FE - ANALYSIS OF DELAMINATION CRACKS IN BENDING OF CROSS-PLY LAMINATES BY VIRTUAL CRACK CLOSURE INTEGRAL METHODS

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A study of delamination growth due to bending in cross-ply laminates is presented. For the understanding of interlaminar fracture behavior of laminated composites modelling of delamination crack growth induced by bending and shear cracks in three point bending specimens is carried out. A plane strain finite element analysis is used to determine the strain energy release rates during delamination of the beam. Solution of contact problem taking into account friction of crack surfaces is obtained. Energy release rates G_I and G_{II} for Mode I and Mode II fracture are calculated by virtual crack closure integral (VCCI) methods. Comparison of energy release rates obtained with and without solution of contact problem have been performed.

INTRODUCTION

Delamination represents one of the most prevalent life-limiting failure modes in laminated composite structures. Delamination may be introduced during processing or subsequently by loading of the structure. Delamination crack growth due to static, fatigue or impact loading reduces the stiffness and may lead to catastrophic failure of the structure.

Delamination damage have been investigated extensively in the literature (see, for example, papers of Wu and Springer (1), Sun and Manoharan (2), Salpekar (3) and Liu (4)). In these papers experimental investigations of delamination crack initiation and propagation under low velocity impact and static loading are presented. Energy release rates G_I and G_{II} for Mode I (crack opening mode) and Mode II (crack sliding mode) fracture of laminated beam specimens using two dimensional (2D) finite element solutions were calculated.

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The modified virtual crack closure integral (MVCCI) method (see Rybicki and Kanninen (5)) was used to compute the strain energy release rates for each fracture mode. The total energy release rate was calculated (see reference (2)) by an analytical solution using Timoshenko's beam theory. A finite element three dimensional (3D) fracture analysis (see reference (4)) for laminated composite plates subjected to transverse concentrated loading was developed. Strain energy release rates for Mode I, II and III fracture were calculated and delamination front for the laminated plate was obtained.

The purpose of the present investigation is the analysis of mixed mode delamination fracture in laminated composites taking into account the contact forces acting on the crack surfaces.

FEM ANALYSIS OF THREE POINT BENDING SPECIMENS

Two cases of three point bending specimens have been investigated. The first case is a [90/0/90] cross-ply laminated beam (see Figure 1) with a center edge notch in the bottom layer. In this case a delamination crack with length *a* runs along the interface between the layers parallel to the fibre direction. This case of delamination crack growth due to a bending crack in graphite/epoxy laminate was investigated in the reference (2).

The second case of three point bending specimen is a [0/90/0] cross-ply laminated beam (see Figure 2) with a center notch in the middle layer. This specimen is for modelling of initial shear crack in the matrix. Delamination crack growth induced by a shear crack in the matrix is also considered on the 0/90 interface between the layers. This case of delamination fracture with two matrix cracks, inclined at 45° in the beam thickness plane, was investigated in the reference (3). It should be noted that in reference (3) the finite element solution was obtained without taking into account the contact forces acting on the crack surfaces. The FE solution for the second specimen shows that crack surface interpenetration developes in the FE model and in order to obtain exact mixed mode energy release rates for this case the contact problem along the crack surfaces should be solved.

The strain energy release rates G_I and G_{II} for mixed mode delamination fracture are calculated by the modified virtual crack closure integral (MVCCI) method (one calculation (1C) formula) and single constant strain elements (see reference (5)). The finite element solution is obtained using program ABAQUS.

For both specimens let us consider (see reference (2)) a cross-ply [90/0/90] and [0/90/0] graphite/epoxy laminated beam of total thickness h=2.187 *mm*, thickness of layers $h_1 = h_2 = h_3$ =0.729 *mm*, beam width b= 10 *mm* and beam length between supports $2L = 50.8\ mm$. The material properties of the single unidirectional fibre reinforced layers are as follows

$$\begin{aligned} &E_1 = 119.9\ GPa = 1.199*10^5\ N/mm^2;\\ &E_2 = E_3 = 9.86\ GPa = 9.86*10^3\ N/mm^2;\\ &G_{12} = G_{13} = 5.24\ GPa = 5.24*10^3\ N/mm^2;\\ &G_{23} = 3.52\ GPa = 3.52*10^3\ N/mm^2;\\ &\nu_{12} = \nu_{13} = 0.3;\\ &\nu_{23} = 0.4, \end{aligned} \qquad (1)$$

where E, G and ν are Young's modulus, shear modulus and Poisson's ratio, respectively. The subscript 1 denotes the fibre direction and the subscripts 2 and 3 denotes transverse directions.

For the solution plane strain conditions are used and due to the symmetry of the problem only one half of the beam is analyzed. The energy release rates for the load $P = 2\ N/mm$ and for the different crack length a were calculated. The value of the finite element length near and at the crack tip is $\Delta a = 0.2\ mm$. These element lengths $\Delta a = const$ are also used for the step by step crack extension procedure and the subsequent MVCCI analyses, respectively.

The mixed mode energy release rates G_I , G_{II} and the total energy release rate $G_T = G_I + G_{II}$ for the first specimen (see Figure 1) are presented in the Figure 3. For the total energy release rate G_T a good agreement with an analytical solution (see reference (2)), obtained by using Timoshenko's beam theory, is observed. Total energy release rate G_T also is calculated by using the increment of the total potential energy of structure and also good agreement is found between this global energy method and the local energy MVCCI method. Furthermore, due to the fine discretisation of the FE beam model, these results show a good agreement with those obtained by the more exact VCCI method which requires two calculations (2C) with crack length a and $a + \Delta a$, respectively (see reference (6)).

For the second specimen (see Figure 2) the exact energy release rates are obtained by the solution of the contact problem and the results are presented in the Figure 4. Three values of coefficient of friction $\mu = 0;\ 0.4;\ 0.8$ are used in the solution. Influence of the value of coefficient of friction on the energy release rates is very small. But it should be noted that FE analysis of this structure without the solution of the contact problem leads to great differences with the exact energy release rates due to crack face interpenetration in the FE model. So, for the energy release rate G_I the difference to the exact values is five times, but for the crack sliding mode energy release rate G_{II} the difference is about 20 %.

For the first specimen the delamination crack growth is found to be stable (see Figure 3). The delamination is due to mixed mode fracture, but the main part of energy release G_T rate is connected with the crack opening mode (Mode I). For the second specimen the delamination crack growth is unstable (see Figure 4). In this case the delamination is also found to be a mixed mode fracture process, but the main part of energy release rate here is connected with the crack sliding mode (Mode II). Both specimens can be used in order to determine delamination fracture thougness for the laminated composite materials.

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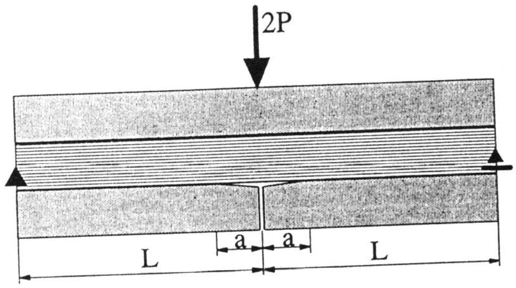

Figure 1 Cross-ply [90/0/90] specimen (case 1)

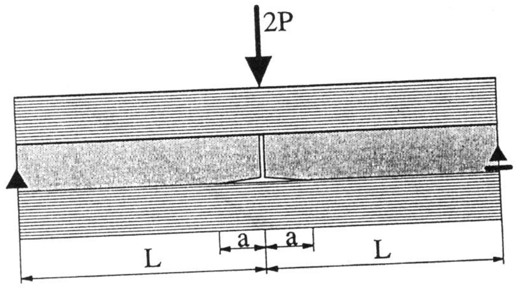

Figure 2 Cross-ply [0/90/0] specimen (case 2)

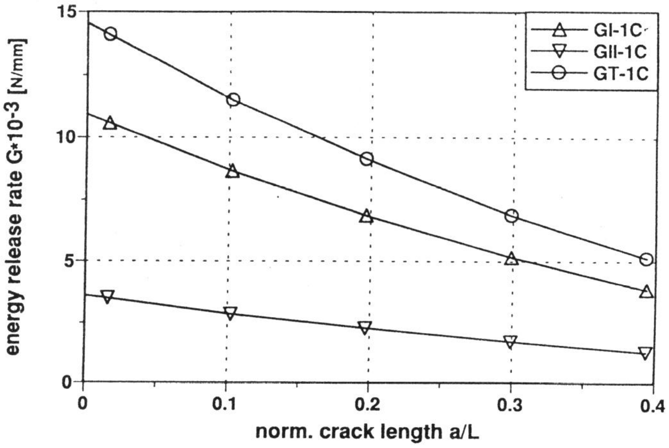

Figure 3 Energy release rates for cross-ply [90/0/90] specimen (case 1)

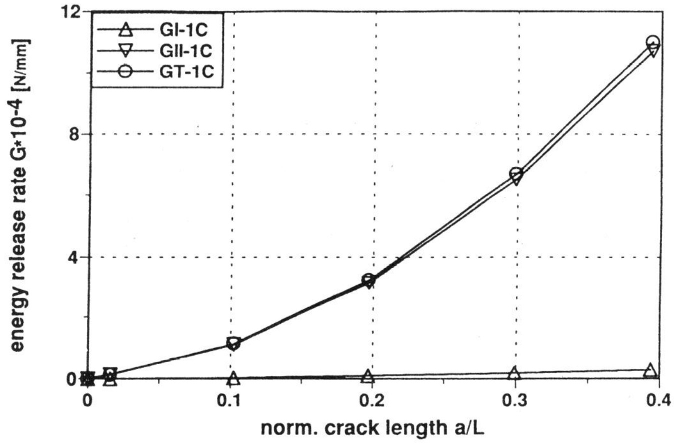

Figure 4 Energy release rates for cross-ply [0/90/0] specimen ($\mu = 0.4$; case 2)