DELAMINATION INITIATION AT THE INTERFACE OF BROKEN AND CONTINUOUS PLIES IN FRP COMPOSITE LAMINATES

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Abstract

Delamination is a very common and the weakest mode of failure in laminated composite structures. Two common phenomena viz. free edges of laminates and broken plies/fibres usually give rise to delamination. Ply or fibre breakage in composite laminates usually occurs as a result of low velocity impact. Consequently, the interface between the broken and the continuous plies becomes the weakest link from the failure point of view of the laminate. It has been reported by the earlier researchers that delamination at the interface usually precedes the final fracture of such broken ply composite laminates. The present work has been aimed at evaluating the delamination initiation stress for unidirectional [0°] GL/E and GR/E laminates having one or more central plies broken. A 3D finite element analysis has been used to model the laminate ply by ply and the initial stress analysis results indicate that delamination will occur at the interface of the broken and the continuous plies which agree with the already published results. Also, the concept of LEFM (Linear Elastic Fracture Mechanics) has been incorporated in the finite element analysis to evaluate the Energy Release Rate (G), at the delamination front to assess the delamination initiation. Effects of various important factors such as number of plies, thickness of the laminate and stiffness of the interfacial resin layer on the delamination initiation has been studied and interesting observations are made. It has been observed that thicker the specimen, lower is the delamination initiation stress for the specimen. Also, it has been concluded from the analysis that as the interfacial resin becomes stiffer, energy release rate at the delamination front decreases.

Introduction

Delamination is a very common and one of the weakest modes of failure in laminated composite structures. So, failure analysis of composite laminates demands an accurate prediction of its initiation and propagation. Delamination in composites occurs mainly in two ways viz. at the free edges of laminates and in the vicinity of broken plies if exists. In case of broken plies, delamination usually occurs at the interface of the broken ply/plies and adjacent continuous plies and this type of delamination generally causes strength degradation in laminate leading to the final fracture [1]. Fracture mechanics approach is often used with critical strain energy release rate (G_c) as a parameter for predicting delamination initiation and propagation. Experimental observations reported in the literature reveal [1,2] that in case of composite laminates having broken ply/plies, delamination occurs at the interface of the broken and continuous plies. LEFM can be used to analyse delamination behaviour wherein energy release rate at the delamination front, G is compared with G_c during propagation. However, in case composite laminates, due to their inherent complications, it is difficult to derive closed form expression for G_c. Also early work in this direction revealed that, unlike isotropic materials, G_c is not a material constant in case of composite materials [3,4]. Already work has been done to correlate G_c with laminate thickness [3] in case of Glass/Epoxy laminates having cut plies using 2D finite element analysis. The main objective of the present study is to determine G_c (delamination fracture energy) by a 3D finite element analysis for a broken ply fibre reinforced composite laminates and to study the effects of parameters like laminate thickness, ply configuration and resin stiffness on G_c.

Delamination initiation stress and G_c

Since interlaminar stresses τ_{xz}, τ_{yz}, and σ_{zz}, are responsible for delamination, the accurate study of delamination thus requires a complete 3D stress analysis. There are two approaches for predicting delamination initiation viz.

1. Mechanics of materials approach and
2. Fracture mechanics approach.

In mechanics of materials approach, many criteria have been put forward for delamination initiation.

In the present study, 'Quadratic Stress Criterion' proposed by Brewer and Lagace [5] has been used. The mathematical form of the same is

$$Q = \left[\frac{\bar{\sigma}_{zz}}{Z}\right]^2 + \left[\frac{\bar{\tau}_{xz}}{X}\right]^2 + \left[\frac{\bar{\tau}_{yz}}{Y}\right]^2 \qquad (1)$$

If $Q > 1$, delamination initiation occurs and
If $Q < 1$, no delamination initiation takes place.

In this expression (1), $\bar{\sigma}_{zz}$, $\bar{\tau}_{xz}$, $\bar{\tau}_{yz}$ are the average stress at the delamination front and are given by

$$[\bar{\sigma}_{zz}, \bar{\tau}_{xz}, \bar{\tau}_{yz}] = \frac{1}{x_c}\int_0^{X_c}[\sigma_{zz}, \tau_{xz}, \tau_{yz}]dx \qquad (2)$$

where x_c is the critical distance over which the interlaminar stresses are averaged and Z,X and Y are the longitudinal strength, longitudinal shear strength and lateral shear strength respectively. Recommended value of x_c is twice the ply thickness [6]. In fracture mechanics approach, strain energy release rate per unit area delaminated is evaluated and compared with G_c [1,3].

Considering a crack of existing length a, the three components of G can be determined using Irwin's crack closure technique [7] as

$$G_I = \frac{1}{\Delta a}\int_0^{\Delta a}\sigma_{zz}(v_t - v_b)da \qquad (3)$$

$$G_{II} = \frac{1}{\Delta a}\int_0^{\Delta a}\tau_{xz}(u_t - u_b)da \qquad (4)$$

$$G_{III} = \frac{1}{\Delta a}\int_0^{\Delta a}\tau_{zz}(\omega_t - \omega_b)da \qquad (5)$$

where, a is the existing crack length, Δa is the virtual crack extension length, u_t, v_t, ω_t are the displacements of the nodes at the top surface and u_b, v_b, ω_b are the displacements of the nodes at the bottom surface at a distance of Δa away from the delamination front.

σ_{zz}, τ_{xz}, and τ_{yz} are the transverse and shear stresses at a distance Δa ahead of the delamination tip.

In the present study, an attempt has been made to evaluate critical strain energy release rate (G_c) by combining both stress based fracture criteria and LEFM i.e. G_c has been calculated as the value of G at the point of delamination.

FE Analysis

A 3D FE analysis has been performed to estimate G_c for delamination initiation using ANSYS (ver 5.0A) FE computer code on a HP workstation. Three dimensional, 8 noded, layered elements **(SOLID46)** embodied in ANSYS have been used to model the laminate ply by ply and orthotropic properties have been input for each ply. Also, 3D contact elements **(CONTAC52)** have been used to model the delamination zone. The interface between the broken and continuous plies have been modelled by a pure resin rich layer as it has already been established that delamination mainly propagates through the interlaminar resin layer [9]. A $[0^\circ]_n$ GL/E laminate of length 100mm, width 20mm and ply thickness of 0.127mm subjected to uniaxial tension has been used for the analysis. The central ply/plies are assumed to be broken at the centre throughout the width. Due to symmetry of the specimen only 1/8th of the laminate has been modelled in the present analysis and each ply has been modelled with 400 elements. Convergence of the solution has been ensured by increasing the mesh density of the elements near the delamination front till there is no change in results. An element size of 0.05 mm x 0.00635 mm x 0.5 mm has been near the delamination front in the present analysis.

Results and discussion

The high magnitude of interlaminar stresses along the interface between cut ply and the continuous ply (Figs. 1(a - c)) indicates that delamination will occur at the interface. Also, the compressive nature of transverse stress at the interface indicates that delamination will be of mode II type. Average stresses are calculated by using Eqn. (2) and the characteristic distance x_c from the delamination front is taken as (Ref. [2])

$$x_c \;=\; 0.3991\,\alpha^{-0.1179}\,n^{0.3662} \qquad \text{———} \qquad (6)$$

where, α is the ratio of numbers of broken to continuous plies and n is the total no. of plies in the laminate.

Effect of broken ply to continuous ply ratio and specimen thickness

Fig. 1(a-c) shows the effect of specimen thickness on the stress distribution at the interface for a constant ratio of number of broken plies to number of continuous plies (α). It has been observed that as the total thickness of the laminate increases, stress concentration near the delamination front increases and as indicated by Fig. 1(b), magnitude of the shear stress (τ_{xz}) responsible for delamination initiation at the interface increases rapidly as the thickness of the laminate increases which indicates that thicker the specimen, more it is prone to delamination and hence less is the nominal stress at which delamination can occur. Fig 2. shows that the strain energy released at the delamination front decreases with the increased number of continuous plies.

Delamination initiation stress

Fig.3 shows the variation in delamination initiation stress with specimen thickness for a constant broken to continuous ply ratio calculated by present FE analysis for both GL/E and GR/E. Thicker the specimen, lower is the magnitude of delamination initiation stress for the specimen. This trend agrees well with the already published resluts of Lagace and Brewer [5].

G_c for delamination initiation

Fig.4 shows the value of G_c for delamination initiation for various laminate specimens as calculated by present FE analysis. In calculating G_c, element size near the delamination front used was 0.05mm in length. These values agree well with the values obtained by using Narin's empirical relations given for calculation of energy release rates based upon the nominal stress at which delamination occurs [8]. Also it has been observed that as the no. of continuous plies increases G_c increases as shown in Fig. 5.

Effect of resin stiffness

Fig. 6 shows the effect of resin stiffness on strain energy release rate, G. As the resin becomes stiffer, energy release rate at the delamination front decreases.

Conclusions

1. In case of unidirectional laminates with broken ply/plies subjected to uniaxial tensile loading, mode I failure due to axial loading is absent since the interlaminar normal stress is compressive at the interface. Also, strain energy release rate in mode III is very small compared to that in mode II. Hence, mode II is the only mode in which delamination occurs.

2. Strain energy release rate at the delamination front decreases as the number of continuous plies surrounding the broken ply increases.

3. Strain energy release rate at the delamination front increases with the increase in interfacial resin stiffness.

4. Delamination initiation stress decreases as the total thickness of the laminate increases for the same ratio of number of broken/continuous plies (α). This could also be inferred from Fig. 1(b), which shows that as the thickness increases, magnitude of the shear stress responsible for delamination

also increases.

5. Critical strain energy release rate is a function of both ratio of number of broken/continuous plies as well as the total specimen thickness (n) and G_c decreases as the number of continuous plies increases.

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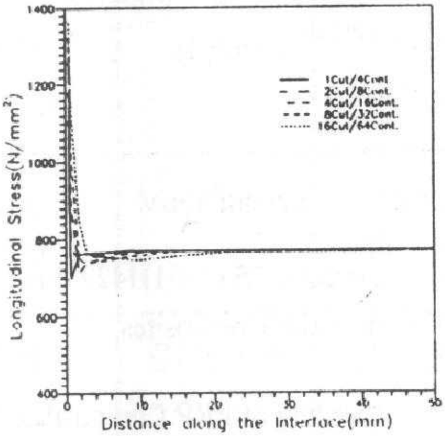

Fig. 1a - Longitudinal stress along the interface for GL/E (applied strain = 0.02)

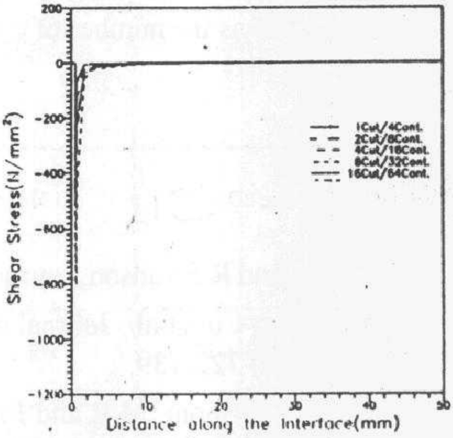

Fig. 1b - Shear stress along the interface for GL/E (applied strain = 0.02)

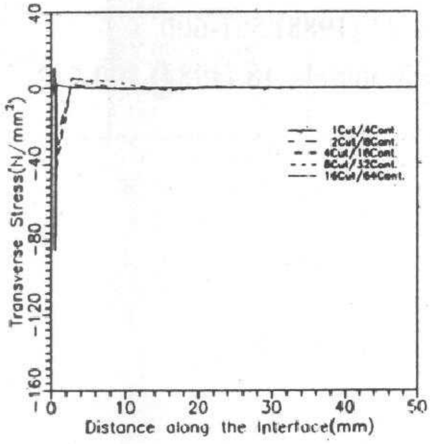

Fig. 1c - Variation of transverse stress along the interface for GL/E (applied strain = 0.02)

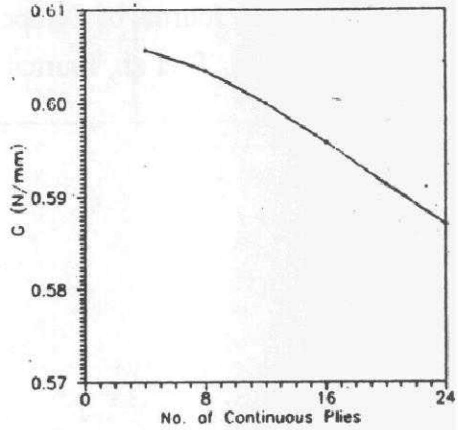

Fig. 2 - Variation in Energy Release Rate with increased number of Cont. Plies.

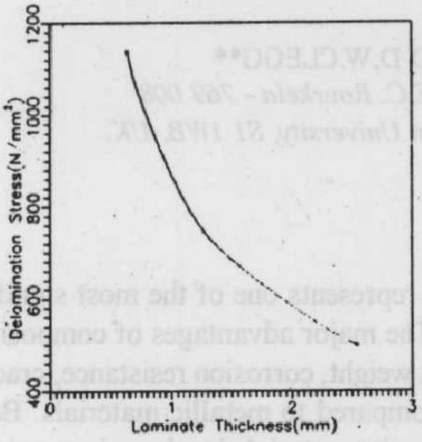

Fig. 3 - Variation of Delamination Initiation stress with Laminate Thickness for GL/E.

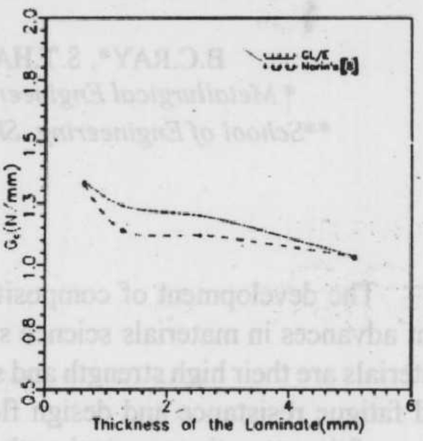

Fig. 4 - Variation of G_c with Laminate Thickness for constant ratio of Cut/Continuous Plies = 0.25

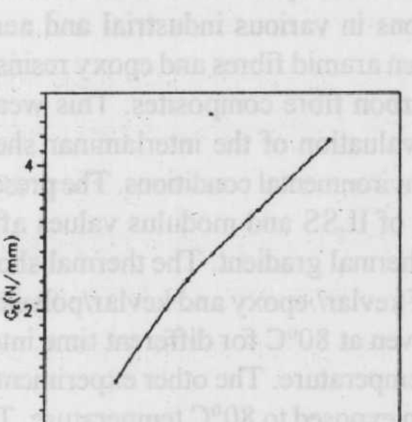

Fig. 5 - Variation in Critical Strain energy Reaease Rate increased no. of Cont. Plies.

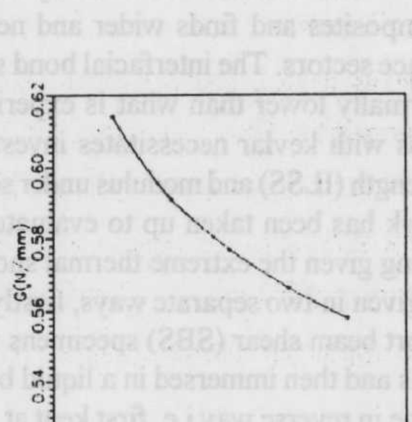

Fig. 6 - Variation of G with Increasing Resin Stifness for 1Cut/4Cont. Laminate (applied Strain = 0.02).