AN XFEM FRAMEWORK FOR ONSET AND CRACK PROPAGATION FOR COMPOSITES BASED ON ACTION PLANE THEORY

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Abstract

The method of XFEM has been proved as reliable and useful for analyzing complex geometries in heavy nonlinear regimes. The main advantage of this approach is the disconnection between mesh and singularities, in a way that a remeshing is not necessary. Even though many researchers working on this field, 3D XFEM models applied to non-standard composite parts, such as tapered structures or joints, are rarely found in the literature. The current paper shows a new methodology for evaluation of structural behavior of structures made of composite materials by using XFEM. The algorithm is implemented in Abaqus and is based on a new criterion for onset and crack propagation direction definition based on Puck's theory. The proposed three-dimensional model for composites based on Extended Finite Method is implemented through Abaqus' subroutines, using optimization algorithms for computational efficiency. Full details are presented. To verify the performance of the model to different stacking sequences and geometry, a sensibility study for the most important parameters of the model is also provided. Finally, experimental results from the literature are shown and used to verify the efficiency and limitations of the proposed algorithm.

1 Introduction

Many advances have been achieved on computing structures made of composite materials even if the concept of damage tolerance in such structures is still a field wide open for researches and present some challenges yet to be resolved and of great interest to aeronautic industry.

Even with modern approaches involving fracture mechanics and RVEs, all failure mechanisms are not simple which brings difficulties to allow micro approaches to be implement in industry level. Is this sense, meso-scale and phenomenological approaches present themselves as alternatives both efficient and not computational consuming. One can easily find in literature models based on Puck's theory. This may be explained by its excellent results in Worldwide Failure Exercise I and II, which stated "exhibiting good predictive capability, none or one fundamental weakness and many relatively minor weaknesses" [1, 2]

The present work aims to evaluate performance of Puck's theory applied to tapred structures for which mechanism of failure is known to be translaminar. These structures are widely used in rotorcraft industries in primary and vital parts as displayed in Fig. 1.

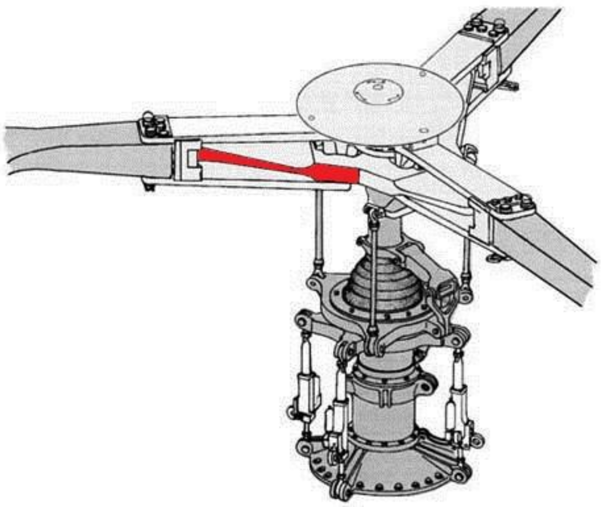

Fig. 1: Helicopter rotorhub, example of tapered structure

2 Methods

To properly reproduce a tapered structure mechanical behavior, it is necessary to model with accuracy matrix and out-of-plane efforts along with eventual fiber failure.

In order to accomplish this proper reproduction, the present model applies a solution via eXtended Finite Element Method (XFEM) in conjunction with Matzenmiller's theory (to simulate mechanisms in the longitudinal direction), and Puck's theory (to simulate failure in the transverse and shear directions) [3]. In addition, a non-local approach was adopted to avoid premature stops in calculus due to convergence problems when fiber-failure occurs. The model was implemented as a material into Abaqus UMAT subroutine, and full details can be seen in [4, 5]. Both onset and propagation of failure is modelized

2.1 Matrix Mechanism

In order to quantify matrix failure, a new coordinate system is defined at each mesh integration point. By averaging the stress tensor in the new orientation system, a failure index is calculated according to Eq. (1) and used to quantify the amount of damage in the matrix at each integration point measured on the action plane. This index will be argument for the determination of the damage variable for inter-fiber mechanism as in Eq. (2). Mechanical property will be degraded by this amount following Eq. (3).

$$IFF_A = \sqrt{\left[\left(\frac{1}{Y^t} - \frac{p_{\perp\parallel}^{t\;*}}{S_{12}}\right)\sigma_{22}\right]^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2} + \frac{p_{\perp\parallel}^{t\;*}}{S_{12}}\sigma_{22} \tag{1}$$

$$\eta_{E/G} = \frac{1 - \eta_r^{E/G\,*}}{1 + c^*{}_{E/G}(IFF_A - 1)^{\xi^*_{E/G}}} + \eta_r^{E/G\,*} \tag{2}$$

$$E_{22} = \eta_E\, E_{22} \qquad\qquad G_{12} = \eta_G\, G_{12} \tag{3}$$

2.1.1 Action plane inclination: Puck's approach

The action plane angle is determined according to Puck by “brute force”, i.e. a sweep made through all possible angles and at each of them IFF calculated in order to determine its maximum. Calculating IFF for each angle for each integration point is highly computational consuming. Fig. 2 shows the failure index plot against the failure angle. A sweep from -90º to +90º is performed taking 1º step. As analysis evolves, failure indexes assume higher values. In this analysis, there is no crack. Index of failure (non-dimensional) behavior against angle of inclination (degrees) along analysis completion is presented.

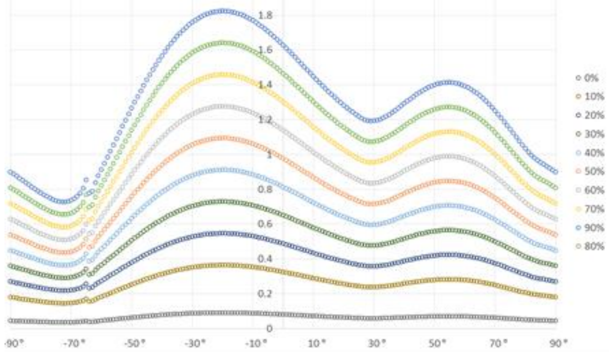

Fig. 2: Example of calculation of action plane inclination as proposed by Puck's Theory.

2.1.2 Action plane inclination: Proposed approach

Fig. 2 clearly shows that there are multiple points of maxima and minima what makes necessary to have a robust approach in order to increase efficiency and avoid a local extremum. In the present work, to solve this issue, it was implemented the approach based on the so called “golden section algorithm”. The interval of interest, in this case [-90,90], was subdivided as per the golden ratio shown in Eq. (4):

$$\varphi = \frac{1+\sqrt{5}}{2} \tag{4}$$

The golden section method was expanded taking into account the hypothesis from[6], which states that no extrema appear closer than 25º from each other. Taking into account this hypothesis, the whole interest interval is subdivided in 9 subintervals. For each of them the golden section method is applied and the maximum is determined across these subintervals

In order to exemplify the performance enhancement by using the proposed approach, Table 1 shows results for each level of precision and compare the amount of calculations performed for each method taking as reference classic Puck with 1° sweep (in bold)

Table 1 – Performance comparison.

Approach	Precision Level		
	1.0°	0.5°	0.1°
Puck (reference)	**1.000**	2.000	10.00
Golden Section	0.061	0.072	0.089
Enhanced Golden Section	0.550	0.650	0.444

2.2 Fiber Mechanisms and the Non-Local Approach

For fiber failure, the brittle and abrupt character is treated with a non-local approach. For each integration point in the mesh, a characteristic neighborhood is defined due to a non-local criterion as described by[7]. It contains the set, herein named Characteristic Volume of Rupture (CVR) of integration points within a distance of the Characteristic Radius (CR) Fig. 3.

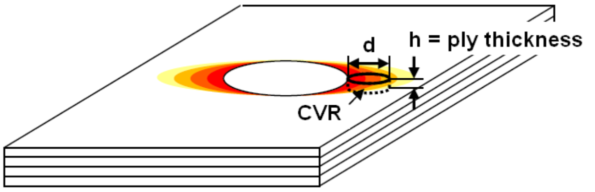

Fig. 3 - The Characteristic Volume of Rupture and Characteristic Radius

The value of the CR is a material characteristic and may be obtained from elementary tests with stress concentrator presence. At each step, the model performs a sweep throughout an application zone in the structure and, for each point, calculates a weighted average of the current longitudinal strain within the region bounded by each set as displayed by Eq. (5).

$$\overline{\varepsilon_{11}} = \frac{\sum^{i} \varepsilon_{11}^{i} V^{i}}{\sum^{i} V^{i}} \tag{5}$$

This procedure intends to minimize concentration, which may affect the convergence during the calculus and it is a space criterion to control high strain rates and gradients. The average strain is passed as argument along with mechanical ultimate longitudinal strain to Eq. (6), which calculates the longitudinal damage variable to be used for updating E_{11}.

$$\omega = 1 - \exp\left(-\frac{1}{m_{t/c}^{*} e_{t/c}^{*}}\left(\frac{\varepsilon_{11}}{\varepsilon_{t/c}^{f}}\right)^{m_{t/c}^{*}}\right) \tag{6}$$

The longitudinal damage variable is then used to upgrade the material properties E_{11}. Therefore, the Eq. (7) shows the degradation of the property due to fiber failure:

$$E_{11} = \omega\, E_{11}^{0} \tag{7}$$

3 Results: Compact tension specimen

To verify the model performance with respect to a real study case, the XFEM framework was applied to evaluate a compact tension specimen with displacement imposed. Three different layups were considered and are detailed in Table 2.

Table 2 – Details of computational analyses for Case Study 2

Stacking (XY plane, Y as reference)	Loading	Expected Behavior
$[0°]_{16}$	Tension	Failure along the fibers direction at 0°
$[90°]_{16}$	Tension	Failure along the fibers direction at 90°
$[45°]_{16}$	Tension	Failure along the fibers direction at 45°

Since the strength in fiber direction is much higher than in transversal, it is expected the failure to go through the structure following the fibers as it can be seen in Fig. 4 (A), (B) and (C).

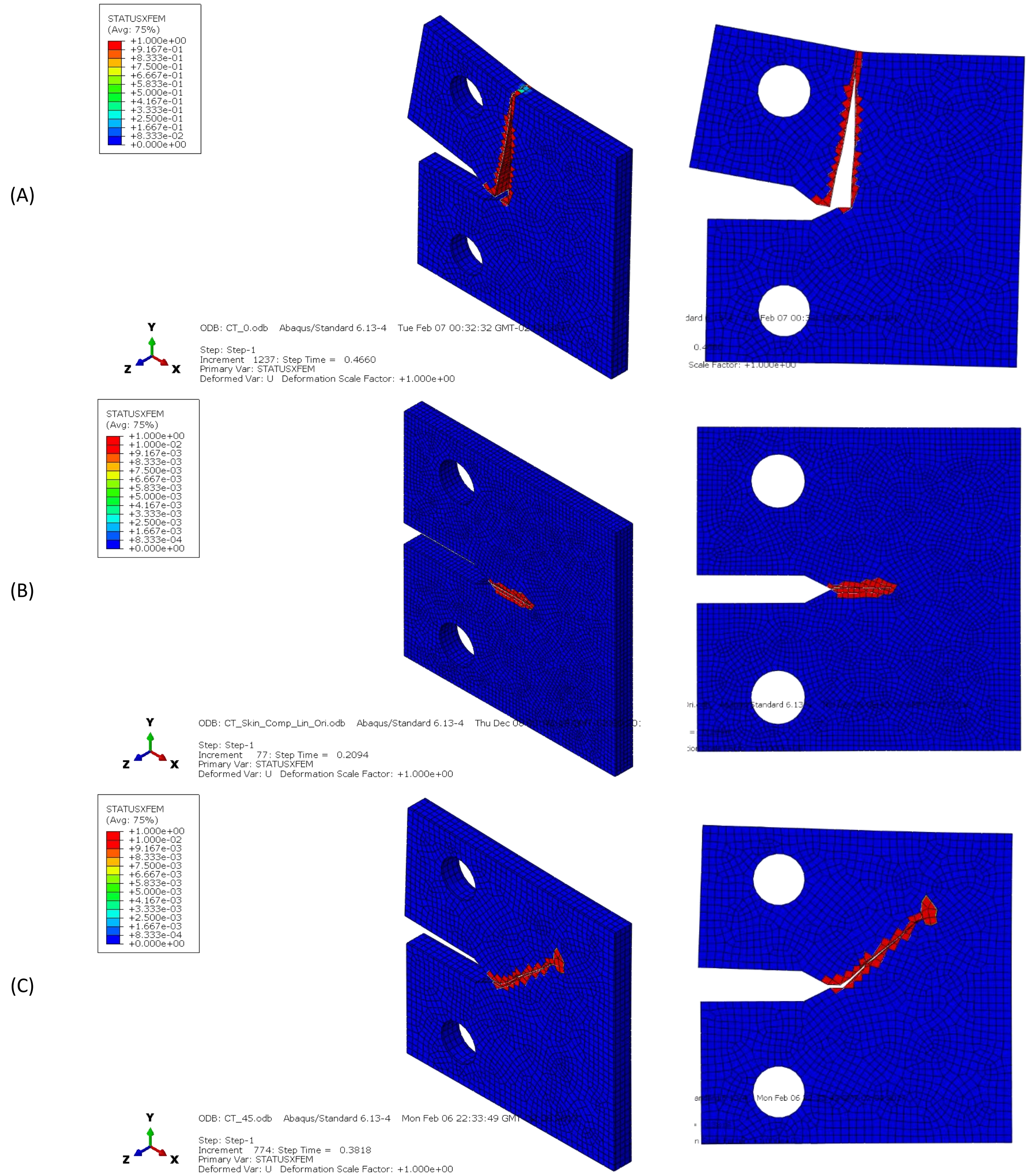

Fig. 4 Status XFEM compact tension results: (A) 0º, (B) 90º and (C) 45º specimen. Non dimensional Boolean indicating enrichment status

These results maybe validated by the experiments performed by [8, 9] in which exactly the same behavior was experimentally found.

4 Conclusion

The present work showed a new framework, combining XFEM and 3D Puck's failure theory, for evaluating onset and propagation of failure (evolution of cracks) composite structures. Besides, the proposed approach for determining crack inclination angle has proven to be robust and pre-cise, filling a gap on the available researches in the field. Compared to the algorithm proposed by Puck, the new methodology has convergence one order higher than the first method developed by Puck; it is 20 times more efficient computationally for a 0.1° precision. Therefore, if more preci-sion is needed, then higher gains are achieved by using the proposed method. Simple tests were simulated both in tension and compression, displaying results as expected.

Apart from being faster, when more complex compact tension experiments were modeled, the numerical results were also in good agreement with available experimental data.

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