Post-buckling delamination propagation analysis using interface element with de-cohesive constitutive law

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Abstract

In this paper, the cohesive zone constitutive law is implemented at interface between delaminated layers to simulate buckling driven delamination propagation in the laminates. The influence of single and multi delaminations on post-buckling behaviour of laminated are investigated and compared by obtained results of other method and the available experiments. It is shown that post-buckling delamination propagation can be predicted well, by utilizing a damageable interface element.

Keywords: Post-buckling;; Single Delamination; Multiple Delamination; Cohesive law

1. Introduction

Delamination is one the most dangerous failure mode that may take place between adjacent plies due to manufacturing defects, impact damage, edge effects and so on. The existence of the delaminations can cause significant reduction in the strength, stiffness and load carry capacity of the laminates under compressive loads. So far, extensive researches have been carried out to determine effect of delaminations on the buckling and post-buckling behaviour of laminated composites.

Delamination propagation simulation follows two distinct approaches, the linear elastic fracture mechanics (LEFM), and damage mechanics. The LEFM assume the insignificant cohesive zone ahead of the crack tip. However, the cohesive zone ahead of crack tip in the composite materials consists of fibre...
bridging, void coalesces and micro cracks make significant material non-linearity. Damage mechanics approach based on theory of cohesive crack model avoids singularity at the crack tip and considers inelastic behaviour of the material. So introduced theory is the preferred approach for delamination propagation simulating in laminates.

Whitcomb et al [1] studied the buckling delamination growth of laminated composite containing square and rectangular embedded delaminations. They employed the VCCT approach to calculate the distribution of energy release rate along the delamination front. They demonstrated that the delamination growth direction depend on the delamination aspect ratio. Wang and Zhang [2] employed the layerwise B-spline finite strip method to study the buckling and post buckling behaviour of debonded composite laminates. They utilized the VCCT approach to calculate the energy release rate through the delamination front for predicting the possible delamination growth. For each increment of applying load in the layerwise B-spline finite strip method a set of non linear equilibrium equations must be solve and the strain energy release rate calculated to assess the delamination growth. While the energy release rate reaches its critical values, the delamination grows by one spline section length along the strip longitudinal direction and again the nonlinear equilibrium equations must be solve for the updated specimen delamination size. They investigated the influence of loading mode on the energy release rate, which indicated that before the buckling the energy release rate of mode 1 is higher than mode 2, however after buckling the energy release rate of mode 2 shows intense increasing trends in comparison with mode 1 energy release rate.

Hosseini-Toudeshky et al.[3] investigated the buckling and post buckling behavior of composite laminates containing through the width and embedded delamination under compressive loads. They modeled the delamination propagation by employing full layerwise plate theory to estimate displacement field of laminates and the interface element to capture the delamination propagation. They developed the nonlinear computer code to simulate buckling delamination growth of the laminated composites by interface and layerwise elements.

The objective of this paper is to employ the non-linear finite element method in conjunction with the interface element to simulate the buckling and post buckling delamination propagation of the laminated composites containing single and multiple through the width delaminations. The modelling is carried out via the ABAQUS 6.9.1 commercial finite element software. The cohesive element is placed in the interface between the adjacent layers, which the delamination is expected to propagate. The bilinear decohesion constitutive law is implemented through cohesive element to predict the initiation and propagation of the delaminations. The DCB specimen is employed to verify the prediction of the cohesive element for the initiation and propagation of the delamination; the results are compared with the available numerical and experimental results. The specimens containing single and multiple delaminations are employed to study the effect of the inner delaminations on the initial buckling and the load carry capacity of the whole laminated composites. The results are compared with the B-spline finite stripe method by Wang [2], and the available experimental data [4]. It is shown that the generally good agreement achieved.

2. Finite element Analysis

The nonlinear finite element analysis is employed within the ABAQUS 6.9.1 commercial code to simulate the delamination propagation of the laminated composites. The laminated composite is discretized by the four node 2D continuum plane strain elements. The 4 node cohesive element is placed in the interface between laminates, which the delamination is expected to growth.

A suitable decohesion constitutive law for the interface element must be selected to ensure the efficient and reliable prediction of delamination growth. Hence, the bilinear constitutive law is employed to simulate the brittle fracture through the interface. The constitutive laws relate the stress to the strain
tensor of the interface element for pure loading mode, however in the mixed-mode loading the effective stress and strain tensors are implemented in the constitutive laws. The constitutive law is comprised of three phases shown in Fig. 1. The first one related to the situation when the effective strain is smaller than $\varepsilon_{m b}^0$, thus the linear elastic behaviour for the interface element is dominated and the decohesion does not take place in the interface. The interlaminar damage onset when the effective strain of the interface element exceeds the $\varepsilon_{m b}^r$ magnitude. According to the types of constitutive law, the interface element stresses follow decreasing trend. This is the second phase of constitutive law. The last phase takes place when the effective strain goes beyond $\varepsilon_{m b}^f$ and the damage parameter reaches the maximum possible value of 1. This indicates the interlaminar decohesion and the interface element is destroyed.

![Fig. 1: Bilinear de-cohesion constitutive law](image)

The effective energy release rate parameter is determined by the area below the stress-strain of the interface element divided by its thickness, $h_\text{in}$. The effective energy release rate is defined as

$$\bar{G}_C = \frac{G_C}{h_\text{in}}$$

where $G_C$ is the energy release rate in the mixed-mode condition which is defined according to the Benzegagh and Kenane criterion in Eq. (6), where $G_{IC,II}$ and $G_{III}$ are the critical energy release rate for the corresponding mode $I, II$ and $III$ respectively. $G_{\text{shear}} = G_{II} + G_{III}$, $G_T = G_1 + G_{\text{shear}}$ and $\eta$ are the parameters achieved from experiment.

Standard quasi-static non-linear buckling and postbuckling analyses were performed using the Newton-Raphson method in the framework of geometric nonlinearity. To buckling activation, and having the first mode shape from an eigen-buckling analysis, a postulated imperfection is inserted in the geometry of model using scaled mode shape as an imperfection.

3. Results and Discussions

3.1. Through-the-width single delamination analysis

This section is concern with the compressive response of the laminated composites with single through-the-width pre-delamination. The laminate stacking sequence is $[0_4 / 0_{12} // 0_4]$, which is made of the T300/976. The symbol // illustrates pre-delamination location in the delaminated specimen. The geometry of specimen with single delamination is shown in Fig. 2(a). The material properties of T300/976 are $E_{11}=139300$ (N/mm$^2$), $E_{22}=E_{33}=9720$ (N/mm$^2$), $G_{12}=G_{13}=5580$ (N/mm$^2$), $G_{23}=3450$ (N/mm$^2$), $\nu_{12}=\nu_{13}=0.29$, $\nu_{23}=0.4$, $G_{IC}=0.0876$, $G_{IK}=0.3152$ (N/mm), $\sigma^0=44.54$ (N/mm$^2$), $\tau^0=106.9$ (N/mm$^2$).

The numerical results for load versus end shortening strain and the load versus maximum out of plane deflection of the sub-laminate and base-laminate are illustrated in Figs. 3. Fig. 3(a) shows the ultimate
load and failure point of the whole laminate. Fig. 3(b) compared the out of plane deflection history of the sub-laminate and base-laminate versus compressive load of the present modeling with respect to Wang et al. results [2]. These figures show the good agreement between the present model and the modelling of Wang et al. [2] The obtained numerical results indicated that the sub-laminate buckled in the compressive load about 200(N). However, by increasing the end shortening strain the delamination propagation is initiated which leads to fail near the compressive load of \( P = 1350\) (N), which is smaller than the similar case without delamination propagation \( P = 1615\) (N).

Fig. 2: (a) The unidirectional laminated composite containing single delamination; (b) the laminated composites with multiple delamination \( [0_4/0_{12}/0_4] \)

Figs. 4 depict the history of the load-strain of the sub-laminate and base laminate. The obtained numerical results of the present model are compared with the Wang et al. [2] and the available experimental results [4]. The obtained results indicated that the local buckling prediction of the present study and the Wang et. al. [2] approach are under the experiments. Such differences may due to the sticking of the sub-laminate through the Teflon thin film in manufacturing process. However, both of the numerical simulations present overestimate value from the experimental ultimate failure load. Considering contact constraint between the delaminated surfaces in interface element, may causes such differences in the delamination-buckling growth behavior of the delaminated specimens in two modeling, while the Wang finite strip method can not consider the contact condition.

Fig. 3: (a) Compressive load versus (a) end shortening strain and (b) out of plane deflection
3.2. Through-the-width multiple delamination analysis

This section is concerned with the effect of through-the-width multiple delamination on the post-buckling behavior of the laminated composites. For this purpose, two delaminations with length of 19.05(mm) and 38.1(mm) are placed at the thickness direction of the laminate. The geometrical properties of the specimen are shown in Fig. 2(b). The compressive load-end shortening strain of the laminated composites is shown in Fig. 5. According to this figure and comparing the results by the results of single delamination specimen, the second inner delamination has significant effect on the ultimate load of laminated composite. The sudden drop of the load in this figure is due to the unstable growth of inner delamination, immediately after that the global buckling takes place and the laminated composite reaches its ultimate load.

Figs. 6(a) and (b) demonstrate the compressive load versus axial strain history of the top and bottom of sub-laminate and base-laminate, respectively. As shown in Fig 6(a), the inner delamination does not have
significant effect on the local buckling load, thus it is approximately equal to the specimen containing single delamination. The local buckling load predictions of both numerical models underestimate the experimental result. Wang’s finite strip method has capability to capture more load increment in the unstable phase of the delamination growth than the present model, because the non-linear finite element along with the cohesive element encounters convergence problems in the unstable delamination growth. The present model reaches an excellent agreement in the ultimate load of global buckling with the Wang’s method, although they underestimate experimental results.

Fig. 6: Comparison between the obtained results from present model, Wang et al.[10] and experiment for specimens with multiple delaminations (a) sub-laminate; (b) base-laminate

4. Conclusion

The buckling driven delamination growth of the laminated composites with single and multiple through the width delaminations were investigated using the softening behavior of the interface via the bilinear decohesion constitutive law. From the obtained numerical results the following concluding remarks are noticed. 1- The compressive load applied to the laminated composites containing delaminations causes the sub-laminate to buckle at the load about \( P=200 \text{(N)} \), which is much lower than the load carry capacity of the virgin laminate. It is shown that the load carry capacity is significantly reduced by the delaminations propagation. 2- The existence of the inner delaminations can significantly influence the post buckling behavior of the laminate. Due to the unstable delamination propagation of the inner delaminations, the compressive applied load encounter a sudden drop and subsequently the global buckling happen in the compressive load, which is much lower than the similar specimen with single delamination.

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