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DELAMINATION OF COMPOSITE LAMINATE PLATE BY SLIDING LOAD MODE

Abstract

The paper presents the mixed-mode delamination response of laminate plate made of two sublaminates. To this purpose a sliding load mode of delamination is proposed as failure model. A quasistatic rate-independent delamination problem of laminate plates with a finite thickness is considered. A rate-independent delamination model for a laminated Kirchhoff-Love plate is obtained. The failure model is implemented in ANSYS code to calculate the mixed-mode delamination response as energy release rate along the lamination front.

Keywords

Delamination, sliding load mode, mixed response mode, laminate, plate.

1 INTRODUCTION

In fracture mechanics the behavior of cracks in bodies is described from a macroscopic point of view in the context of continuum mechanics. The crack is considered in a geometrically idealized form as a mathematical cut or slit in the body. This means that a purely plane separation of the body is assumed, which leads to either two crack faces (2D) or to two crack surfaces (3D). Then, an ideal sharp crack tip is assumed. Actually, the tips of physical cracks always have of course a finite radius of curvature. However, in comparison to the crack length and the body dimensions, it can be regarded as infinitely small. Therefore, the shape of the crack tip is clearly defined. In this point fracture mechanics differs from the theory of notch stresses. Regarding the deformation of a crack, a distinction is drawn between three independent movements of the two crack faces relative to each other.

The classical delamination study based on plate theory assumes that the laminate plate is composed of two plate elements in the delaminated region and the single plate element in the undelaminated region [1, 2, 3, 4, 5]. This is equivalent to using a two layer plate model, using the Kirchhoff plate kinematics. Classic delamination models based on plate theories give a good estimate of total energy release rate (ERR), but they may provide inaccurate results when utilized to separate ERR into mode components except in particular cases [6]. A notable underestimation of the EER mode components may arise since shear effects are neglected and the local crack tip strain state is not accurately described. Therefore the classical plate based delamination models have been improved by the global/local analysis.

The global/local analysis is effective for 2D delamination problem and it is known as the crack tip element method (CTE) [7]. CTE method cannot be used for general delamination and then it has been modeled by using sublaminates governed by transverse shear deformable laminate theory, thus obtaining a reasonable approximation to the mode separation solution [8].

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2 SUBLAMINATE MODELING

The delamination plane separates the delaminated structure into two sublaminates of thickness h_1, h_2, both of which are assumed to the in-plane dimensions. Each sublaminate is presented by an assemblage of first order shear deformable plate elements bonded by zero-thickness interfaces in the transverse direction. Each plate element represents one or several physical fiber reinforced plies with their material axes arbitrarily oriented. Adhesion between the plates inside each sublaminate is enforced by using constraint equations (CE) implemented through Lagrangian multipliers [9, 10]. The first order shear deformation finite plate elements are joined at the interfaces inside each sublaminate using constraint equations or rigid links characterized by two nodes and three degrees of freedom at each node.

The theory of crack growth may be developed by using the Griffith energetic approach introduces the concept of energy release rate G as the energy available for fracture on the one hand, and the critical surface energy G_C as the energy necessary for fracture on the other hand [9]. The ERR can be written as a function of stress resultants acting upon sections adjoining the crack border [11, 12]. ERR is a global measure of energy available at the crack tip, but it does not represent the way in which the crack could advance. The components of the ERR can be defined as the work done by the normal, shear and tear interface tractions through the corresponding interface relative displacements, as the crack advances. The constitutive equation of the interface involves two stiffness parameters, k_z, k_{xy}, imposing displacement continuity in the thickness and in-plane directions, respectively, by treating them as penalty parameters. The relationship between the components of the traction vector $\boldsymbol{\sigma} = [\sigma_{zx}, \sigma_{zy}, \sigma_{zz}]^T$ acting at the lower surface of the upper sublaminate, in the out-of-plane (z) and in the in-plane (x and y) directions, respectively, and the corresponding components of relative interface displacement vector $\boldsymbol{\Delta} = [\Delta u, \Delta \mathrm{v}, \Delta w]^T$ is expressed in matrix form as $\boldsymbol{\sigma} = \boldsymbol{K}\,\boldsymbol{\Delta}$, where $\boldsymbol{K}$ is diagonal matrix of stiffness parameters k_{xy} and k_z.

Delamination grows on the region of the delamination front where the following condition is satisfied

$$\left(\frac{G_I}{G_I^C}\right)^{\alpha} + \left(\frac{G_{II}}{G_{II}^C}\right)^{\beta} + \left(\frac{G_{III}}{G_{III}^C}\right)^{\gamma} \geq 1, \tag{1}$$

where α, β, γ are mixed mode fracture parameters determined by fitting to experimental test results, $G_I^C, G_{II}^C, G_{III}^C$ are assume to be critical values of ERR, independent of their location along the delamination front.

$$G_I(A) = \left(\frac{1}{2}\frac{R_A^z \Delta w_{B-B'}}{\Delta_x \Delta_y}\right),\; G_{II}(A) = \left(\frac{1}{2}\frac{R_A^x (\Delta u)_{B-B'}}{\Delta_x \Delta_y}\right), G_{III}(A) = \left(\frac{1}{2}\frac{R_A^y (\Delta v)_{B-B'}}{\Delta_x \Delta_y}\right), \tag{2}$$

where R_A^z, R_A^x, R_A^y are the reactions in the spring element connecting node A of delamination front in the z, x, y - directions, $\Delta w_{B-B'}, \Delta u_{B-B'}, \Delta v_{B-B'}$ are the relative z, x, y - displacements between the nodes B and B' located immediately ahead of the delamination front along its normal direction passing through A.

3 DELAMINATION EXAMPLE, RESULTS AND DISCUSSION

A square plate comprising two subplates with thicknesses h_1 = 0.5 mm, h_2 =1 mm is investigated. The subplates are uniform loaded in sliding mode. The plate geometry is shown in Fig. 1. The mechanical characteristics of the upper sublaminate (AS4D/9310 – two layers) are: E_x = 134 GPa, $E_y = E_z$ = 7.7 GPa, G_{yz} = 2.76 GPa, $G_{xy} = G_{xz}$ = 4.3 GPa, $\nu_{xy} = \nu_{xz}$ = 0.3, ν_{yz} = 0.4. The mechanical characteristics of the lower subplate (T300/5208 – four layers) are: E_x = 136 GPa, $E_y = E_z$ = 9.8 GPa, G_{yz} =5.2 GPa, $G_{xy} = G_{xz}$ = 4.7 GPa, $\nu_{xy} = \nu_{xz}$ = 0.28, ν_{yz} = 0.15. The response mode components of energy release rate along the delamination front are calculated.

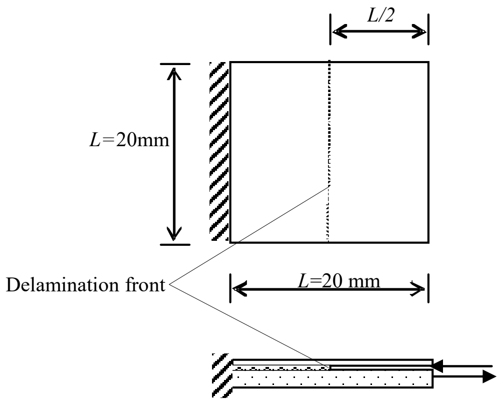

Fig. 1: A square plate geometry

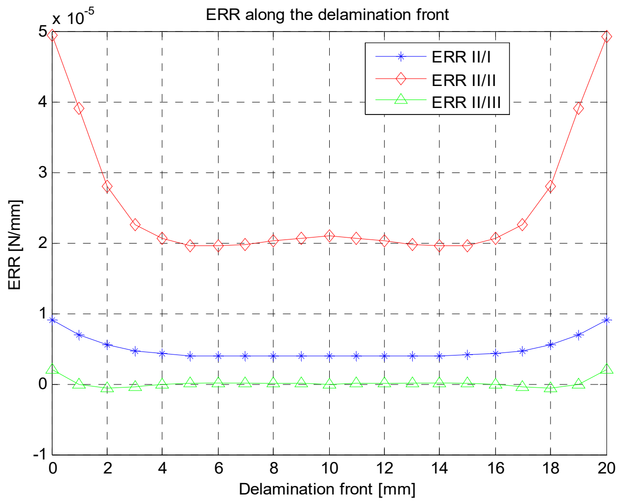

Fig. 2: Results of individual components of ERR for sliding load mode

Two plates have been used to model the delaminated plate in the thickness direction. Each is modeled with SHELL181 elements. The projection on the *x*-*y* plane of the finite element mesh, assumed equal for the plate and the interface models. The mesh is refined in a zone of 5x20 mm^2 centered with respect to the delamination front. In this zone, the length of the plate and interface elements in the *x*-direction is 0.125 mm, whereas along the *y*-direction it is 1 mm. A force of 1 N/mm is imposed in the *x*-direction (sliding load mode II (Fig. 1)). Two subplates have been used to model the delaminated plate in the thickness direction. Interface elements, necessary to connect the two sublaminates, are implemented by using a combination of rigid links MPC 184 defined by two nodes and three degrees of freedom at each node. The delamination front was created by spring elements COMBIN14, in each offset node of the delamination front by three elements. The offset nodes can be generated by rigid links. The interface between subplates was modeled by constrain equations. When CE are used in place of rigid links, for each mid-plane node of the upper plate model, three coincident nodes located on the lower surface of the plate are created. Similarly, for each mid-plane node of the lower plate model, three coincident nodes located on the upper surface of the plate are created. Three COMBIN14 elements connected to the three pairs of coincident nodes placed at the delamination plane are introduced, each one acting in differ translation direction. For mixed-mode response conditions, a complete modeling of interface elements has been implemented. The stiffness of the spring elements binding the subplates is chosen as 10^8 N/mm^3.

4 CONCLUSIONS

A two-subplate orthotropic model [13] loaded by mode II was proposed as failure model. The material characteristics of the sublaminates were calculated by homogenization [14]. Subplates were modeled by using shear deformable elements in program ANSYS. The individual components of ERR for loading mode II and response modes I, II and III, respectively along the delamination front are plotted in Fig. 2. The ERR results have maximum values on the free edges of the model, therefore it is expected that the delamination proceeds from the free edges. Results have shown that response mode II is predominant and the response mode III is negligible.

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