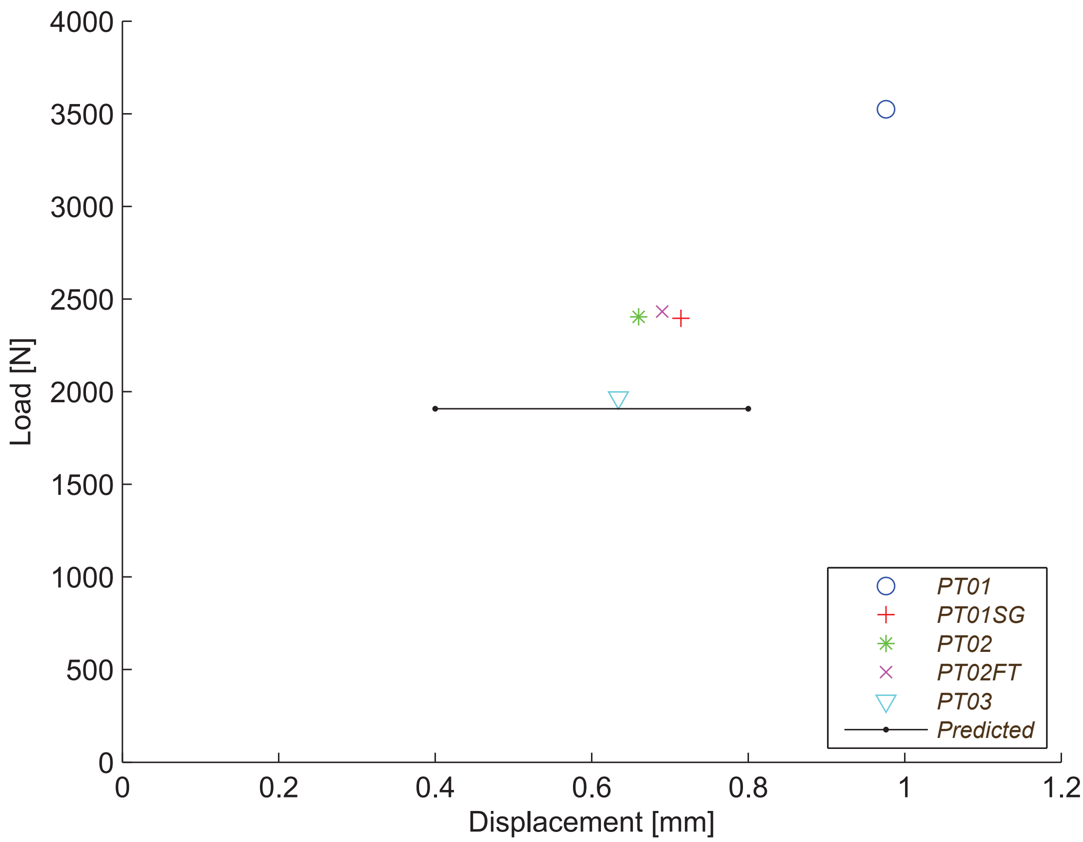

Figure 6. FE predicted load for onset of damage with experimental sub-critical failure load.

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