

Compressive behavior of composite panels with deeply embedded delamination

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Abstract: The compressive behavior of laminates with a deeply embedded circular delamination was studied numerically and experimentally. In the finite element analysis (FEA), virtual crack closure technique (VCCT) and B-K law were employed to simulate the delamination growth, and the contact of the two substrates was considered. The effect of the delamination size and through-thickness position on the compressive behavior of laminates with an artificially embedded circular delamination was discussed. It is found that the through-thickness position affects the buckling mode, which then strongly influences delamination growth speed and direction, as well as the dominant component energy release rate (ERR). The numerical results agreed well with the experimental results.

Key words: composite; compressive failure; delamination propagation; buckling;
VCCT (virtual crack closure technique)

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Delamination is the dominant mode of failure in composites, which may result from the manufacturing flaws, low-velocity impact in service and so on^[1]. Though there have been quite a few experimental studies^[1-3] and numerical simulations^[4-7] researching the delamination buckling and residual strength of delaminated laminates, few focused on the compressive behavior of the composite laminates with a deeply embedded delamination. However, when referring to the delaminations due to manufacture flaws, the statistics indicate that delaminations usually happen in deep through-thickness positions, especially from 1/3 to 1/2 of the thickness^[8]. Therefore, a study on laminates with a deeply embedded delamination is significant. The present paper introduces the experiment procedure and the finite element modeling of composite laminates with a single circular embedded delamination. The simulation results were validated by experiment data and also a detailed

post-analysis check. In the finite element analysis (FEA), virtual crack closure technique (VCCT) was employed to calculate the energy release rate (ERR) components and to simulate the delamination growth. In addition, a parametric study of delamination size and through-thickness position of two kinds of lay-up laminates is performed. The ultimate delamination shape from FEA is also compared with that from ultrasonic C-scan results.

1 Experiment

In the study, the laminates were made of prepreg of T300/QY8911 and the average mechanical properties measured after curing from strain-gauged unidirectional coupons were: $E_{11} = 142$ GPa, $E_{22} = 9.31$ GPa, $G_{12} = G_{13} = 4.81$ GPa, $G_{23} = 3.0$ GPa, $\nu_{12} = \nu_{13} = 0.317$. The critical ERR of Mode I was 252 J/m^2 and Mode II was 665 J/m^2 . The two stacking sequences were type A $[45/-45/0/-45/0/45/0/-45/45/45/90/45/-45/-45/$

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45/0]_s and type B [45/−45/0/−45/0/45/90/−45/0/45/90/45/0/−45/90/0]_s, in which the nominal ply thickness was 0.12 mm.

The dimensions of specimens are presented in Fig. 1. Each specimen contained a circular embedded delamination in the center of the plate with diameter of 50 mm or 60 mm. To ensure that the delamination was accurately set at the center of the specimens, ultrasonic C-scan was used before cutting. The delamination was located at the interface of the layers by inserting a single polytetrafluoroethylene film of 100 μm in thickness between plies, either at $\frac{h}{2}$ or $\frac{h}{3}$, which were named F2 and F3 respectively for convenience. In type A specimens, F2 and F3 were after the 16th and 10th ply respectively, and in type B specimens after 16th and 11th ply. Therefore, the experiment selected 8 cases in total, each with 3 replicates.

The compression test was conducted according to ASTM Standard D7137-07^[9]. In accordance to the standard, the boundary conditions are shown in Fig. 1. To evaluate the degradation caused by the embedded delamination, 140 mm × 12 mm dimensioned specimens without delamination were tested separately in accordance with ASTM Standard D6641.

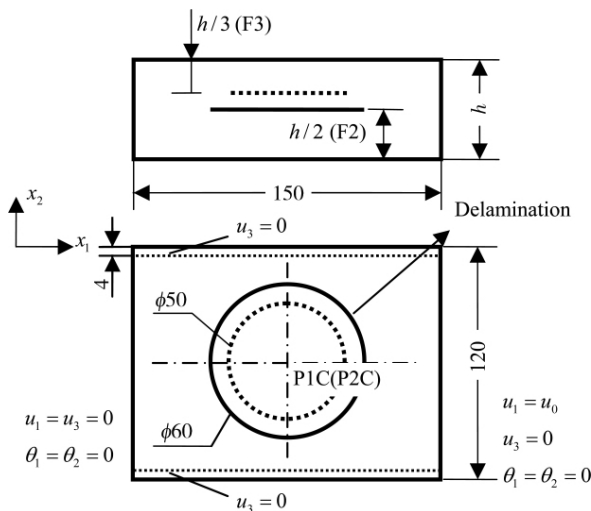


Fig. 1 Geometry and boundary conditions of the specimens

2 Finite element modeling

The full model of the specimens was employed and analyzed using ABAQUS 6.8 software. As illustrated in Fig. 2, S4 and S3 shell elements based on the first order shear deformation theory were used to discretize the model. The boundary conditions set in FE(finite element) model were shown in Fig. 1 and a uniform axial displacement u_0 was applied on the loading edge.

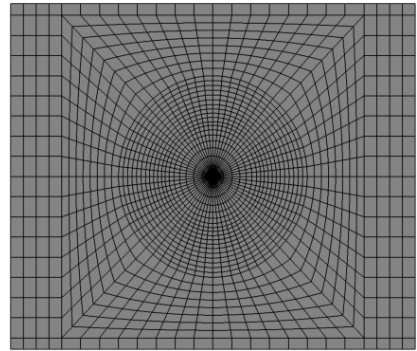


Fig. 2 Mesh of FEA model

In the FE model, the whole laminate was split into upper and lower substrates with the same mesh in Fig. 2, in which the reference surfaces were respectively shifted to the bottom and top surfaces in order to consider the thickness of the laminates. On the two reference surfaces, a contact pair was employed to prevent the penetration of the upper and lower substrates. The corresponding two nodes of the upper and lower substrates in the initially intact areas were tied as a node pair in all the freedom degrees. Fig. 3 shows the schematic of delamination front. The delamination propagation was simulated by releasing the tied node pair into two separate nodes if the crack propagation criterion (B-K (Benzegagh-Kenane) law^[10]) $f = G_{\text{equi}}/G_{\text{equic}}$ reached 1.0 within a given tolerance f_{tol} , where G_{equi} and G_{equic} were the equivalent and critical ERR, respectively. Components I, II, III of ERR in B-K law were calculated by VCCT^[11]. In B-K law η was selected as 1.0. According to Ref. [11],

$$G_{\text{equic}} = G_{\text{IC}} + (G_{\text{IIC}} - G_{\text{IC}}) \left(\frac{G_{\text{II}} + G_{\text{III}}}{G_{\text{I}} + G_{\text{II}} + G_{\text{III}}} \right)^{\eta} \quad (1)$$

η is around 1 to 2 for carbon fiber/epoxy materials and around 2 to 3 in glass fiber/epoxy materials. To assure $\eta = 1.0$ was a sensible value, η was changed from 1 to 1.75 in the post-analysis, and the results showed that the maximum fluctuation of the peak compressive load was within 0.2%.

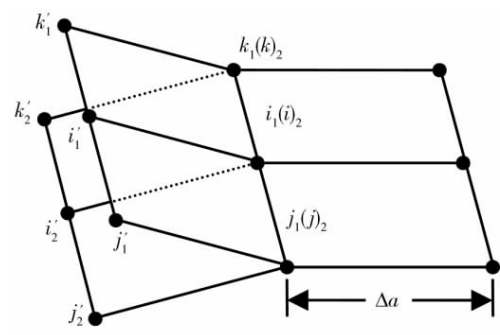


Fig. 3 Schematic of delamination front

In order to initiate the buckling of the laminates, a small initial out-of-plane displacement perturbation (about 0.1% of a single ply thickness) was prescribed near the center of the circular delamination. To ensure calculation accuracy as well as to achieve numerical convergence, automatic incrementation control in ABAQUS was employed and the initial, minimum and maximum compressive increment sizes were specified as 0.001, 1^{-10} and 0.005. Viscous damping for relative motions of the contact pair at all slave nodes was used, in which an appropriate automatic contact factor was introduced to prevent chattering of the contact pair.

In the present work, detailed post-analysis check was done to validate the FEA results. Parameters such as η , f_{tol} in B-K law, automatic contact factor, and the mesh size were changed in an advisable range in the simulation. The FEA results showed that the selected values were sensible.

3 Results and discussion

The residual compressive strength from experiment and FEA are compared in Table 1, showing a good agreement between them. In addition, a typical ultimate shape of delamination

from ultrasonic C-scan imaging of experimental results is shown in Fig. 4. The delamination shapes from FEA results, for instance which in Figs. 6 and 7, agreed well with that of experimental results.

Table 1 Compressive strength from experiment and FEA/MPa

Case	Experiment	FEA	Error/%
A	716	-	-
B	923	-	-
D50F3A	286	292.73	2.2
D60F3A	285	287.48	0.1
D50F3B	326	369.05	13.2
D60F3B	309	316.04	2.2
D50F2A	333	343	3.1
D60F2A	262	280.12	6.8
D50F2B	336	322.03	4.3
D60F2B	327	298.49	8.6

Note: A, B denote 140 mm × 12 mm dimensioned specimen of laminate type A and type B respectively.

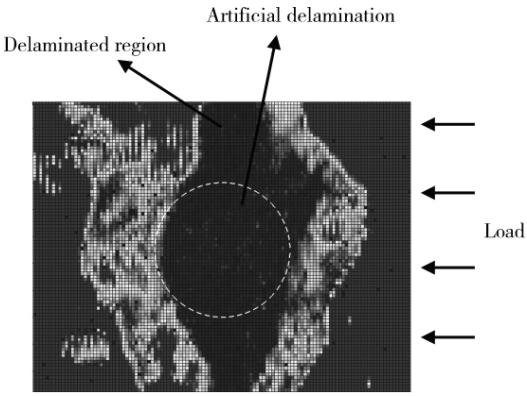


Fig. 4 Typical ultimate shape of delamination from ultrasonic C-scan imaging

3.1 Effects of delamination through-thickness position

Case D50F2A, D50F3A and an assuming case D50F8A without corresponding test specimen are analyzed to illustrate the effects of delamination location along the thickness, in which the delamination of D50F8A located after the 4th ply, about $\frac{h}{8}$ of the laminates. Table 2 shows

the compressive strain and load when local buckling, mixed-mode buckling, antisymmetric buckling, delamination initiation and the peak compressive load ($P_{\max}$) happen, the number in the bracket denoting their chronological sequences. Fig. 5 depicts the computed compressive load and the deflection of substrate center

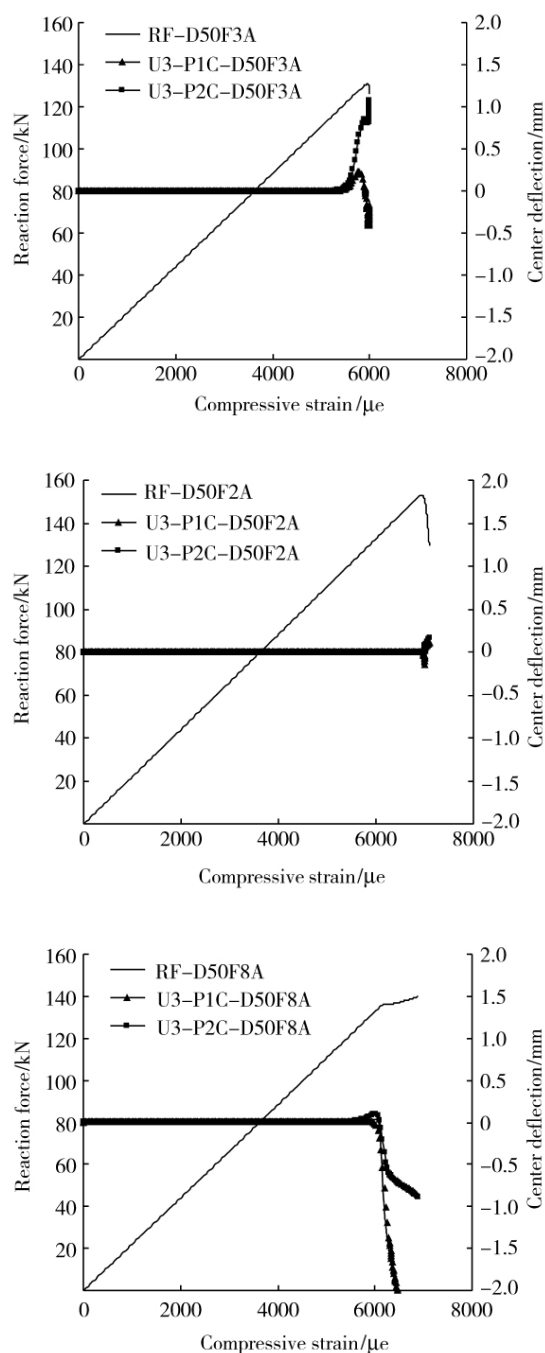


Fig. 5 Computed compressive load and the deflection of substrate center P1C and P2C against the compressive strain in case D50F2A, D50F3A, D50F8A

P1C and P2C (see Fig. 1) against the compressive strain for the three cases. In Figs. 6 and 7, the deformation shapes and corresponding delamination regions of D50F3A and D50F2A are presented. Figs. 5, 6 and 7, together with Table 2 indicate that when the location of the delamination becomes deeper in thickness, the buckling mode would shift from local mode to mixed mode and then to antisymmetric global mode in the present lay-up configurations.

As implied in Table 2 and Fig. 6(b), the delamination of D50F3A propagated stably at the angle of about 73° when the plate deformed at mixed mode. But when the deformation of the plate changed dramatically into antisymmetric shape, the delamination became unstable and the direction of propagation changed to the angle of 90° as shown in Fig. 6(c). For D50F8A, delamination propagated stably at the angle of 90° in mixed mode and led to a significant decrease of the compressive modulus when the compressive load was still increasing (see Fig. 5).

As shown in Table 2 and Fig. 7, in case D50F2A, the plate immediately deformed into antisymmetric shape and reached $P_{\max}$ almost simultaneously. Then the delamination initiated at the angle of 90° (in Fig. 7) and developed abruptly, which severely accelerated the decreasing of the compressive load. The compressive behavior of D50F2A was typical for all the cases with delamination depth F2 of type A and type B, and also similar to that of D50F3B (in which the delamination location F3 is after the 11th ply).

Therefore, antisymmetric buckling exerts stronger influence on the delamination propagation than mixed mode, since all cases deformed in this mode always delaminated unstable and the delamination propagated in the transverse direction of load regardless of the ply angle near the delamination and the lay-up configuration.

Delamination through-thickness position influences the buckling mode, which decides the dominant component of the ERR driving the delamination propagation. In case D50F2A the mixed mode rate G_s/G_t (in which $G_s = G_{II} + G_{III}$,

Table 2 The compressive behavior of case D50F2A, D50F3A, D50F8A

		Local mode	Mixed mode	Antisymmetric mode	Delamination initiation	Reach P_{max}
D50F8A	Strain/ $\mu\epsilon$	5 540(1)	6 090(2)	—	6 230(3)	6 880(4)
	Load/kN	122.65	134.77	—	136.28	139.69
D50F3A	Strain/ $\mu\epsilon$	—	5 500(1)	5 980(4)	5 860(2)	5 960(3)
	Load/kN	—	121.62	130.42	129.25	130.67
D50F2A	Strain/ $\mu\epsilon$	—	—	6 800(1)	6 970(3)	6 930(2)
	Load/kN	—	—	151.14	152.34	153.09

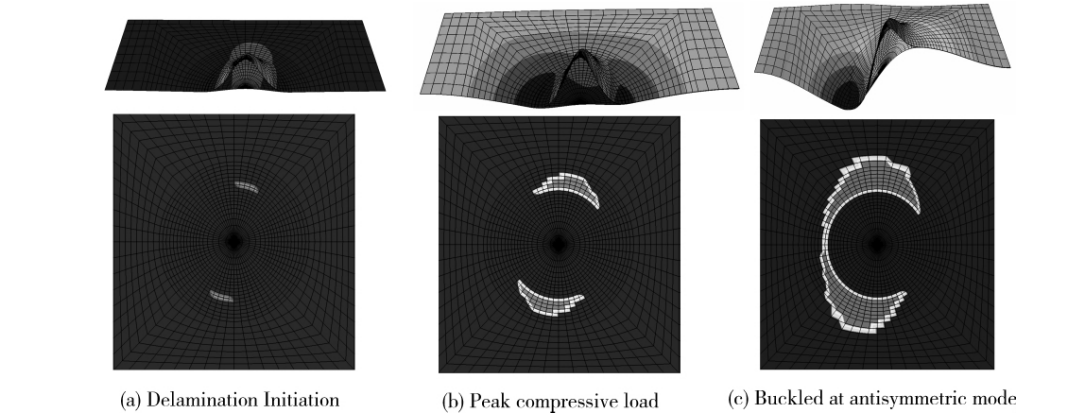


Fig. 6 Deformation ($\times 20$) and delamination shape of model D50F3A

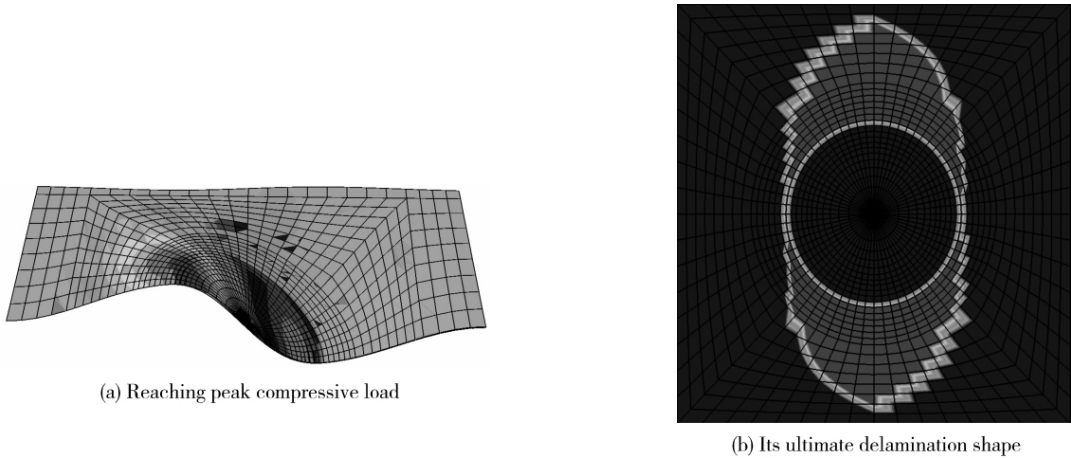


Fig. 7 Deformation ($\times 10$) of model D50F2A when (a) reaching peak compressive load and (b) its ultimate delamination shape

$G_t = G_l + G_s$) was equal to 1 at the delamination initiation front, but this value of D50F3A and D30F8A were about 0.2 as shown in Fig. 8.

3.2 Effects of diameter

Though peak compressive load always decreased with the increase of the delamination size in the same lay-up configuration (Table 1), the

influence of diameter on buckling was not obvious. In studies of Gu et al^[3] and Riccio et al^[4], laminates with single circular delamination near the surface buckled in the mixed mode when the delamination size increased. In cases with delamination located at the midplane of the laminates, global buckling happened, symmetrically or an-

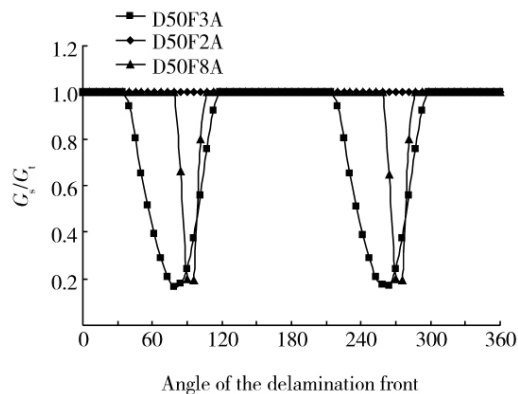


Fig. 8 Distribution of G_s/G_t at the artificial delamination front of case D50F2A, D50F3A and D50F8A, in which angle 0° parallels the applied load direction

tisymmetrically (in Refs. [6,12] and the present work). But in cases with a delamination of moderate depth (F3) in the present work, the buckling and the failure mode varied with the delamination diameters.

The compressive load of D60F3A was 128.329 kN, close to that of D50F3A, but the compressive behavior of the two cases was distinct. Case D50F3A has been introduced in detail above. For case D60F3A, the plate first deformed symmetrically at 124.74 kN in global mode (Fig. 9 (a)), then quickly reached the peak compressive load when snapped-through to antisymmetric mode (Fig. 9 (b)). The compressive load then decreased as the deformation amplitude increasing. When load decreased to 127.43 kN, the delamination began to propagate rapidly at the angle of 90° and the compressive load decreased sharply.

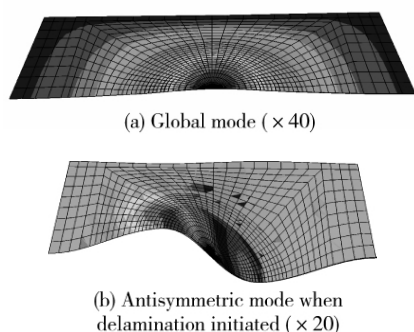


Fig. 9 Deformation of model D60F3A

4 Conclusions

The compressive behavior of laminates with a deeply embedded circular delamination is studied numerically by FEA using VCCT. In addition, comparison between numerical results and experimental results, and a detailed post-analysis check are conducted to verify the FE modeling. Based on the analysis in the paper, conclusions as follows can be drawn:

1) Mixed mode buckling and antisymmetric buckling could emerge in laminates with a deeply embedded large circular delamination, shifting from the former one to the latter one when the through-thickness position becomes deeper.

2) When an embedded delamination is deeper in thickness, buckling and delamination become unstable, leading to the fracture of laminates, which is more abruptly than that of laminates with a delamination near the surface.

3) When an embedded delamination is deeper in thickness, the shear mode component of ERR instead of the opening mode component become dominant to drive the delamination growth, and the direction of delamination propagation is more strongly influenced by the buckling mode.

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