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Prediction of induced delamination development in $[\theta/90]_s$ composite laminates using a computational analytical approach

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ABSTRACT

Most of the conducted studies on investigating the effect of induced delamination formation have been devoted to the cross-ply laminates under uniaxial loading. In this paper by implementing an energy-based theory, the induced delamination onset due to matrix cracking has been studied in $[\theta/90]_s$ composite laminates subjected to general in-plane remote stresses. For this purpose, the formation of induced delamination has been analyzed based on generalized plane strain assumptions and new stiffness matrix for constructed damage state is obtained for damaged laminate. Afterward, some interrelationship constants, which only depend on the material properties of undamaged lamina, are derived. Using these interrelationship constants, a simple equation for Gibbs free energy is acquired. By differentiating the Gibbs free energy equation with respect to the delamination length, a simplified equation is obtained for evaluating the energy release rate, which can be applied for prediction of delamination formation. In addition, ANSYS finite element software is used to evaluate the damaged material properties and strain energy release rate of damaged laminates numerically. The obtained results show that there is an acceptable agreement between developed analytical and numerical methods with the difference less than 5%.

1. Introduction

Composite materials are a serious alternative for traditional materials like metals in many fields, which exhibit complex fracture behavior due to their structural nature, and various mechanisms of fracture. The well-known damage mechanisms in the composite laminates are fibers-matrix deboning, matrix cracking, induce delamination and fiber fracture. However, in the most cases, the first probable fracture damage mode is matrix cracking. Matrix cracking is a kind of intralaminar damage mode, which grows along the thickness of the layer and parallel to the fiber direction. This type of damage is created due to the lack of proper connection between the fibers and the matrix. Investigating the effects of matrix cracking on the response of composite laminates have been done based on different approaches, including the shear lag [1–4], Variational [5–9], stress transfer methods [10–16] as well as crack opening displacement COD-based models [17–25]. Matrix cracking is not the final failure modes of material and it is formed in the loads far below the final load of the structure. Matrix cracking reduces the mechanical and thermal properties and leads to other harmful fracture modes including the induced delamination in composite laminates. Delamination causes the change in the stress distribution of composites by decreasing the stiffness of the laminate.

Many types of researches have been devoted to studying the delamination formation in multilayered composites. Large numbers of successfully performed studies on delamination formation can be generally divided into three groups including experimental studies, macro-scale analytical studies as well as numerical studies.

In the investigated experimental methods, O'Brien and Hooper [26] performed quasi-static tensile tests on composite laminates and observed the matrix cracks are formed on the free edges of laminate, which are followed by the interlayer induced delaminations originated from the tips of matrix cracks. Then, Zubillaga et al. [27] performed an empirical study focusing on the occurrence of matrix cracking and the interlayer induced delamination. They tested five different laminates of Carbon/Epoxy subjected tensile stress and observed different results. Their results were compared with the recently developed fracture criteria, which were in good agreement.

In the performed numerical methods, Camanho and Matthews [28] developed a 3D finite element model (FEM) for simulating coupling between layers in laminated composites for the first time. They used the results of FE and obtained an approximate graph for determining the stress along the thickness. They applied this method to determine the stresses of contacted regions and predicted the initiation of induced delamination according to the interlayer criterion. Then, Wimmer and

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Pettermann [29] presented a semi analytical-numerical model for simulating the delamination formation. They obtained a nonlinear solution with the combination of crack growth criterion and finite element method for the initiation and growth of delamination. Subsequently, Blázquez et al. [30] used the boundary element method (BEM) to determine the stress at the tips of the matrix cracking in the 90-degree layers. They compared the obtained results with the fracture mechanics outcomes. Later, Chen et al. [31] developed an FE model to analyze the progressive failure in the presence of matrix cracking and the induced delamination. They employed an affected elasto-plastic combined model and used a user-defined material subroutine to calculate the plasticity and fracture events in the different plies via an implemented ABAQUS code. In addition, the Cohesive Zone Model (CZM) was applied to simulate induced delamination. Their developed model was capable to simulate the intra and interlayer damage modes as well. Then, Jae et al. [32], used the advanced finite element method to predict the initiation, propagation, and interlayer induced delamination size. They used virtual crack closure technique (VCCT) to analyze the interlayer induced delamination. They applied 2D Elements with variable in-plane displacements and constant through the thickness displacement and applied the Legendre polynomials to define the expression of displacements.

In the investigated analytical methods, for the first time, O'Brien [33] examined the initiation of the delamination in composite laminates quantitatively and developed an analytical method for obtaining the energy release rate of induced delamination formation. He obtained a closed form relation for strain energy of delaminated composite under quasi-static load and identified the critical strain energy of delamination formation. Then, he applied the developed formulation to obtain the initiation and growth of interlayer induced delamination. In another attempt, O'Brien [34] obtained a novel equation for calculating the strain energy release rate associated with the induced delamination between the local layers. He measured critical strain energy for induced delamination in the Graphite/Epoxy composite laminates and used it to evaluate local delamination formation in these multilayers. Then after, he presented a simple technique to get the strain threshold for delamination formation and obtained the axial stiffness reduction due to edge delamination as well as induced delamination formation in composite laminates. Subsequently, O'Brien [35] applied CLT in the presence of thermal and moisture effects to obtain the stress distribution of composite laminate with matrix cracking subjected to uniaxial loading. Then, he calculated the energy release rate of delamination formation due to matrix cracks in the off-axis layers and used the expanded results to obtain the contribution of mechanical, thermal, and moisture stresses on the obtained energy release rate. Nairn and Hu [36] analyzed the delamination formation in cross-ply composite laminates using the Variational method. They calculated the stiffness reduction due to induced delamination by considering simple assumptions. They used 2D stress analysis to obtain the total energy release rate, stiffness and longitudinal thermal expansion reduction coefficients and applied these results to calculate the energy release rate of induced delamination formation. Kashtalyan and Soutis [37] examined the interlayer induced delamination due to matrix cracks and used the 2D shear-lag method to determine the stresses of composite laminates in the presence of matrix cracking and delamination. They replaced the damaged layers by an equivalent intact layer with reduced material properties to determine the strain energy release rate of delamination formation. Farrokhabadi et al. [38] developed a new micromechanical method for analyzing matrix cracking and induced delamination formation. They considered a single unit cell containing both matrix cracking and induced delamination and obtained the distribution of stresses and displacements and used them to determine the strain energy release rate. McCartney et al. [39] examined the induced delamination formation in cross-ply composite laminates and predicted growth of interlayer induced delamination due to matrix cracking under progressive loading including a combination of biaxial forces and thermal stress by using the energy balancing method and the crack-closure technique. They assumed the variation of stresses and temperature to be constant during the growth of the delamination. They observed that all the results confirm each other and are in good agreement with the result obtained by O'Berin [34]. In another research, Zubillaga et al. [40] presented a fracture criterion for the induced delamination formation caused by matrix cracks in symmetric composite laminates. This fracture criterion was presented in the framework of fracture mechanics rules by comparing the energy release rate of induced delamination with the fracture toughness of the interface. The obtained failure load was consistent with the experimental results. Kashtalyan and Soutis [41] developed an analytical model for induced delamination formation and used the 2D shear lag method to determine the perturbation stress and obtain the strain energy release rate associated with interlayer induced delamination. They also investigated the effect of induced delamination formation on stiffness degradation of composite laminates.

Considering the previously performed researches, the following issues can be extracted.

(1) While experimental methods are simple and useful for identifying the material response, the obtained results by this approach are restricted to the type of stacking sequence and loading conditions.
(2) The numerical methods suffer from the high computational time and divergence problems.
(3) While, the energy-based analytical methods which are applied by McCartney et al. [39] are one of the most prominent and precise approaches among the investigated analytical studies, however, they are limited to study the induced delamination in cross-ply laminates.

To overcome the shortcoming of the previously developed approaches, the purpose of the present study is to develop a precise analytical model for analyzing the effects of induced delamination formation in more complex laminates including $[\theta/90]_s$ under general in-plane remote loadings. The extended model is inspired from the proposed method by McCartney et al. [39], which is limited to the analysis of induced delamination in cross-ply laminates only. To proceed, by considering the simplified assumptions, the stiffness matrix of delaminated composite with $[\theta/90]_s$ lay-up will be derived. Afterward, using crack closure conditions in different directions, some superior interrelationship constants, which are only depended on the ply material properties of undamaged lamina will be derived. These constants connect the material properties of damaged laminate contain induced delamination into undamaged laminate. Using these interrelationship constants, a simplified equation is obtained for evaluating the energy release rate, which can be applied for prediction of delamination formation. Finally, the FE model is used to verify the developed analytical results. It is worth to note that the extended relationships in the paper are only valid for in-plane tensile and shear remote stresses. In the case of compressive axial stresses, by neglecting the bucking phenomenon, the layer 90° could tolerate the applied loading in the delaminated zone. As a result, in this case, the classical relationships can be applied for obtaining the stiffness of laminate with the good percentage of precision.

2. Methodology

In this section, an analytical method is developed to estimate the energy release rate due to induced delamination formation in general symmetric composite laminates with $[\theta/90]_s$ lay-up subjected to a desired in-plane remote loading based on generalized plane strain condition assumption. To extend the analytical model, a unit cell with a special matrix cracking density is extracted from a composite laminate which is subjected to a uniaxial loading (Fig. 1). This unit cell, which is subjected to a general in-plane remote loading, is prone to induced delamination formation with arbitrary length. For simplification of the