THE EFFECT OF EDGE DELAMINATION ONSET AND GROWTH ON THE POST BUCKLING BEHAVIOR OF LAMINATED COMPOSITES BY USING DE-COHESIVE ELEMENTS

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Abstract

In this study, the influence of edge delamination onset and growth on the postbuckling behavior of laminated composites is studied. Meanwhile, the main concerning is about the possible interlaminar degradation of laminated composites and its direct effect on the load carry capacity and functionality of working structures. For this purpose, the interface element with bilinear constitutive law is developed to capture possible delamination onset and growth and the ANSYS commercial software package is used to handle the nonlinear finite element analysis. The obtained numerical results depicted that the unstable delamination growth is mainly responsible for the structural collapse under compressive load.

1 Introduction

Delamination is the most insidious and commonly occurring failure mode in the composite structures, which may take place due to manufacturing defects, edge effects, and foreign impact. Meanwhile, existence of delaminations in the interface of adjacent plies results in significant reduction in load carry capacity and stiffness of working structures under compressive loads. Afterward, unexpected catastrophic collapse of structures because of undetected delamination is inevitable. For the working composite structures under compressive loads, regional lower stiffness because of delamination would increase the possibility of local buckling which significantly reduces performance of composite structures. The occurrence of local buckling may result in damage evolution and consequent delamination growth, which would considerably diminish the flexural stiffness due to debonding of layers, and expedite global buckling and final collapse. For designing composite structures under compressive load, the load carry capacity of the structures is limited to the initial local buckling load and the postbuckling phase of compressive response of the structure is ignored. However, if deep understanding of the postbuckling behavior with the possibility of delamination growth is achieved, the lighter and more efficient structural design will be performed. So far, extensive researches have been carried out to consider the effect s of interlaminar stress and free edge on delamination onset and damage accumulation. Moorthy and Reddy [1] studied the effects of interlaminar stresses on delamination growth in laminated composites. Meanwhile, they employed the layerwise plate theory to assess the displacement field of composite laminates. In addition, interface model incorporated with penalty function is used to capture delamination growth. Sarvestani and Sarvestani [2] studied the effects of free edge on interlaminar stresses of composite laminates under extension and bending loading condition. Thus, they developed an analytical solution based upon first-order shear deformation theory and Reddy's layerwise theory to assess the interlaminar stresses. They performed extensive analysis on the interlaminar normal and shear stresses along the interface and through the thickness specifically for region near free edges. Moreover, they considered the effects of boundary conditions on free edge stresses. Amrutharaj and Lam [3] studied the delamination onset and growth in the free edge of angle ply laminate under uniaxial tension loading condition. They employed the fracture process zone to remove the singularity related to conventional fracture mechanic approach. In addition, two distinct simulations for stress displacement relation in the fracture process zone are considered, one based upon linear relationship and the other with constant stress up to critical displacement. The obtained numerical results depicted that the two considered stress-displacement relationship in the fracture process zone did not affect the overall mechanical behavior of the specimen noticeably. Lindemann and Becker [4] performed an optimization on the laminate composites to minimize the tendency of laminate to be delaminated in loading condition. They considered two analyses one based upon analytical solution by using classical plate theory and defining effective delamination moments and the other by capturing interlaminar stresses in finite element analysis.

The aim of this paper is to simulate the buckling and postbuckling behavior of laminated composites containing edge delamination. Thus, the delamination is captured via the interface element with de-cohesive constitutive law in the non-linear finite element simulation. The modeling is carried out via the ANSYS 12 commercial finite element software and the associated cohesive element is developed via the user programmable feature subroutine (UPFS). The cohesive elements are implemented in the interface region between the adjacent layers, which the delamination is more probable to propagate. Moreover, in this analysis the significant of edge effect on the delamination onset and growth is shown while extensive analysis is still required to clarify its potential threat for under compression composite laminates.

2 Delamination Propagation Simulation

To capture delamination propagation, two approaches are mainly considered, which are based on fracture mechanics and damage mechanics perspectives. In the fracture mechanics approach various perspectives including virtual crack closure technique (VCCT), J-Integral, and virtual crack extension technique (VCET) are employed to notice damage accumulation. All these approaches rely on determination of precise location of nodes in the crack front region to calculate energy release rate for detection of delamination growth. It is noteworthy to mention that fracture mechanics approaches have limitations and difficulties in numerical implementations. Thus, the fracture mechanics approaches are not applicable for the specimen with pre-delamination but also a complex remeshing tool is required for each stage of delamination accumulation. Recently, damage mechanics approaches via the cohesive zone model have attracted the attention of researches. Simulations based upon cohesive zone model dependant on the determination of constitutive law to capture the engaged mechanism in delamination propagation. Moreover, the bilinear de-cohesion constitutive law has the capability to predict the onset and growth of the delaminations simultaneously. Not only its dependency on mesh density is lower than fracture mechanics approach but also the remeshing tool is not required in capturing delamination propagation. Therefore, the cohesive zone model does not contain the limitation of the fracture mechanics approaches, but severe convergence difficulties related to the softening zone of the constitutive laws decrease the applicability of this method for large size complex simulations. It is noted that such numerical instabilities would be diminished by increasing number of elements in the cohesive zone.

Balzani and Wagner [5] developed a formulation for the interface element with capability of capturing delamination growth under mix mode loading condition. Moreover, they considered two forms of constitutive laws including bi-linear and exponential to study the effect of shape of constitutive laws on the delamination growth. In this paper, the bilinear constitutive law is used due to its simplicity and its excellent capability in prediction of brittle crack growth. In the next section the formulation of bilinear constitutive law will be explained in the framework of Balzani and Wagner approach.

3 Results and Discussions

In this section, the numerical results concerning the postbuckling behavior of laminated composites containing edge delamination are presented. The developed interface element with the bi-linear De-cohesive constitutive law is embedded within the finite element analysis to capture the accumulation of damage in the interface region. Having conducted the postbuckling analysis required an imperfection, which can be obtained by performing the Eigen buckling analysis and combining the distinct mode shapes. In the analysis, the laminated composite is discretized with 8 node solid element and the interface element is used to capture the delamination growth in the region in which delamination is expected to propagate. Moreover, the finite element analysis is handled through the ANSYS 12 commercial software package. The mechanical property of laminated composites and the cohesive zone model parameters are presented in Table 1. The number of elements employed to create finite element analysis is around 26600, given mesh independency of results. Thus, the CPU time for all cases was approximately the same, which is about 7 hour on the hardware package with properties of Intel Core i7 1600(MHz) and 4 GB DDR-3 physical memory.

Material Properties	Laminate	Interface Properties	Cohesive Zone
$E_{11}(N/mm^2)$	139300	$G_{Ic}(N/mm)$	0.0876
$E_{22}(N/mm^2)$	9720	$G_{IIc}(N/mm)$	0.3152
$G_{12}(N/mm^2)$	5580	$G_{IIIc}(N/mm)$	0.3152
$G_{23}(N/mm^2)$	3450	$\sigma_n^0(N/mm^2)$	44.54
υ_{12}	0.29	$\tau^0(N/mm^2)$	106.9
υ_{23}	0.4		

Table 1. Material properties of laminated composite and interface region

It is noteworthy to mention that the penalty stiffness in the cohesive element affect the total mechanical behavior of the interface region. Meanwhile in other to avoid inaccuracy in of delamination growth, the initial stiffness is assumed to be formulated as function of virtual interface thickness and the elasticity modulus . To clarify the effect of edge delamination and its possible growth behavior on the postbuckling response of composite laminates, specimens with geometrical configuration as shown in Fig. 3 are considered.

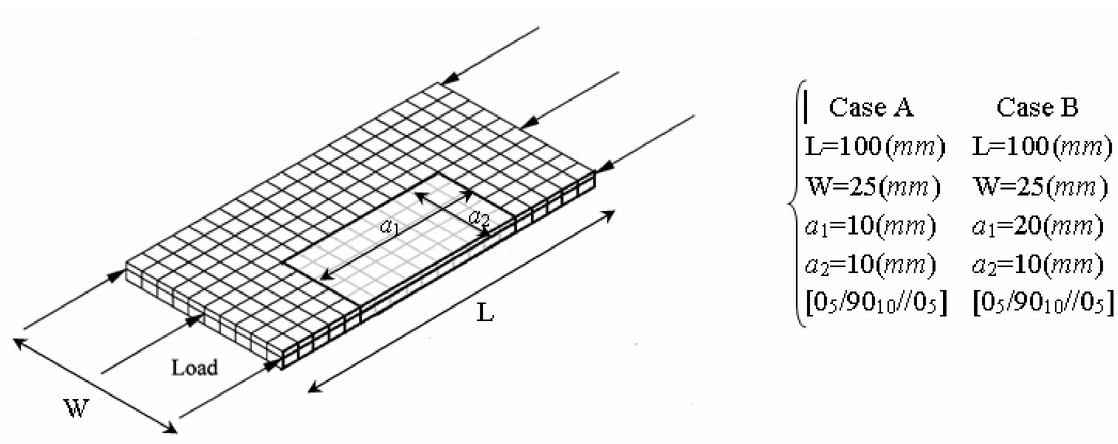

Figure 1. Geometrical configuration of composite laminates with edge delamination

It is noted that the symbol // illustrate the existence of edge delamination between adjacent layers. The employed mesh configuration of deformed laminate is depicted in Figure 1.

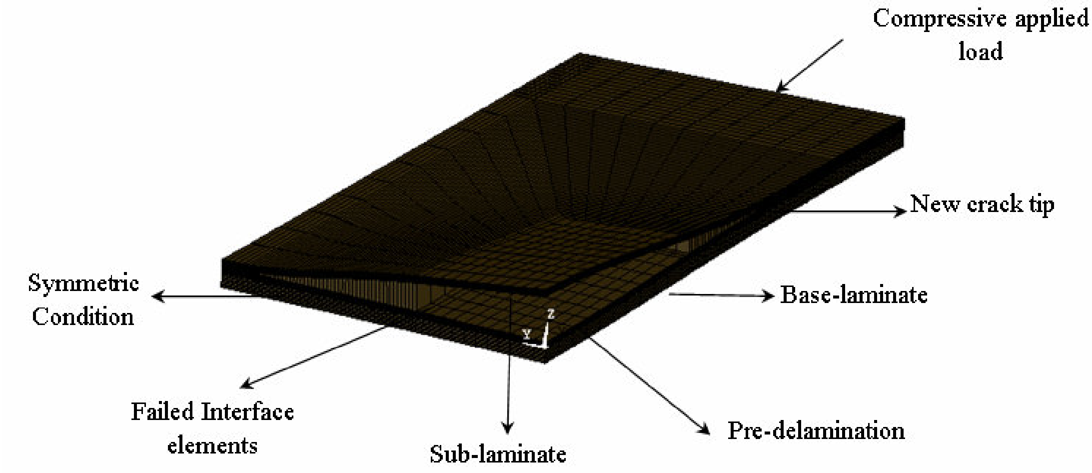

Figure 2. Mesh configuration in the deformed laminate composite

The obtained results for compressive resultant load versus applied end shortening strain for both mentioned cases are presented in Figure 2. Regard to this figure, consideration of delamination propagation significantly influences the load carry capacity of the laminated composite. The obtained results emphasize that delamination growth deteriorates the performance of the laminated composite while under compressive loads catastrophic collapse of the structure will be inevitable. In addition Fig. 5(a), 5(c) indicated that the unstable delamination growth behavior would be reduced by increasing in delamination size. Thus, the load drop of the laminate with smaller delamination is lower than the other case with larger delamination.

The out of plane displacement of the laminated composite versus compressive resultant load is shown in Fig. 5(b), 5(d). which illuminates the effect of delamination growth on the postbuckling behavior. It clarifies that delamination growth imposes larger out of plane displacement for both of sub-laminate and base-laminate and speeds up the global buckling and final collapse of the structure. It can be observed from these figures that in the specimen with larger delamination (case B) the local buckling in the sub-laminate occurs in load around 80(N/mm) while the other specimen with smaller delamination has local buckling load around 150(N/mm). It is to be noted that the unstable delamination growth takes place after the local buckling occurrence. Hence, whenever the local buckling come up in the laminated composite structures it may increase the possibility of unstable delamination growth and following significant stiffness reduction. Therefore, in the design of practical cases we should care about the local buckling and its effects on decreasing of final failure load.

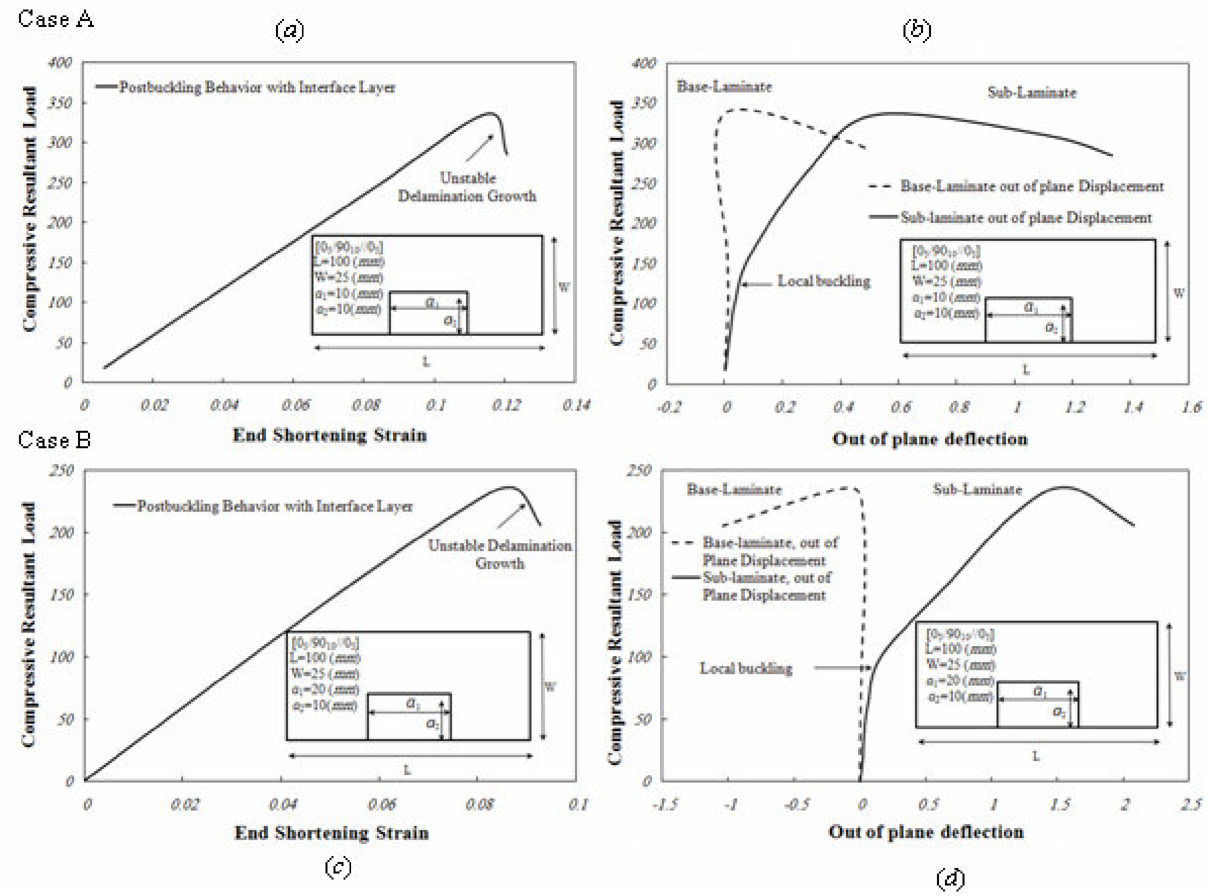

Figure 5. Compressive response of laminated composite with edge delamination. a) Case A, Resultant load-end shortening behavior b) Case A, Out of plane deflection versus applied compressive load c) Case B, Resultant load-end shortening behavior case d) Case B, Out of plane deflection versus applied compressive load.

Figure 3 depicts the evolution of damage in the interface region of composite laminates. It can be observed from this figure that unstable damage growth reduce the effective stiffness of interface region and consequent softening would diminish the performance of structure significantly. It is noteworthy to mention that relatively fine mesh is employed in the free edge region to capture the possibility of edge effect on delamination growth. Due to limitation of the employed hardware in handling finite element analysis extensive investigation on the edge effect event in composite structures under compressive load could not be performed.

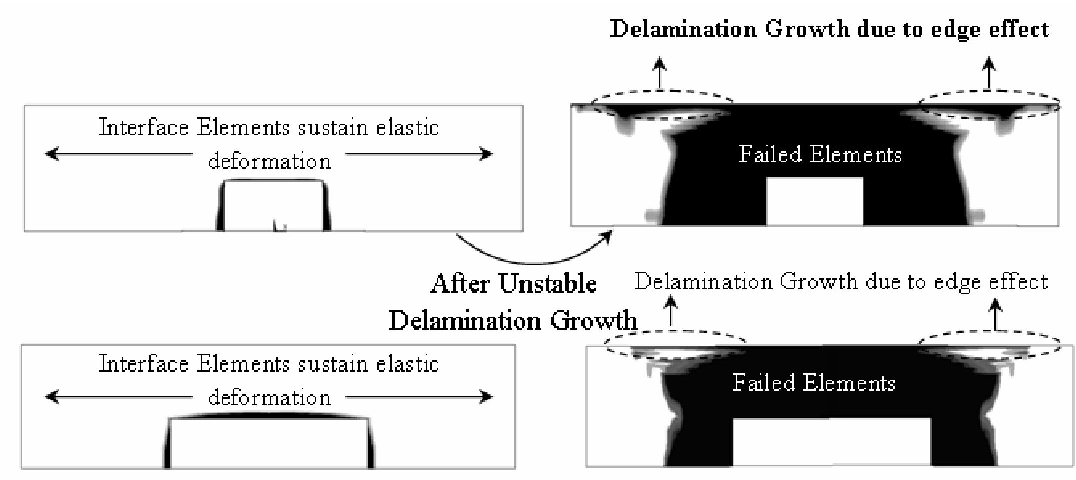

Figure 3. Damage evolution countour in the interface region

4 Conclusion

In this study, the postbuckling behavior of laminated composites containing edge delamination was investigated. The possibility of delamination onset and growth was captured via developing the interface element with de-cohesive constitutive law. Meanwhile, the nonlinear finite element analysis was performed via the ANSYS software. In the present analysis due to the involvement of both geometrical and material nonlinearities, severe numerical instability was observed which is mainly originated from oscillation of stress in the cohesive zone length. Thus, the simulations with interface element are noticeably mesh dependant. The obtained numerical results prove the fact that the unstable delamination growth in the interface region of adjacent layers would considerably diminish the efficacy and reliability of composite laminates containing edge delamination. Moreover, the free edge effects may contribute to the onset and growth of edge delamination, which should be consider as a threat even for the perfect laminates.

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