Prediction of Intra-lamina Crack Propagation in Fiber Reinforced Composite Laminate

Mr. Xuan Wang & Dr. Simon Wang
Aeronautical and Automotive Engineering, Loughborough University, Leicestershire, LE11 3TU, United Kingdom.

Introduction

Fiber reinforced composite materials are widely used in corrosive environments and especially in aeronautical and automotive industries because of their superiority to metals or alloys in resisting corrosive attack. Nevertheless the composite materials may be severely weakened in the presence of moisture or other aggressive environments, such as the strength in acid environments decreases as compared with that in air.
As matrixes can only delays the corrosion effects, if the aggressive medium can travel through the matrix, either by diffusion or through micro-cracks, corrosion of the interface and fibres can occur and lead to serious macro-crack propagation by foreign impacts in a hostile condition after long service life.
Therefore the intra-lamina crack propagation of fiber reinforced composite materials became a major concern during application in now days. Due to large difficulty of obtaining its physical and mechanical properties; especially in obtaining energy release rate in crack tip during propagation. This paper proposed that normal and shear imaginary springs were located along quasi-static crack till crack tip in order to obtain energy release rate; and Matlab used here as a simulating tool.

Theoretical and Numerical Development

Types of Crack Mode

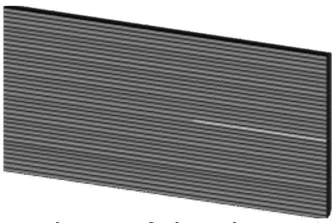
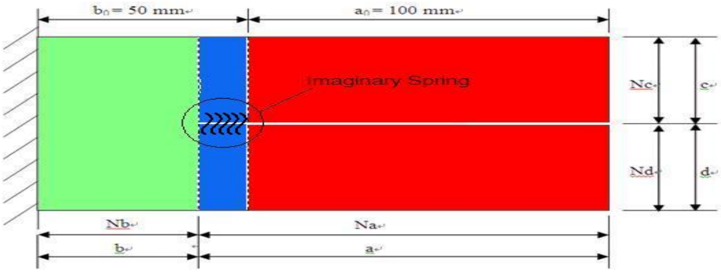
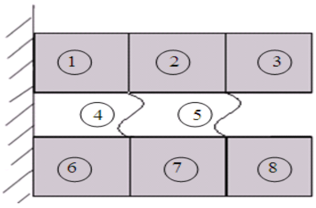


Figure 1 shows shape of the plate with crack, one ends of the plate is operated under force, and forced a crack to propagate from one end the other.
Loads are applied at one end of the beam, and the crack is forced to propagate from one end towards the other. Three different crack modes were discussed. They are Mode I, Mode II and Mixed Mode.

Cracked Plate Simulation



The Figure 2 is showing a geometric system of a plate with an existing crack and imaginary springs at crack tip.
The Green region represents an area of the plate with no crack and any damages. The Blue region represents an area with the quasi-static crack and imaginary spring around. The Red region represents an area with a complete crack.
The Na, Nb, Nc, Nd represents number of meshed elements in a, b, c, d region respectively, and imaginary springs were only applied starting from right hand side dots line.



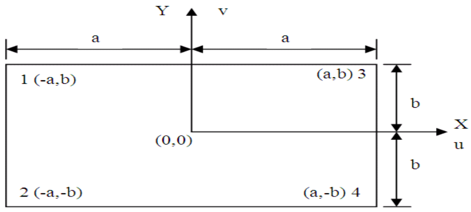
The above Figure 3, the numbered 1, 2, 3, 6, 7, 8 are the meshed elements around the crack; the 4, 5 are the imaginary springs. The springs were applied along the quasi-static crack till its tip.
Loading **P** is distribution loads that applied on each meshed element at the end of plate, and **P=1**N is fixed for all conditions.
Analytical calculation of ***Energy Release Rate*** by beam bending theory has been done for all three loading conditions.

$$U = \int_{whole} \frac{1}{2}\frac{M_x^{2}}{EI}dx$$

A factor of energy release rate has been found and this factor was the values that used to compare with FEM simulation's results.
For the Mode I, the G_I factor (will be written in term of G_{If} in the following articles) could be easily found that it is $\frac{12a_0^2}{c^3}$ for the normal loading condition; Mode II has the energy release

rate factor $G_{IIf} = \frac{2.5a_0^2}{c^3}$ for the shear loading condition; and the Mixed Mode has both of G_{If} and G_{IIf} that the G_{If} has then been found as $\frac{3a_0^2}{c^3}$ and G_{IIf} is the same as the Mode II which is $\frac{2.5a_0^2}{c^3}$.

Finite Element Method (FEM) Simulation



The rectangular has been chosen to be the finite element. The figure 4 shows the coordinate geometric of the element. Thus a 8×8 stiffness matrix formed as $\begin{bmatrix} k_{11} & \cdots & k_{18} \\ \vdots & \ddots & \vdots \\ k_{81} & \cdots & k_{88} \end{bmatrix}$

Spring Element

The spring element is a one-dimensional finite element where the local and global coordinates coincide. The stiffness of spring was expressed by **ks**. The element stiffness matrix for spring element is given as following matrix k':

$$k' = \begin{bmatrix} ks & -ks \\ -ks & ks \end{bmatrix}$$

And multi-spring approached has been done by Matlab program to make the method adaptable and robust in various situations.

Convergence Studies for Plates with Crack

The convergent studies contained Mode I, Mode II and Mixed Mode. A composite material property was applied on the convergent studies. Matlab program simulated each Mode condition and the **Energy Release Rate factor G_f** was recorded for each convergent study and compared with **Beam Beading Theory Results.**

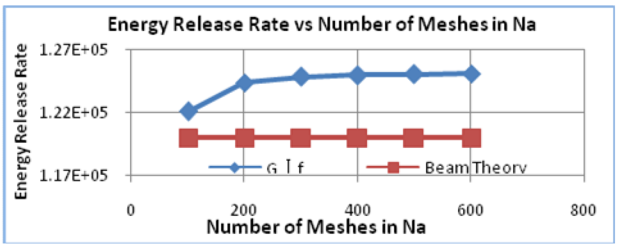
The convergent studies carried out following tasks:

Increasing number of meshes on **Na**

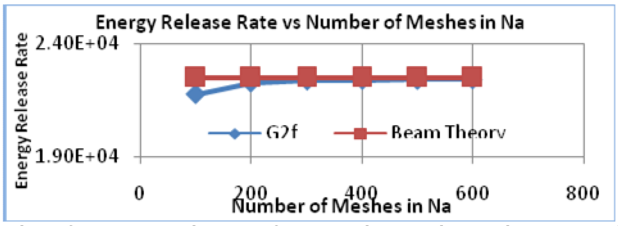
Increasing spring stiffness **ks**

Increasing number of meshes on **Nb**

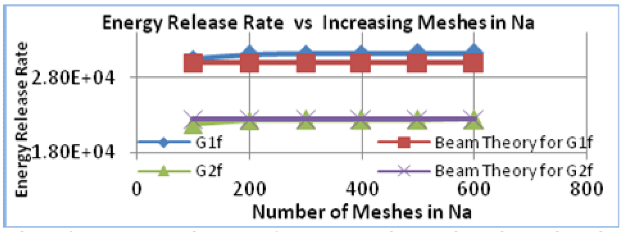
Increasing number of meshes on **Nc**, **Nd** & depth of **c**, **d** at the same time.



The figure 5 shows for Mode I that the G_{If} converged as the number of mesh in Na increased.



The figure 6 shows for Mode II that the G_{IIf} also converged as the number of mesh in Na increased.



The figure 7 shows for Mixed Mode that both of G_{If} and G_{IIf} converged while the number of mesh in Na increased.

Conclusions

1. Beam bending theory will not be valid if applying on plate analysis.
2. At a low number of meshes, each element has large stiffness which leads to significant error at the beginning of test.
3. As the mesh get finer and finer that the simulation condition much more close to real one, the error became very small and results tends to be a constant value.
4. Hugely increase spring stiffness ks input value would not make serious effects on energy release rate.
5. The energy release rate would not be affected by increasing number of meshes on Nb
6. When the loading is fixed, increase the depth of c, d, which means raise the stiffness of both upper and lower plate that caused energy release rate decreasing.

Reference

1. Macrosopic crack propagation due to stress-corrosion cracking in unidirectional GFRP composite: micromechanical theory and its application - H.Sekine
2. On the equivalence of stress intensity and energy and energy approaches in bridging analysis - L. K. Jain & Y W Mai
3. Direct numerical simulation of the extension of stress-corrosion crack in glass fibers embedded in laminates in acid environments - Hideki Sekine, Ning Hu & Hisao Fukunaga
4. Prediction of Delamination Propagation in Composite Laminated Beams - Fu Yuhan