# PREDICTION OF PROGRESSIVE FAILURE IN WOVEN GLASS/EPOXY COMPOSITE LAMINATED PANELS

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## ABSTRACT

*A progressive failure analysis of woven glass/epoxy laminated plates is developed via the non-linear finite element analysis. A progressive failure analysis algorithm has been developed and implemented as a user subroutine in a finite element code (ABAQUS) in order to model the non-linear material behavior and to capture the complete compressive response of woven composite plates made of glass-epoxy material. Tsai-Hill failure theory has been employed in the progressive failure methodology to detect failure of the woven composite laminates. The reliability of the numerical analysis has been validated against the results obtained from quasi-static compression tests. It has been found that the results obtained via the progressive failure analysis correlate reasonably well with the experimental results.*

**Keywords:** *Progressive failure analysis, finite element analysis, woven composites, failure theory*

## 1.0    INTRODUCTION

Composite materials are widely used in advanced structures in aerospace, automobile, marine, and civil engineering applications due to their superior properties over conventional engineering materials such as metals. The high strength and stiffness-to-weight ratio of composite materials have attracted the aerospace industry in particular. The use of composite materials for aircraft primary structures can result in significant benefits on aircraft structural cost and performance. Carbon fibre fuselage structures are expected to be realized with future generations of aircraft. Such applications of composite materials are expected to reduce the weight of aircraft structures by about 30-40% and to reduce the cost about 10-30% as compared to the conventional metallic structures [1]. Accurate prediction of the damage behaviour of composite laminated structures

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will lead us to the design of efficient structures which will in turn reduce the cost of manufacturing significantly. The use of numerical simulation tools such as the finite element method allow us to replace structural component testing with 'virtual testing' to predict the damage behaviour and the mode of failure of composite laminated structures. Accurate determination of failure modes and their progression helps either to devise structural features for damage containment or to define fail safe criteria.

The ability to predict the initiation and growth of damage in composite laminated structures is important to evaluate their performance and to develop reliable, safe designs which exploit the advantages offered by composites. Since most composite materials exhibit quasi-brittle failure with little or no margin of safety through ductility, as offered by many metals, the propagation of quasi-brittle failure mechanisms in composite structures must be well-understood. Under normal operating conditions, laminated composite structures can exhibit local damage mechanisms such as matrix cracks, fibre breakage, fibre-matrix debonding and delaminations which contribute to final failure. Strength-based failure criteria are commonly used to predict these phenomena. However, for most of the cases, failure criteria can only predict the onset of the different damage mechanisms occurring in composite materials. For composite structures that can accumulate damage before structural collapse, the use of failure criteria is not sufficient to predict ultimate structural failure. To bridge this gap, the past recent years have seen the development of numerical methodologies to address the progressive failure of composite materials [1-8].

To date, the complex behaviour of composite laminates under various loading conditions are still not well understood and requires further numerical investigations in order to better understand their behaviour especially in the post failure region. Studies of damage behaviour of woven fabric or bi-directional composite laminates are limited. Therefore, woven fabric glass/epoxy composites have been used in this study as case study to demonstrate the capability of the progressive damage analysis methodology.

In this paper, a progressive failure methodology for composite laminates using finite element analysis is developed for predicting the failure of brittle fibre-reinforced composites for static stress analysis. A stress-based failure criterion has been employed in the progressive failure algorithm for modeling material non-linearity in composite laminates. Woven glass/epoxy panels are fabricated and tested experimentally for comparison and validation with the numerical results.

## 2.0 COMPRESSION TESTS

Experiments were conducted to evaluate the performance of the woven panels made of C-glass/epoxy ($200g/m^3$ density) subjected to compression load. Glass-epoxy flat panels with and without centrally located circular cut-out which consists of eight layers with different fibre orientations were fabricated using the hand lay-up technique and were cured at room temperature. Four types of flat rectangular symmetric composite panels with and without cut-outs were fabricated. The stacking sequence and fibre orientations studied are as listed in Table 1:

Table 1: Stacking sequence and fibre orientations of panel A, B, C and D

| | |
|---|---|
| Panel A | Glass/Epoxy composite panel without cut-out- $[0/90]_{2s}$ |
| Panel B | Glass/Epoxy composite panel with cut-out- $[0/90]_{2s}$ |
| Panel C | Glass/Epoxy composite panel without cut-out- $[45/-45]_{2s}$ |
| Panel D | Glass/Epoxy composite panel with cut-out- $[45/-45]_{2s}$ |

Figure 1 shows the fabricated specimens and Figure 2 illustrates the schematic drawing of the geometry of fibre glass laminated panels containing a central circular hole with length *l*, of 320 mm, width *w*, of 60 mm, average thickness *t*, of 2.5 mm, and the cut-out diameter *D* of 38 mm. The plates without cut-outs have the same dimensions and geometry as that of the plates with cut-outs. Effective length is 210 mm.
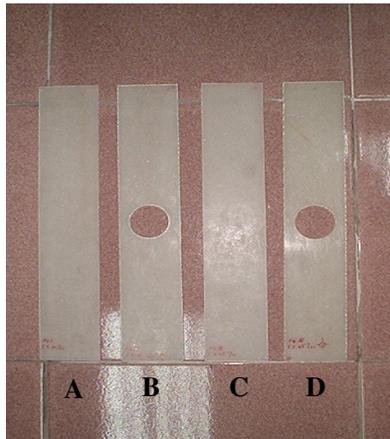


Figure 1: Test specimens
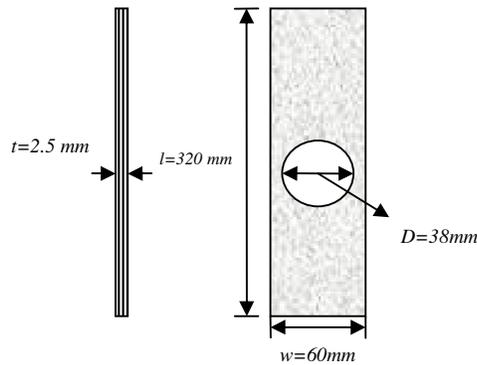


Figure 2: Geometry of the fiber-glass laminated plate with central hole

The fine or perforated fiber-glass laminated plates are subjected to uniform uniaxial compression load, *P* in *y*-direction as shown in Figure 3. The lower and upper horizontal edges of the plate are clamped into the clamping zone. The depth of the plate which are clamped both top and bottom of the test samples are $d_1=d_2=55$ mm. The two unloaded vertical edges are unconstrained from the transverse in-plane motion, which is defined as a moveable edge or free support. In all cases, the cut-out boundary is a free edge as well.
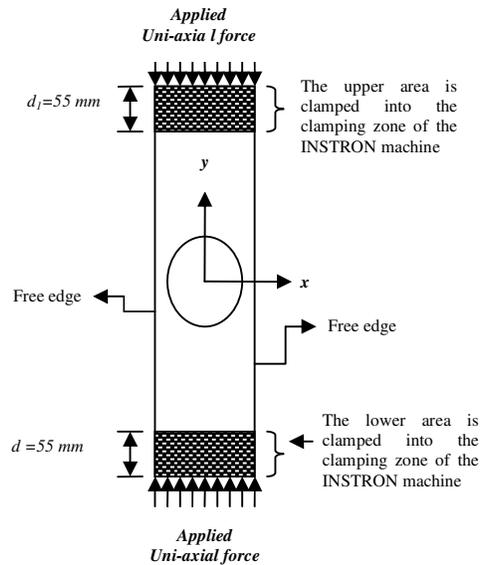


Figure 3: Load and boundary conditions of the test specimen



Figure 4: The test set-up for the compression test

The experiment is performed under quasi-static compressive loading for all the twelve composite panels up to failure using the servo-hydraulic testing machine, INSTRON (Figure 4). It is observed that all the laminated plates buckled globally until complete failure occurred as expected (Figure 5).



Figure 5: Buckled shape of panels with cut-outs

### 2.1 Composite Failure Theory

Tsai-Hill theory is based on the distortion energy failure theory of Von-Mises distortional energy criterion for isotropic materials as applied to anisotropic materials. It is assumed that failure in a composite material occurs when the distortional energy is greater than the failure distortional energy of the material. Hill [9] was the first to adopt the Von-Mises energy criterion to anisotropic materials. Based on the distortion energy theory, Tsai [10] then proposed that a uni-directional lamina could fail if equation (1) was violated

$$(G_2 + G_3)\sigma_1^2 + (G_1 + G_3)\sigma_2^2 + (G_1 + G_2)\sigma_3^2 - 2G_3\sigma_1\sigma_2 - 2G_2\sigma_1\sigma_3$$
$$- 2G_1\sigma_2\sigma_3 + 2G_4\tau_{23}^2 + 2G_5\tau_{13}^2 + 2G_6\tau_{12}^2 < 1$$

$$\tag{1}$$

$$(G_2 + G_3)\left(\sigma_1^T\right)_{ult}^2 = 1 \tag{2}$$

$$(G_1 + G_3)(\sigma_2^T)_{ult}^2 = 1 \tag{3}$$

$$(G_1 + G_2)(\sigma_2^T)_{ult}^2 = 1 \tag{4}$$

$$2G_6\left(\tau_{12}\right)_{ult}^2 = 1 \tag{5}$$

$$G_1 = \frac{1}{2}\left( \frac{2}{\left[\left(\sigma_2^T\right)^2_{ult}\right]^2} - \frac{1}{\left[\left(\sigma_1^T\right)^2_{ult}\right]^2} \right) \qquad (6)$$

$$G_2 = \frac{1}{2}\left( \frac{1}{\left[\left(\sigma_1^T\right)_{ult}\right]^2} \right) \qquad (7)$$

$$G_3 = \frac{1}{2}\left( \frac{1}{\left[\left(\sigma_1^T\right)_{ult}\right]^2} \right) \qquad (8)$$

$$G_6 = \frac{1}{2}\left( \frac{1}{\left[\left(\tau_{12}\right)_{ult}\right]^2} \right) \qquad (9)$$

$$\left[\frac{\sigma_1}{\left(\sigma_1^T\right)_{ult}}\right]^2 - \left[\frac{\sigma_1\sigma_2}{\left(\sigma_1^T\right)^2_{ult}}\right] + \left[\frac{\sigma_2}{\left(\sigma_2^T\right)_{ult}}\right]^2 + \left[\frac{\sigma_{12}}{\left(\sigma_{12}\right)_{ult}}\right]^2 < 1 \qquad (10)$$

Where, $\sigma_1$, $\sigma_2$ and $\sigma_{12}$ are the local stresses in a lamina with reference to the material axes and

$(\sigma_1^T)_{ult}$ = Ultimate longitudinal tensile strength in fibre direction.(direction 1)
$(\sigma_2^T)_{ult}$ = Ultimate transverse tensile strength in matrix direction (direction 2)
$(\sigma_{12})_{ult}$ = Ultimate in-plane shear strength (in plane 1-2)

Equation (10) is used to detect ply failure in the progressive failure analysis.

### 2.2    Progressive Failure Analysis

For composite structures that can accumulate damage before structural collapse, the use of failure criteria is not sufficient to predict ultimate structural failure. Failure criteria can only predict the onset of the damage occuring in composite materials. In order to simulate non-linear material behaviour in composite structures a progressive damage methodology has to be implemented in the finite element static analysis of composite structures. A methodology for a progressive failure analysis is illustrated in Figure. 6. In this research, Tai-Hill failure theory algorithm was coded in the ABAQUS/Standard user subroutine USDFLD [11] which was then linked with the nonlinear analysis. The elastic material properties were made to depend on the field variables which themselves could be a function of any Gauss point quantity such as stress, strain and etc.
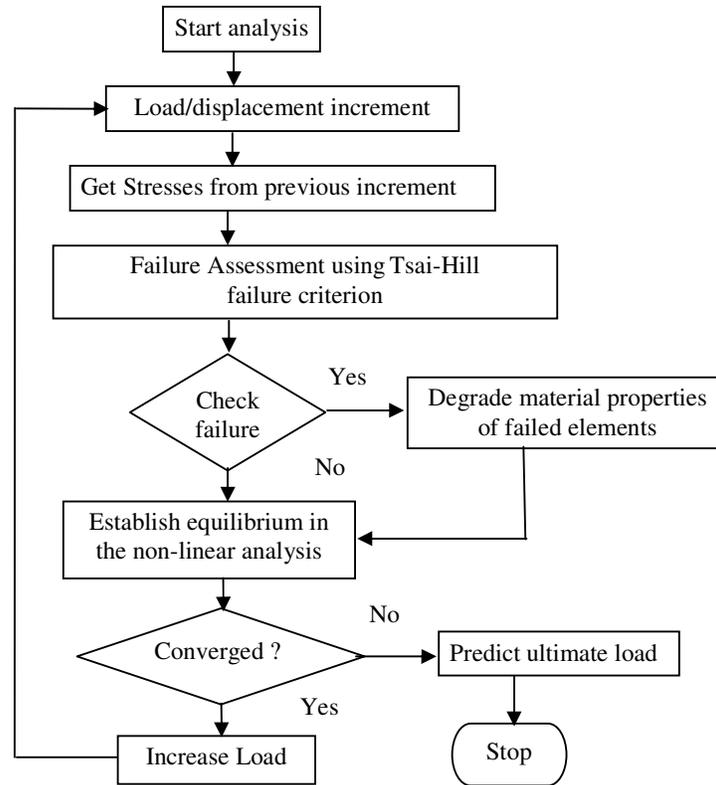
Figure 6: Progressive failure algorithm

When failure occurs, a change in the stiffness is calculated based on the material degradation model. In this material degradation model, all of the elastic material properties at that particular Gauss point are reduced to zero once the failure criterion of Equation (10) is violated. Plane local stresses i.e. $\sigma_1$, $\sigma_2$ and $\sigma_{12}$ from the previous increment are called into the subroutine at the start of the current increment and used to evaluate the failure criterion stated in Equation (10). Once the failure criteria are met, the field variables are updated and used to reduce the material properties to zero of their original value.

The redefinition of field variables is local to the current increment. Therefore, any history dependence must be introduced with user-defined state-variables that can also be updated in the USDFLD. History dependence is very crucial for progressive damage modeling because once failure is detected at a Gauss point, it must remain in that condition and must not 'heal' after the stresses are re-distributed. This adjustment accounts for the nonlinearity associated with material damage. The load step is then incremented until final failure of the composite structure is detected. In most finite element models final structural failure is identified at the load level at which static solution fails to converge.

### 3.0    FINITE ELEMENT SIMULATION

The four woven composite panels are modeled in ABAQUS/Standard finite element software. The geometry, boundary conditions, and loading of the plate are similar to that of the test specimens. The material and strength properties were obtained from coupon tests conducted at UPM [12] and are described in Table 2.

Table 2: Mechanical properties of C-glass/epoxy 200g/m$^3$

| Properties | C-glass/Epoxy 200g/m$^3$ |
|---|---|
| $E_{11}$ | 12.246 GPa |
| $E_{22}$ | 11.339 GPa |
| $v_{12}$ | 0.158 |
| $G_{12}$ | 2.340 GPa |
| $(\sigma_1^T)_{ult}$ | 181.552 MPa |
| $(\sigma_2^T)_{ult}$ | 172.462 MPa |
| $(\sigma_{12})_{ult}$ | 39.626 MPa |

A prescribed incremental compressive displacement is applied to one end of the plate, while the opposite end is fully built-in. The other two edges are free. Since the plate is perfectly flat, an initial geometrical imperfection is required to be introduced before the non-linear static analysis can be carried out successfully. This can be achieved by superimposing the buckled mode shape into the nonlinear post-buckling analysis in ABAQUS/Standard. The amplitudes of the first buckling mode shape are chosen and scaled accordingly to calculated offsets, which are added to the original nodal coordinates, i.e., the maximum imperfection displacement applied is equal to the plate-thickness times the geometrical perturbation factor. Imperfection sensitivity study has been performed and it has been found that a maximum imperfection magnitude of 20% of the plate thickness for all the panels was chosen since the results compared well with that of the experiments.

Therefore, in the non-linear static analysis which follows, the in-plane compressive loads will produce out-of-plane deformations of the panels from the onset of the load application. The analysis is performed using the S4 shell element. It is a four-noded, general purpose shell element, with six degrees of freedom per node and full in-plane integration point.

A user defined subroutine USDFLD which contains the Tsai-Hill failure theory has been written in FORTRAN and is linked with the non-linear post-buckling analysis in order to model the material non-linearity in composite laminates. Figures 7 and 8 show the deformed state of the selected panels with and without cut-outs under compression.
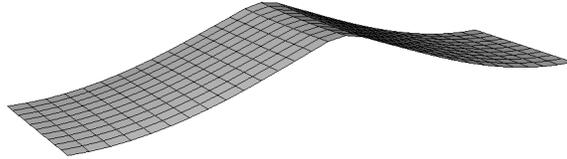
Figure 7: Deformed shape of the glass/epoxy flat rectangular plate without cut-outs
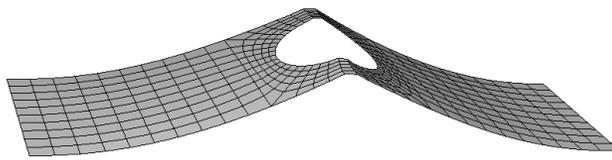


Figure 8: Deformed shape of the glass/epoxy flat rectangular plate with cut-outs

## 4.0    RESULTS AND DISCUSSIONS

In this section, the results obtained through finite element analyses on the four composite panels, with and without cut-outs, are presented. These are then compared with experimental results.

Figures 9-12 show the load versus end-shortening curves for the tested and simulated panels with and without central holes for all four fiber-glass laminated panels, and different angle orientations. The load-displacement behaviour of the simulated panels correlates reasonably well with the experimental results. It is interesting to note that all the tested panels behave in a similar fashion where, their behaviour is almost linear initially before reaching the peak loads. Beyond those peak points of the load-displacement curves, majority of the laminates experienced large displacements before failure. It has been observed that cross-ply laminates possess the greatest strength as expected since they are subjected to only a uni-axial compressive force.

On the other hand the behaviour of simulated panels via finite element analysis are also consistent with the test results for all the panels. Of all the panels, panel D shows the best agreement with the results obtained from the experiment in terms of the overall compressive behaviour. Table 3 compares the ultimate loads for the simulated panels and the experiments. It is noted that good agreement in the values of the ultimate load between the simulation and experimental has been achieved which proves that the progressive failure analysis using Tsai-Hill failure

criterion is capable of simulating damage with material non-linearity for composite laminates with reasonable accuracy. Since Tsai-Hill theory is an interactive type of failure criterion, it does not provide the information on the mode of failure of the failed lamina. Non-interactive failure theories in conjunction with the progressive failure analysis should be used instead, if mode of failures are required. However, this is not the objective of this research.
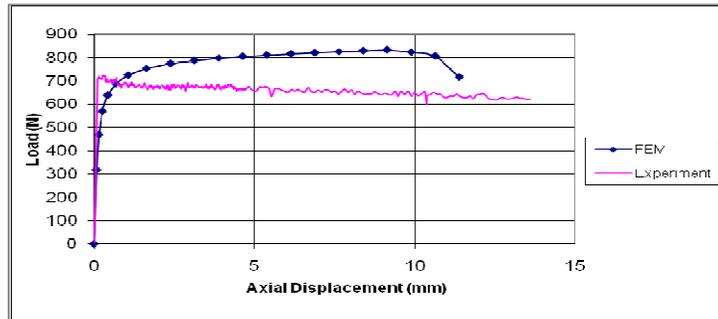
Figure 9: Load-displacement curve for Panel A ([0/90]$_{2s}$)
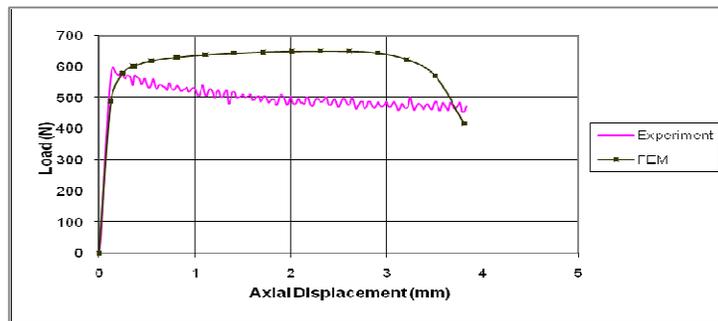
Figure 10: Load-displacement curve for Panel B ([0/90]$_{2s}$)
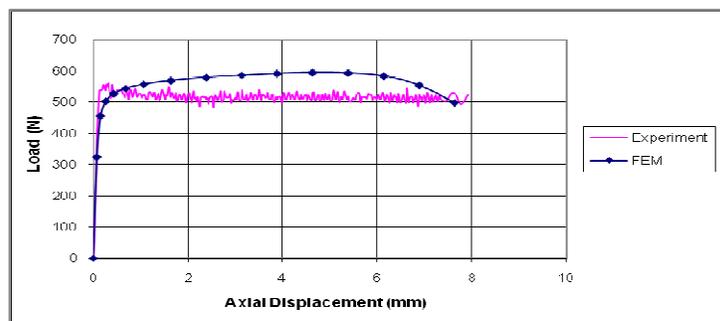
Figure 11: Load-displacement curve for Panel C [45/-45]$_{2s}$
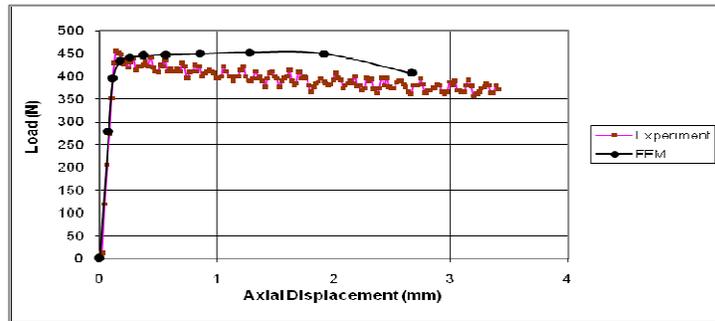
Figure 12: Load-displacement curve for Panel D [45/-45]$_{2s}$

Table 3: Comparison of the ultimate load between experimental
analysis and the finite element analysis using progressive
damage methodology based on Tsai-Hill failure theory

| | Ultimate Load (N) | | |
| Specimen | Experiment | Progressive failure analysis using FEM (Tsai-Hill theory) | %Difference |
|---|---|---|---|
| Panel A | 718.44 | 831.01 | 13.5 |
| Panel B | 600.44 | 650.83 | 7.7 |
| Panel C | 559.80 | 594.80 | 5.85 |
| Panel D | 455.39 | 452.30 | -0.65 |

### 5.0    CONCLUSIONS

A progressive failure of glass/epoxy woven laminated plates has been developed via the non-linear static finite element analysis. A progressive failure analysis algorithm has been successfully developed and implemented as a user subroutine in a finite element code (ABAQUS) in order to model the non-linear material behavior and to capture the complete compressive and post-buckling response of woven composite plates made of glass-epoxy material. Tsai-Hill failure theory has been employed in the progressive failure methodology to detect failure of the woven composite laminates. The reliability of the numerical analysis has been validated against the results obtained from quasi-static compression tests of four different panels with and without central hole. It has been found that the results obtained via the progressive failure analysis agree reasonably well with the experimental results. This confirms the accuracy of the progressive failure methodology.

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