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On computational modeling of postbuckling behavior of composite laminates containing single and multiple through-the-width delaminations using interface elements with cohesive law

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A B S T R A C T

This paper presents an extensive analysis on effect of various parameters on the postbuckling behavior of laminated composites. The analysis is performed by developing an interface element with de-cohesive constitutive law. The debonding of adjacent plies has been simulated to illustrate the effects of delaminations growth on the post buckling behavior of the laminated composites. A parametric study is carried out to investigate the effect of size, location, distribution of delaminations, and layups configuration on the postbuckling response of composite panels concurrent with propagation of delamination. The obtained numerical results are validated against existing numerical and experimental results.

1. Introduction

Delamination is one of the most common and dangerous failure modes in laminated composites. Some of the causes of delaminations are manufacturing defects, impact load, and edge effects. Delaminations can bring about significant reduction in the strength, stiffness and load carrying capacity of laminated composites under compressive loads. Numerous computational and experimental studies have been carried out to determine the effect of delamination on the buckling and postbuckling behavior of laminated composites. Whitcomb and Shivakumar [1] studied effects of delamination on the buckling and postbuckling behavior of laminated composite suffering from rectangular embedded delaminations. They used the Virtual Crack Closure Technique (VCCT) to calculate the distribution of energy release rate along the delamination front. They showed that the aspect ratio of delamination shape plays an important role in the delamination growth direction. Gu and Chattopadhyay [2] studied the mechanism of buckling and postbuckling of graphite/epoxy laminated composites containing delamination. In their analytical and experimental studies, the effects of structural parameters such as stacking sequence, delamination size and its location were considered on the buckling and postbuckling behavior of laminated composites. Hwang and Huang [3] performed a nonlinear buckling analysis based on the finite element method to investigate the compressive buckling and postbuckling behavior of laminates containing two delaminations. They considered the effect of various delaminations positions on the critical buckling load of laminated composites. They observed that the buckling load was mainly affected by a near-to-surface delamination. Kyoung et al. [4] studied the buckling and

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Nomenclature

d	damage parameter
$\mathbf{D}$	instantaneous stiffness matrix
G_c	critical mixed mode energy release rate
$\bar{G}_c$	the effective energy release
G_{Ic}, G_{IIc} and G_{IIIc}	critical energy release rates for corresponding modes I, II and III
h_0	interface element thickness
$\boldsymbol{I}$	identity matrix
$\mathbf{K}$	interface penalty stiffness
$\mathbf{u}$	displacement vector
(X, Y, Z)	global coordinate system
β	ratio of the normal strain to the shear strain
ε	strain tensor
ε_m	effective strain
ε_m^0	threshold effective strain
$\varepsilon_z^0, \gamma^0$	onset strain components
ε_m^f	fracture effective strain
η	mode mixity empirical parameters
σ	stress tensor

postbuckling behavior of cross-ply laminated composites containing multiple circular embedded and through-the-width delaminations. Their modeling accomplished through the Lagrangian non-linear finite element analysis. Hwang and Liu [5] showed the buckling and postbuckling response of laminated composites containing multiple through-the-width delaminations with a triangular distribution along the thickness. Obtained experimental results demonstrated that the critical loads of delamination growth of specimens with a single delamination were considerably higher than that of similar specimens with multiple delaminations. Aslan and Sahin [6] studied the effect of delaminations size on the local buckling load and compressive failure of laminated composites. They found that the local buckling stress of intact laminates with symmetric stacking sequence is higher than that of laminates with anti-symmetric stacking sequence. However, for similar specimens containing multiple delaminations, the reduction in the buckling stress of the symmetric laminated composites is higher than that of the anti-symmetric ones. Hunt et al. [7] studied buckling and postbuckling behavior of delaminated struts based upon four-degree-of-freedom Rayleigh–Ritz approach. They observed that the length and the position of delamination affect the postbuckling behavior considerably. Ovesy and Kharazi [8] studied the postbuckling behavior of laminated composites analytically. Their developed analytical method is based on the first order shear deformation theory within the framework of Rayleigh–Ritz technique. Park and Lee [9] performed a parametric study on the buckling behavior of laminated composites containing embedded rectangular delamination. They proposed a 3D element with enhanced assumed strain (EAS). A significant improvement was observed in the performance of EAS element in comparison with incompatible elements. Obdrzalek and Vrbka [10] studied the effect of delaminations with irregular shapes on the postbuckling behavior of laminated composites. For the specimens with delamination located near the mid-plane, they observed that the onset of delamination growth would be more sensitive to delamination shape. Baker et al. [11] studied the compression after impact (CAI) strength of fully orthotropic laminated composites using an existing strip model. They indicated that non-symmetric laminates can exhibit damage tolerance close to that of an anti-symmetric laminate for some ply counts, and better than that of symmetric solutions in most cases.

All the aforementioned papers studied the effect of delaminations on the buckling and postbuckling behavior of laminated composites without consideration for the possibility of delamination growth. For this purpose, fracture mechanics has been extensively employed to capture delamination growth. Gaudenzi et al. [12] developed a model based on the VCCT approach along with the modified incremental continuation method to simulate the unstable propagation of delamination in a specimen with a circular embedded, and one with a through-the-width delamination. Sheinman et al. [13] investigated effect of the local buckling of the sub-laminate on delamination growth. They showed that the ratio of thickness to length has remarkable effects on the propagation of delamination. Riccio et al. [14] considered the effect of the length and the position of delamination along the thickness on the stable and unstable delamination growth. They showed that inner delaminations around the mid-plane tend to propagate unstably. Kutlu and Chang [15,16] developed an analytical model based on the large deformation theory for the analysis of the postbuckling behavior of laminates containing multiple delaminations. Moreover, to verify the developed analytical and finite element simulations, they performed an extensive compression test on various flat and cylindrical composite delaminated panels. Zhang and Wang [17] took advantage of layerwise B-spline finite strip method to study the buckling and postbuckling behavior of delaminated laminates. They utilized the VCCT approach to calculate the energy release rate along the delamination front. For each applied load increment, a set of nonlinear equilibrium equations need to be solved in order to calculate the energy release rate. When the energy release rate becomes greater than the critical value, delamination grows by one spline section length along the strip, and again a new set

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