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Analysis of embedded delamination growth in laminated composite using cohesive surface method

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Abstract

In this paper, the finite element method (FEM) is used to study the delamination growth and post buckling of composite laminates containing embedded delamination under the compressive loading. Delamination decreases an elastic buckling load of the composite structures and leads unexpected structural failure at loads below the design level. The investigated composite laminates which are made of carbon fiber/epoxy have the stacking sequence of $[90/(0/90)_3//(0/90)_{14}]$ containing a circular as well as square delamination. The symbol // illustrates the position of delamination in the laminate. For modeling and analysis the laminate, the three-dimensional continuum shell elements have been used via the ABAQUS 6.12 software. Furthermore, the surface-based cohesive behavior is utilized to simulate cohesive zone model (CZM) which is applied for damage propagation. In addition, the surface to surface contact has been applied in the delamination zone to prevent overlaps between elements through simulation. Two different approaches have been adopted to solve buckling problem: linear, based on the solution of eigenvalues problem, and nonlinear. The Riks method was used to solve the nonlinear system. The load/displacement behavior of embedded delamination growth for composite laminates is presented. Results reported in this study are focused on the effects of the shapes and geometry imperfections on post buckling response as well as. Validation of the circular delamination specimen has been performed with experimental and previous numerical data.

Keywords: Composite Laminate, ABAQUS, Delamination Growth, Cohesive surface, Post buckling

Introduction

Delamination is one of the most common failure modes in composite laminates, that caused by edge effects, impact, manufacturing process as well as fatigue loading. Delaminations can lead to a collapse of structure especially when the composite are under compressive or shear loading. When the structure is loaded in compression, the delaminated zone of the laminate may first buckles and then grows. The presence of delamination can cause significant reduction in stiffness and strength of the laminates. As a result, in order to improve the design knowledge, a better understanding of the delamination is required. Many researches have been conducted both numerically and experimentally investigation of the buckling and growth of delamination in composite laminates.

Withcomb et al. [1] studied the buckling of composite plate with square and rectangular embedded delaminations. They employed the virtual crack closure technique (VCCT) for predicting the delamination growth and could calculate the total strain energy release rate due to delamination growth. Tafreshi et al. [2] developed a finite element models to study buckling and damage propagation in composite plates with embedded delaminations. They utilized the modified crack closure technique to calculate energy release rate. Their results demonstrated that the delamination growth potential depends on the shape of delamination region and local buckling mode. They also demonstrated that the local buckling mode was highly influenced by the laminate stacking sequence. The buckling and post buckling behavior of debonded composite laminates were investigated by Wang and Zhang. [3]. In their analysis, the layer wise b-spline finite strip method was used which is an efficient method based on layer wise laminate theory to study the local and global response of composite laminates under static or impact loading conditions. In order to predict the delamination growth they used energy release rate. Nilsson et al. [4] studied the delamination buckling and growth of cross ply composite panel using numerical and experimental methods. They showed that for all delamination depths, the delaminated panels failed by delamination growth below the global buckling load of the undamaged panel. In addition, they found that the energy release rate of laminate is increased when global buckling mode takes place. Hosseini-toudeshky et al. [5] discussed the buckling and post buckling behavior of composite laminates containing through the width and embedded delamination under the compressive load. They used the layer-wise plate theory to estimate the displacement fields. Furthermore, they used the interface elements between two layers to model the delamination growth in ANSYS program. They concluded that the behavior of delamination growth and buckling mode of the composite plates depends on the size of delamination and stacking sequence of the laminates. Albiol [6] investigated the buckling and post buckling behavior of composite laminates containing embedded delamination in the composite laminate with artificial delamination. They studied the effect of various parameters on predicted response in the post buckling.

By reviewing the performed studies on the delamination growth in the literature, it can be found that, no one attempt has been done on the modeling of delamination growth using the cohesive surface in ABAQUS software. The cohesive surface provides the simple way to model cohesive connections and the governing laws are very similar to those for cohesive elements with traction-separation behavior. The cohesive surface model will be used because the interface thickness is very small. On applying the cohesive surface approach, it can be observed that this model has some benefits including the reduced computational time, easy modeling as well as good convergency The aim of present study is to investigate the post buckling response of composite panels containing delaminations inserted at two different shapes. The primary objective is to study the geometrical imperfection size on the post buckling behavior. Therefore, the cohesive surface which is a surface interaction property has been modeled to predict delamination propagation. The nonlinear finite element simulation is carried out via the ABAQUS 6.12 software. The model for the composite plate is also based on previous work [6]. The obtained results will be compared with available numerical and experimental data of Albiol [6].

2. Finite element analysis

In this section, the slender composite panels containing the circular and square delamination are used to handle the procedure. The laminates have been modeled by eight nodes 3D layered continuum shell elements, which look like the three dimensional continuum solids, but their kinematic and constitutive behavior is similar to conventional shell elements. Simultaneously, the CZM between two sub-laminates has been developed by a surface-base cohesive behavior which is intended for situations that the interface thickness is negligibly small. The cohesive behavior is defined as the interaction properties between two surfaces that can be developed to simulate the delamination at interfaces directly in terms of traction versus separation. The available traction-separation model in ABAQUS standard assumes initially linear elastic behavior which relates the normal and shear stresses to normal and shear separation across the interface as

$$t=\begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix}=\begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix}\begin{Bmatrix} \text{¢}_n \\ \text{¢}_s \\ \text{¢}_t \end{Bmatrix}=K\text{¢} \qquad (1)$$

Where t is nominal traction stress vector and includes t_n, t_s *and* t_t. t_n is normal traction and t_s, t_t are the shear tractions. In addition, the corresponding separations are denoted by δ_n, δ_s and δ_t.

The mechanism of failure consists of two ingredients including a damage initiation criterion and damage evolution. Damage initiates when the cohesive response at a contact point degrades. Therefore, it is assumed to initiate when a quadratic interaction function involving the contact stress ratios reaches a value of one. Damage initiation has been assigned by the quadratic failure criterion

$$\left\{\frac{\langle t_n\rangle}{t_n^0}\right\}^2+\left\{\frac{t_s}{t_s^0}\right\}^2+\left\{\frac{t_t}{t_t^0}\right\}^2=1 \qquad (2)$$

Where t_n^0, t_s^0, t_t^0 represent the values of the highest contact stress. The damage evolution law shows the cohesive stiffness degradation. Fig.1 shows the cohesive law for single loading. A scalar damage variable, *D*, represents the damage at the contact point [7]as

$$D=\frac{\delta_m^f(\delta_m^{max}-\delta_m^0)}{\delta_m^{max}(\delta_m^f-\delta_m^0)} \qquad D\in[0,1] \qquad (3)$$

In which δ_m^{max} refers to the maximum value of the effective separation, δ_m^f is the effective separation at complete failure and δ_m^0 is relative to the effective separation at the initiation of damage. The constitutive response of Fig. 1 can be written as

$$\begin{aligned} &t=K_p\delta && \delta<\delta^0 \\ &t=(1-D)K_p\delta && \delta^0\le\delta<\delta^f \qquad (4) \\ &t=0 \qquad K_p=0 && \delta\ge\delta^f \end{aligned}$$

According the linear elastic fracture mechanism method, mixed mode delamination growth occurred when $G_T\ge G^C$, where critical fracture energy G^C is the energy release rate in the mixed-mode condition and $G_T=G_I+G_{shear}$. The softening law is applied in Benzeggagh-Kenane mode interaction criterion to predict mixed-mode delamination propagation, which is given by

$$G_f^C+(G_m^C+G_f^C)\left\{\frac{G_{shear}}{G_T}\right\}^{¦}=G^C \qquad (5)$$

Where G_I^C, G_{II}^C and G_{III}^C are the critical energy release rate for mode I, II and III. $G_{shear}=G_{I}+G_{III}$ and η are the parameters achieved from the experiments. The post buckling analysis contains two steps: the first one is eigenvalue buckling analysis which is a linear perturbation procedure and is generally used to estimate the critical load and first mode shape. The second one is the post buckling analysis of the structure that contains geometrical imperfection on the perfect geometry. The imperfections are introduced by modifying the geometry of the plate before the initiation of post buckling phase. The response of some structures depends on the imperfection geometry. It is worth noting that, the nonlinear static procedure in ABAQUS/standard is performed to model quasi-static events.

3. Results and discussion

In this section the compressive behaviors of HTA/6376C composite laminate containing circular and square embedded delamination are investigated. The geometric configuration of each specimens including the length, width and the shape and position of delamiation have been illustrate in Fig 2. While, the radius size of circular delamination in Fig. 2a is D=0.06 m, the length of square embedded delamination in Fig 2b is a=0.054 (m). However, the through the thickness position of both them is the same (h/H=1/5). In addition, the mechanical properties of the unidirectional lamina and cohesive zone model are E_{11}=131 GPa, E_{22}=E_{33}= 11.7 GPa, G_{12}=G_{13}=5.2 GPa, G_{23} =3.9 GPa, ν_{12} = ν_{13} =0.3, ν_{23}=0.5, N=30 MPa, S=T=30 MPa, G_{I}^{C}= 260 (J/m^2) and G_{II}^{C}=G_{III}^{C}=1025(J/m^2) [6] respectively. The penalty stiffness of the cohesive zone is considered to be 10^{15} N/m^3 [6]. A circular and square cohesive zone region is placed between upper and lower laminate to simulate the delamination propagation. Due to symmetrical loading and geometry respect to the x and y axes, only one quarter of the structure has been simulated. Fig .3 shows the boundary conditions and mesh pattern of each laminates. The behavior of a typical composite laminate plate containing delamination which is under the compressive loading, can be represented by the out of plane displacement of two specified control points. As the load increases, the thinner Sub-laminate buckles first and the local buckling will be occurred consequently. Then after, the distance between the two control points U and L increases (the point L does not change in the position). The global buckling mode is observed when the thin sub-laminate is dragged toward the base-laminate. The mixed buckling mode may appear between local and global buckling mode. The compressive load respect to out of plane displacements for composite panel containing circular and square delamination with two different sizes of imperfections are shown by graph to examine the influence of them on the structural response. Figs.4 and 5 show the compressive load versus the out of plane displacement for composite panel containing circular delamination with two different imperfections. The results are compared with available numerical and experimental outcomes [6].The obtained results in Fig. 4 reveal that in the case of circular delamination, a better agreement with experimental data can be achieved when the considered imperfection is about 0.1% of the plate thickness. This figure also indicates that at the load around 60kN, the local buckling is happened. By increasing the end shortening, the delamination propagation is initiated prior to global buckling. For the plates with the imperfection amplitude of 0.1%, with an increasing opening of the delamination, the both sub-laminate and base-laminate deflect downward (Fig.6). However, for the composite plates containing circular delamination with imperfection amplitude of 1%, the delamination propagates but the base laminate deflects upwards and delamination tends to close. The graphical obtained results depict that the cohesive surface damage variable (CSDMG) changes from zero for cohesive element with no damages to one for completely damaged zone. Red elements illustrate completely damage zones. In Fig.7, the load-deflection relations of composite laminates with square embedded delamination shape are obtained. The results for two geometry imperfection in the composite panels with the square delamination show the same kind of trend. This means that for two imperfections small differences in the responses can be seen and the same type of deflection behavior is observed. However, in the composite plate containing circular delamination when the imperfection gets larger, different response patterns will be observed. The compressive load versus the out of plane displacement for composite panel containing square embedded delamination with two different imperfections of 1% and 0.1% is shown in Figs. 7 and 8. The obtained results reveal that in this case, there is a slight difference between the obtained results of two imperfections.

In general, the comparison the obtained results in present study shows that the applied procedure of present study for modeling the embedded delamination growth in composite laminates has enough accuracy and reability. The main differences between the model presented in this study and circular delamination composite plates described by Albiol are the lower computation time and easy modeling, especially in 3D models, which is due to using the cohesive surface approach. While the cohesive modeling depends on the mesh size and requires fine meshing, surfaced based cohesive is typically easier to define mesh.

Conclusion

The finite element model using ABAQUS is presented to study the growth of embedded circular and square delamination and post buckling behavior of composite laminates. The cohesive surface was used to predict the delamination growth. The results of present study reveal a good agreement with experimental and numerical results. The outcomes obtained by cohesive surface model were compared with cohesive element method. The compared results illustrated that by considering surface base method, the taken CPU time for simulation, was decreased. The other significant benefits of using this method are simplification on modeling and better FE convergency. In this study the influence of the different imperfection and different shape were also investigated. The obtained data showed that the delamination propagation and global buckling mode depend on strongly to the shape of the delamination and the presence of initial imperfections. The numerical results in terms of load-displacement curves, damage growth, post buckling shapes were investigated as well. It was concluded that buckling and post buckling of structures are sensitive to initial imperfections.

Figures and Drawings

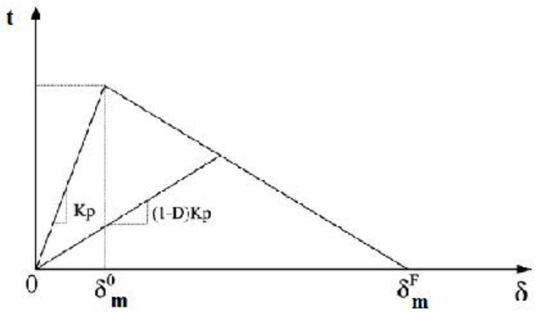

Fig. 1: Linear damage evolution law for cohesive surfaces

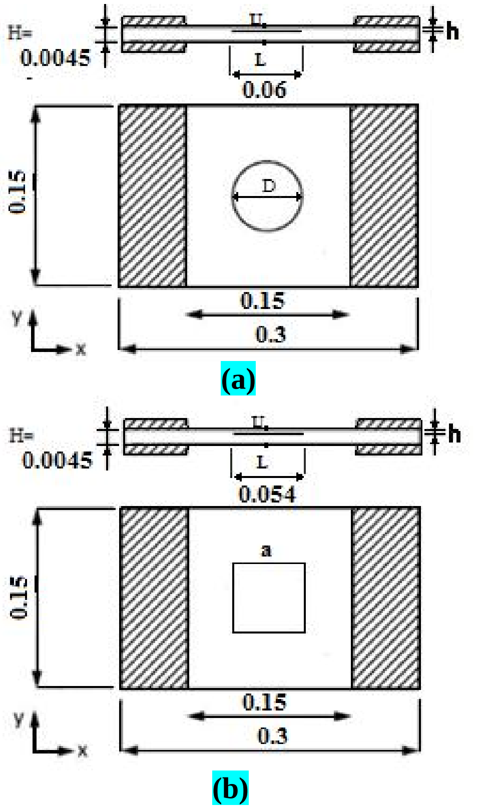

Fig. 2: Geometry of the HTA/637C specimens with a stacking sequence of $[90/(0/90)_3//(0/90)_{14}]$

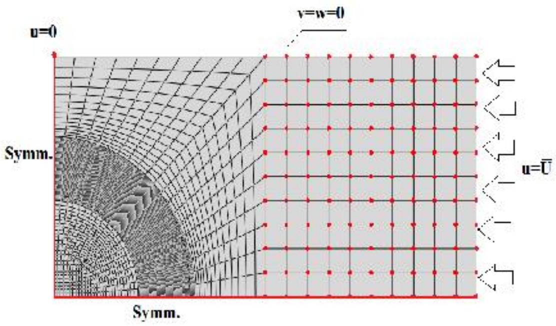

Fig. 3: Boundary condition in composite laminate containing the circular embedded delamination

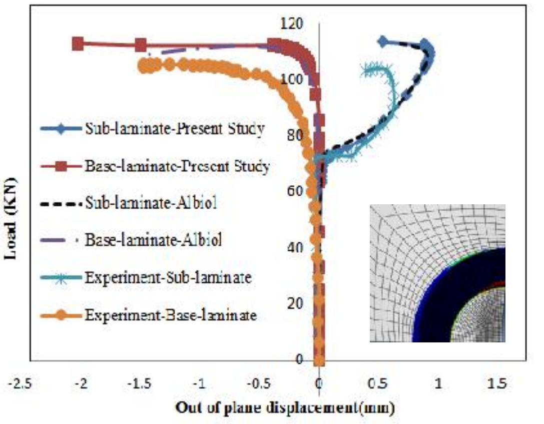

Fig. 4: compressive load versus out of plane deflection corresponding to the 0.1% imperfection amplitude for circular delamination

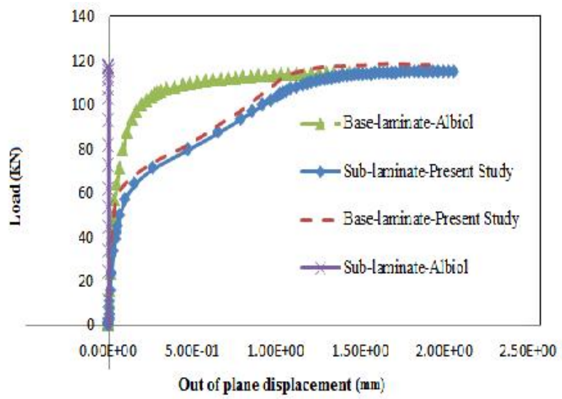

Fig. 5: compressive load versus out of plane deflection corresponding to the 1% imperfection amplitude for circular delamination

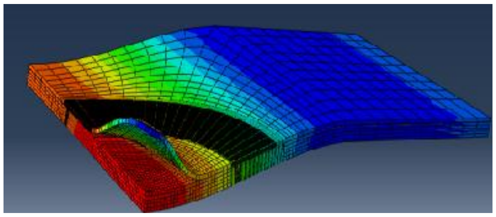

Fig. 6: Global buckling mode for circular delamination imperfection amplitude of 0.1%

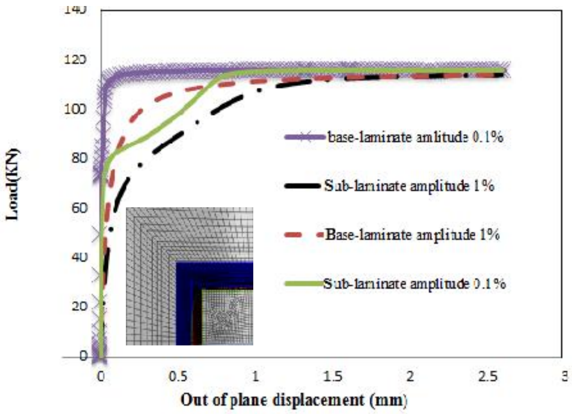

Fig. 7: compressive load versus out of plane deflection corresponding to the 0.1% and1% imperfection amplitude for square delamination

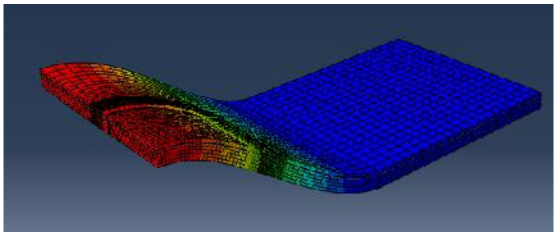

Fig. 8: Global buckling mode for circular delamination imperfection amplitude of 0.1%

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