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Compressive Behavior of a Glass/Epoxy Composite Laminates with Single Delamination

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ABSTRACT

The buckling and postbuckling behaviors of a composite beam with single delamination are investigated. A three-dimensional finite element model using the commercial code ANSYS is employed for this purpose. The finite elements analyses have been performed using a linear buckling model based on the solution of the eigenvalues problem, and a non-linear one based on an incremental-iterative method. The large displacements have been taken into account in the nonlinear analysis. Instead of contact elements a new delamination closure device using rigid compression-only beam elements is developed. Effect of delamination length, position through thickness and stacking sequence of the plies on the buckling and postbuckling of laminates is investigated. It has been found that significant decreases occur in the critical buckling loads after a certain value of the delamination length. The position of delamination and the fiber orientation also affect these loads.

Keywords: Delamination; Buckling; Postbuckling; Composite materials

1 INTRODUCTION

ALONG with the progress of industries, the qualities of engineering of structural materials have been improved and their usefulness has been increased. Owing to their low weight and high strength, composite materials are widely used in various industries like automobile, construction and weight-sensitive aeronautical industries.

However, composite structures are subjected to various damages due to the manufacturing defects, external impact or compression and fluctuating loads during their service life. Delamination is one of the most important damages in layered composites. Delamination results in degradation of a structure both in stiffness and strength. Composite laminates with delamination are vulnerable against compressive loads. They may easily buckle in a lower level of compressive load depending on the size, position and shape of the delamination. Once delamination occurs, stresses within the composite laminate will be redistributed. This will then lower the compressive load carrying capacity of the composite laminate. High inter laminar stresses at the free edges, impact and fabrication defects are among the main causes for occurrence of delamination. Three types of buckling may occur in a composite laminate subjected to in-palne compressive load depending on the size and through thickness position of delamination. These types of buckling are shown in Fig. 1. Many researchers have investigated the effect of delamination on composite laminates in recent years. Kachanov [1] considered a single delamination near surface and through-width assuming a thin film problem. Chai et al. [2] developed a one-dimensional model to investigate the behavior of delaminated composite laminates. Other investigators studied the effect of delamination on the behavior of composites numerically or experimentally [3-11]. In the present investigation, the residual buckling strength of composite laminates under in-plane uniaxial compression is studied numerically using a three-dimensional finite element model. Using the developed model, the effects of delamination length-through thickness orientation of plies on the critical buckling load are studied.

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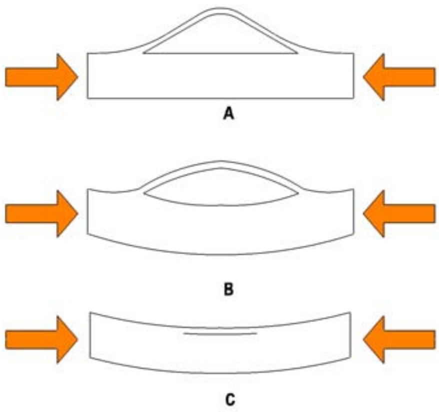

Fig. 1
Buckling modes; A: local, B: mixed, C: global.

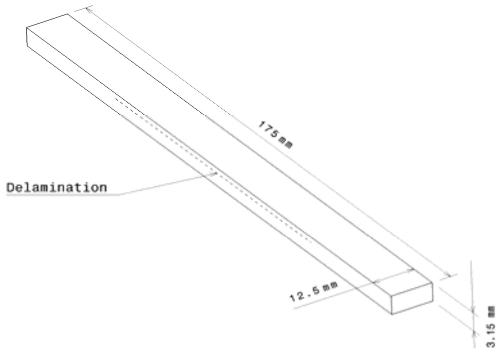

Fig. 2
The specimen and its dimensions.

Table 1
Mechanical properties of glass/epoxy composites

Property	Value
Thickness (mm)	0.315
v	0.047
E_{11}	16280
E_{22}	16280
G_{12}	3728
G_{23}	1296
G_{13}	1296

2 PROBLEM STATEMENT

A cross-ply composite beam consisting of 10 woven glass/epoxy plies was chosen for the study. The material properties of this composite are listed in Table 1. The properties were obtained from characterization tests, which were performed by the authors. The Young's modulus, shear modulus, and Poisson's ratio are denoted as E, G, and v, respectively. The subscript 1 represents the fiber direction, 2 the direction transverse to the fiber, and 3 the normal direction to ply plane. The gauge length of the specimen l, the width w, and the thickness H, were selected to be equal to 175mm, 12.5mm, and 3.15mm, respectively. The Dimension specimen is shown in Fig. 2. Delamination was considered in the middle of specimen. Buckling and postbuckling behavior of six laminates with different delamination size and different through thickness position (40, 60, 80, 100, 140, 160 mm) are studied and the effect of fiber orientation in these specimens is investigated.

3 FINITE ELEMENT MODELING

Linear (or eigenvalue) buckling and nonlinear buckling analyses are two techniques for predicting the buckling load and buckling mode shape of a structure. Linear buckling analysis based on stress softening theory determines the bifurcation points of a perfect structure, where two or more load deflection curves intersect. In eigen buckling analysis, eigenvalues and eigenvectors need to be solved. Eigenvalue equation has the form of:

$$[K]\{\Phi_i\} = \lambda_i [S]\{\Phi_i\} \tag{1}$$

where $[K]$, $\{\Phi_i\}$, λ_i, and $[S]$ are structure stiffness matrix, eigenvector, eigenvalue and stress stiffness matrix, respectively. In the nonlinear buckling analysis, the load is increased gradually to find the point where the solution begins to diverge. During each load increment the stiffness matrix must be adjusted to reflect the nonlinear changes in the structure stiffness, otherwise errors will accumulate. This could be accomplished using the Newton-Raphson equilibrium iterations. It is also important to recognize that an unconverged solution does not necessarily mean that the structure has reached its critical load, because it can also occur due to numerical instability. Tracking the load-deflection history in the analysis could help to decide the actual structure buckling. A three-dimensional mesh has been generated 20-node quadratic Solid95 element for crack tip region and 8-node linear Solid45 for the specimen [12]. Singular wedge elements, which are shown in Fig. 3, were used around the crack tip to describe the singular behavior. Due to symmetry in the geometry and loading conditions, only half of the domain has been meshed and constrained. To do nonlinear buckling analysis, it is necessary to provide an initial small geometric imperfection (in the order of 0.0001 mm). This small initial imperfection can be created from the mode shape obtained by the linear buckling analysis. To prevent the overlapping of sub-laminates instead of using contact elements, which is CPU intensive, a new method has been employed. In this method, compression-only beam elements (Beam10) are used between two sub-laminates. A compression beam element only transmits compressive loads. The finite element model of the specimen is depicted in Fig. 4.

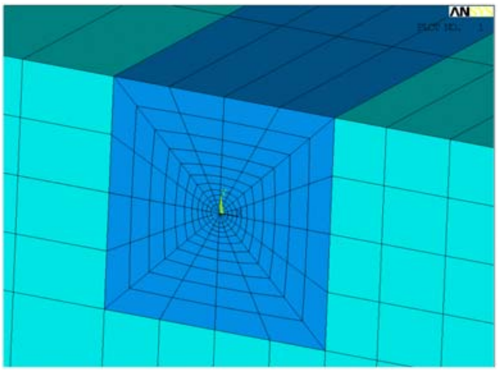

Fig. 3
Singular crack tip elements.

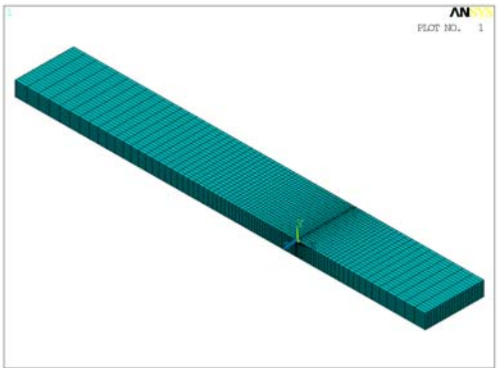

Fig. 4
Finite element model of the specimen.

The graphical method developed by Southwell [13] is used to determine the buckling loads. Southwell's plot is a method to predict the buckling load of initially imperfect columns. The Southwell method is a very useful graphical method to estimate the critical buckling load. The method was actually developed for columns, but experiments have shown that the method can also be used to give a reasonable estimate of buckling loads for plates. Consider a simply supported column of length *l* and flexural rigidity *EI*, under compressive load *P*. The initial curvature of the column is described by the following Fourier series

$$\delta(x) = \varpi_n \sin\left(\frac{x\pi}{l}\right) \tag{2}$$

where ϖ_n is the amplitude of a sine wave representing each mode of the initial imperfection, *l* is the column length, and x is a coordinate parallel to the direction of force. Southwell showed that the total deflection on δ_T at the center of the column may be approximated by

$$(w-w_0)_{x=\frac{l}{2}} = \frac{\varpi_1}{1-P/P_{Cr}} - \varpi_1 = \varpi_1 \frac{P/P_{Cr}}{1-P/P_{Cr}} = \delta \tag{3}$$

where P_{cr} is critical buckling load. This equation can be rearranged in a form representing a straight line:

$$\frac{\delta}{P} = \frac{\delta}{P_1} + \frac{\varpi_1}{P_1} \tag{4}$$

Hence, P_{cr} will be the slope of the line showing variation of δ with respect to δ/P.

4 RESULTS AND DISCUSSIONS

In this section, results of the nonlinear finite element analysis are compared with the results obtained from the eigenvalue buckling analysis. At first the delamination considered to occur between first and second layers. Results presented in Table 2 show good agreement between the linear and nonlinear buckling analyses. Fig. 5 shows the deformed shape obtained from the nonlinear analysis. Beam elements which have been used to prevent the overlapping of sub-laminates are shown in this figure. Deformed shapes for three different delamination lengths (short, medium, and long) are shown in Fig. 6. As expected, three types of buckling modes namely, local buckling, global buckling and mixed mode are observed in the finite element analysis. Fig. 7 shows the variation of load with respect to out-of-plane deflection as obtained from large displacement nonlinear analyses for different length of delamination between the first and second layers. In long delamination lengths, buckling took place only in delaminated plies (local buckling, delamination length 140, 160 mm). When the delamination length decreases with increasing the load, initially the entire laminate deflects. Then, as the load reaches the critical buckling load, buckling occurs in the delaminated sub-laminate (mixed buckling mode, delamination length 60, 80, 100 mm).

Table 2
Buckling load from linear and nonlinear analyses

Delamination lenght (mm)	Nonelinear analysis (N)	Eigenvalue analysis (N)
20	91.1	96.25
30	51.5	54.68
40	28.2	31.92
50	17.7	20.13
60	12.1	14.06
70	8.3	10.38
80	6.4	7.97

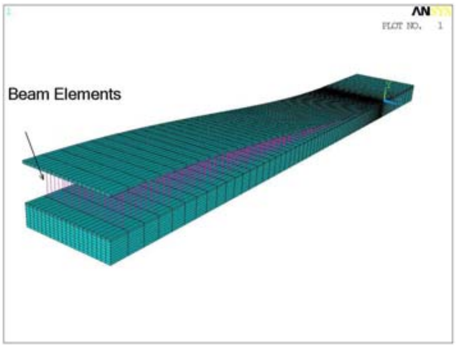

Fig. 5
Deformed shape of the beam obtained from nonlinear analysis.

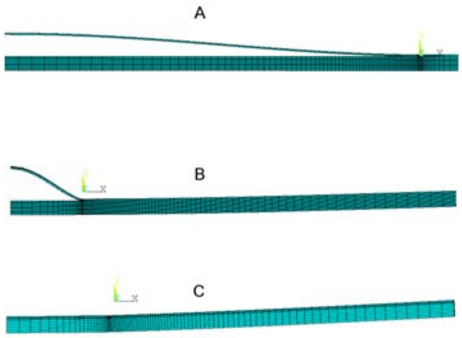

Fig. 6
Deformed shapes for different delamination lengths; A: Local buckling mode, B: mixed buckling mode, and C: global buckling mode.

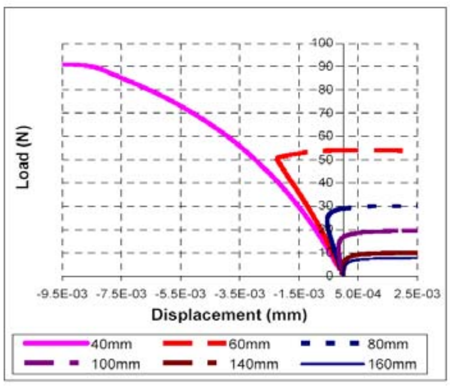

Fig. 7
Out-of-plane deflection versus compressive load.

For short delamination lengths, the entire laminate and the delaminated layer buckle simultaneously with entire laminate (global buckling, delamination length 40 mm). The effect of delamination length, through thickness position of delamination and stacking sequence of layers on the critical buckling load is considered next. In order to study the effect of delamination length on the buckling load, nine different delamination lengths are considered (20, 40, 60, 80, 100, 120, 140, 160, and 180 mm). The effect of delamination lengths is studied for different positions of delamination through thickness. Fig. 8 shows the buckling load for various delamination lengths in different delamination positions. Increasing the delamination length reduces the buckling load. Rate of this reduction is higher when delamination occurs in outer plies (i.e. between the first and second layers).

Fig. 9 shows the critical buckling load in different position of delamination through thickness for different delamination lengths (horizontal axis defines the position of delamination between different plies from outer ply to middle ply of the beam). For short delamination lengths, the position of delamination does not significantly change the buckling load, but increasing the delamination length increases the effect of the position of delamination on the buckling load.

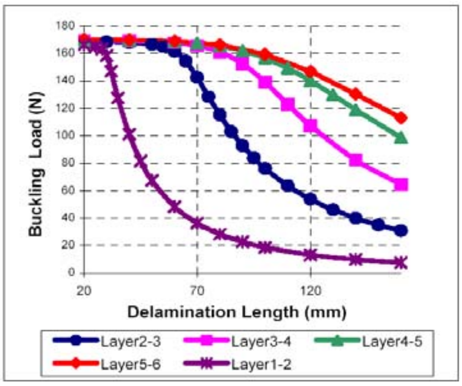

Fig. 8
Buckling load vs. delamination length for different delamination position.

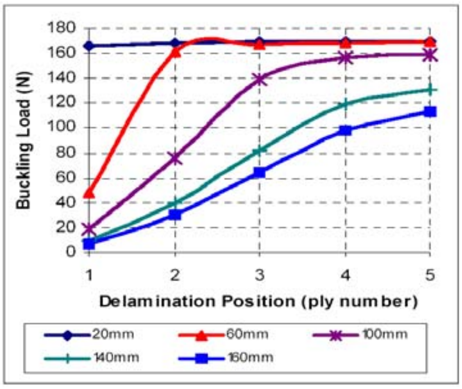

Fig. 9
Buckling load vs. position of delamination between different plies.

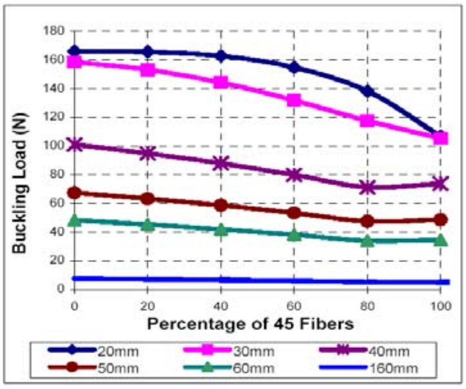

Fig. 10
Buckling load versus percentage of ±45 plies.

Due to the widespread application of composites with ply angles 0/90 and ±45 in industrial designs, the effect of amount of plies 45^o orientation in buckling behavior is also studied. To do so, in different analyses from the middle ply of the specimen, ply angles one by one changed from 0/90 to ±45.The effect of this modification on the critical buckling load of the laminate with delamination between the first and second layers is shown in Fig. 10. For long delamination specimens, changing the ply angles from 0/90 to ±45 does not affect the critical buckling load. But in shorter delaminations, due to the presence of the global buckling mode, increasing the percentage of 45-degree fibers reduces the critical buckling load.

5 CONCLUSION

A finite-element analysis of composite columns containing a delamination has been conducted. Eigenvalue buckling analysis provided the critical buckling load and the buckling shape of the laminates. A geometrically nonlinear analysis utilizing the mode shape which is obtained through a linear analysis combined with the Southwell graphical method have been used to determine the buckling load. To prevent the overlapping of sub-laminates instead of contact elements, which are computationally expensive, only-compression beam elements have been used. The results show that the delamination significantly affects the buckling load and both eigenvalue and nonlinear buckling analysis methods can closely predict the buckling load; however, the eigenvalue analysis produced non-conservative buckling loads. The effect of different parameters, such as the delamination length, through thickness position of delamination and amount of 45-degree layers on buckling load are studied. The results show that the effect of delamination length parameter on buckling load increases when delamination occurs in outer plies. For shorter delamination lengths, due to the global buckling mode, the position of delamination does not affect the buckling load. Using the 45-degree plies instead of 0/90 degree plies generally decreases the critical load. However, for longer delaminations, it does not affect the critical load.

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