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Compressive properties of homemade carbon fiber composite laminates with delamination defect

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Abstract: Large numbers of aircraft composite structures were researched, and the distribution of delamination sizes and through thickness positions in the composite laminates were investigated. An experiment was conducted to probe into the effect of delamination sizes and through thickness positions on the compressive strengths of laminates with single embedded circular delamination with the most dangerous delamination sizes and positions defined from the distribution. A shell model was established for compressive strength prediction, and the virtual crack closure technique (VCCT) was employed for the strain energy release rate calculation. The finite element (FE) prediction was in good agreement with the experimental measurements, for the predicted compressive strengths stood within 10% error of experimental results. It was observed that the compressive strength was highly effected by the delamination size, while the through thickness position of delamination did not have significant effect on the compressive strength.

Key words: homemade carbon fiber; composite; compressive strength;
virtual crack closure technique; element simulation

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Introduction

For the consuming request on the performance of aircraft, the materials of structures need to be much improved. Then carbon fibre composites are introduced in widely application for their obvious benefits, such as high specific strength and stiffness. And the usage rate has become one of the important advanced symbols of aircraft structures. However, composite laminates are susceptible to delaminations that cause a significant reduction in compressive strength and therefore reduce the performance advantage of composite materials obviously. In the past

two decades many investigations were performed on the compressive behavior and damage propagation of delaminated composite structures experimentally, analytically^[1-7]. But most of the researches are focused on the buckling and post buckling behavior of laminates with one delamination or multiple delaminations close to the surface^[8-13]. Several researches have studied the distribution of delamination sizes and locations through the laminate thickness.

Firstly, based on the long time checking on the composite structures of aircraft under use, large amount of statistic data about the delamination positions and delamination sizes were accu-

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mulated. This study makes a full analysis on it, obtaining the most dangerous delamination sizes and positions. According to this, a test was conducted for the compressive performance research of homemade carbon fiber composite laminates with embedded delamination with dangerous sizes and positions. Also laminate thickness was considered to be one of the important factors that affects the compressive strength. Thus we take three kinds of laminates with different thickness and different stick sequences into consideration. Then the virtual crack closure technique (VCCT) was employed for the laminate compressive strength prediction. To compare with the test result, it shows that the positions of delamination through thickness are most important for the compressive strength. And the model proposed by this paper can properly predict the compressive strength, which will supply some inference for engineering application.

1 Distribution of delaminations

Much effort had been devoted to inspect the delaminations of composite structures that were used on the aerofoil of one type of aircraft by non-destructive-identification. The distribution of delamination sizes and locations were obtained, as shown in Fig. 1 and Fig. 2. In Fig. 1, it can be seen that most of delaminations also distribute in deep locations, especially the $h/3$ and $h/2$. Therefore, the $h/3$ and $h/2$ are the critical locations for the composite laminates. In

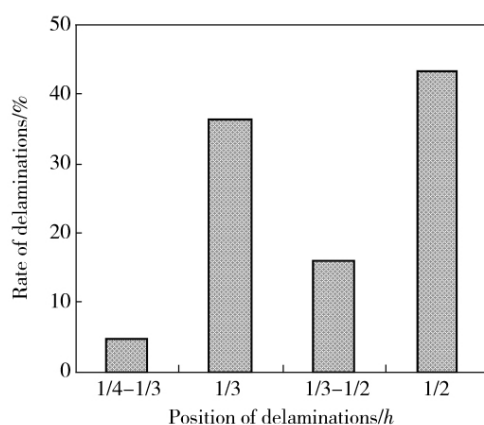


Fig. 1 Positions of delaminations

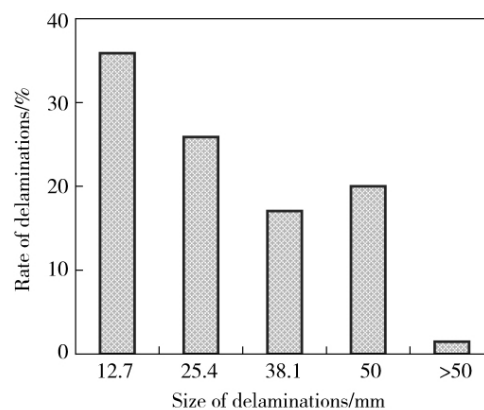


Fig. 2 Sizes of delaminations

Fig. 2, it shows that 78% of the delaminations are smaller than $\phi 38.1$ mm, a small decrease compared to that from manufacturing flaws; 20% of the delaminations are between $\phi 38.1$ mm and $\phi 50$ mm, 10% increase, and only 2% are bigger than $\phi 50$ mm. Thus, $\phi 38.1$ mm and $\phi 50$ mm are considered to be the critical sizes of delaminations which will be chosen for experimental work.

2 Experiment

2.1 Material

CCF300 carbon fiber; QY8911 reinforced resin.

2.2 Instrument

Test machine: Instron 1195; ultrasonic C-scan machine; IUCS type; strain gauge: BA120-2AA (11) by Hanzhong 521 Factory, H-610 adhesive.

2.3 Manufacture of specimen

The laminates for experimental work were manufactured from carbon fiber/bismaleimide preimpregnated tapes of 0.12 mm in thickness. The prepreg tapes were made of CCF300 continuous high tensile strength carbon fibers preimpregnated with QY8911 toughened bismaleimide resin. Afterwards, the hand lay-up method was employed for producing three types of laminates: laminate "A", laminate "B" and laminate "C", in which type "A" is a $[45/-45/0/-45/0/45/90/0/45/90/-45/0]$ s oriented laminate, and type "B" is a $[45/-45/0/-45/0/45/0/$

$-45/45/45/90/45/-45/-45/45/0]$ s oriented laminate as well as type “C” is a $[45/-45/0/-45/0/45/90/-45/0/45/90/45/0/-45/90/0]$ s laminate. The laminates were cured in the hot press at 185°C for 2 h and at 200°C for 3 h in accordance with a standard curing cycle recommended by the manufacturer. They are 2.88, 3.72, and 3.84 mm in thickness respectively.

The laminates for test were manufactured with delaminations of different sizes and different positions through thickness obtained from the study in the previous section. Two kinds of locations and three kinds of sizes used in the work are listed in Table 1. Delaminations were introduced during lay-up by inserting a single polytetrafluoroethylene (PTFE) film of $100\text{ }\mu\text{m}$ in thickness between piles. The experiments selected five $150\text{ mm}\times 120\text{ mm}$ dimensioned specimens, each of which had to be cut from one plate with a diamond-encrusted-edged slitting saw. To keep circular delamination accurately located in the centre of the specimen, ultrasonic C-scan was used before cutting.

Table 1 Locations and sizes of delaminations in the laminates

Laminate type	Delamination position	Delamination diameter/mm
CCF300/QY 8911 (type A, type B, type C)	$h/2$	38
		50
		60
	$h/3$	38
		50
		60

2.4 Test procedure

The compression test was conducted in accordance with ASTM Standard D7137-07. The position of strain gauges is shown in Fig. 3, which was used for measuring the axial strain and the compressive modulus. Fig. 4 shows the hold state of specimens under compression. The $140\text{ mm}\times 12\text{ mm}$ dimensioned laminate without

delamination was separately tested in accordance with ASTM Standard D6641.

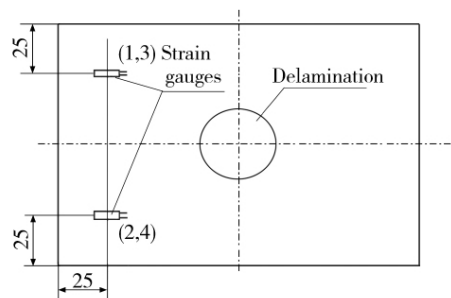


Fig. 3 Positions of the strain gauges (unit:mm)

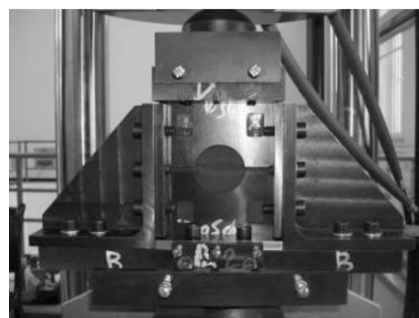


Fig. 4 State of specimen under compression

3 Results and discussion

The experimental compressive strength for three different types of laminates (types “A”, “B”, “C”) and laminates with delaminations at different locations and of different sizes is given in Fig. 5 to Fig. 7. In these figures, it can be seen that the compressive strength decreases when the diameter of the delamination increases. With the increase of the delamination diameter from 0 to 38.1 mm the compressive strength decreases by more than 60%. But there are no significant differences between the compressive strengths with the diameter of 38, 50, and 60 mm. It means that when the delamination sizes reach to some degree, the effect of delamination sizes becomes faint.

The variation of location does not have any significant effect on the compressive strength as shown in the Fig. 5 to Fig. 7, for the compressive strengths of laminates with delamination in the position of $h/3$ are very close to those of

$h/2$. As the positions of $h/2$ and $h/3$ all belong to deep positions through laminate thickness, when subjecting to compressive load, the delamination in laminate firstly propagates, and then when it reaches the edge of laminate, the failure happens. For these two kinds of laminates, their failure mechanism is almost the same, so there are no significant differences between the compressive strengths.

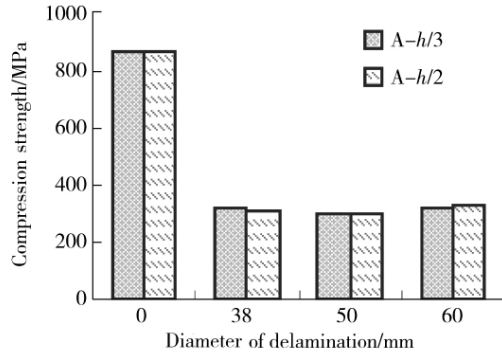


Fig. 5 Compression strength of A-composite laminates

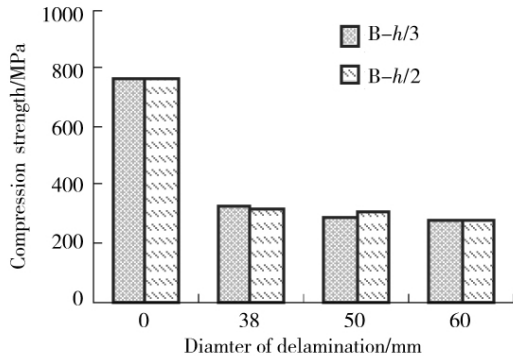


Fig. 6 Compression strength of B-composite laminates

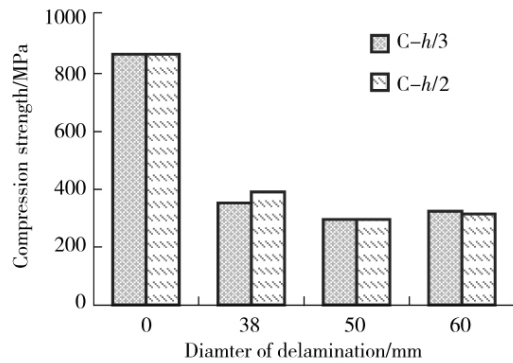


Fig. 7 Compression strength of C-composite laminates

Moreover, the effect of laminate thickness on the compressive strength was also examined. The compressive strength of the thinner laminate was predicted to be smaller than that of the thicker laminate because to the thinner laminate, it is easier for the laminate to buckle. The measured values did not demonstrate this thickness effect probably due to the fact that a higher degree of the coefficient of variation conceals the effect of thickness. Therefore, on the basis of the result mentioned above, it is understood that the delamination is one of the most serious failure modes in laminated composite materials.

4 Finite element analysis

Finite element analysis is employed to make prediction of compressive strength for comparison with the experimental results. In this study, shell element model is used in conjunction with a criterion proposed by Benzeggagh and Kenane^[14] (B-K criterion) to determine the delamination growth. For the strain energy release rate (SERR) contributing to delamination growth is usually obtained in the finite element (FE) analysis. The virtual crack closure technique (VCCT)^[15] is applied for extracting SERR values from FE results, based on the assumption that the strain energy released during crack propagation is equal to that closing the opened crack surfaces as shown in Fig. 8. Also the VCCT allows the total SERR value to be divided into three loading mode components: opening, sliding shear and tearing shear, making a good conjunction with the B-K criterion. The critical energy release rate G_c calculated by B-K criterion is defined as

$$G_c = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{shear}}{G_t} \right)^\eta \quad (1)$$

Where: G_{Ic} , G_{IIc} and G_{IIIc} are the critical strain energy release rates of mode I, II, and III respectively, $G_{shear} = G_{II} + G_{III}$, $G_t = G_I + G_{shear}$, and η is an experimental parameter. FE analysis calculations of SERR are compared with the failure criterion to determine whether delamination propagation occurs.

The models of laminates were created in the ABAQUS V6. 8 finite element system and the standard shell elements were used for analysis. The finite element mesh was constructed from two layers of shell elements, with dimensions $150\text{ mm} \times 100\text{ mm}$. The two layers of elements were tied at the interface, except for the delamination area where contact boundary conditions prevented penetration of elements during the processing of compression. For the laminate, compressive load was applied to the model in the direction of the long axis of the panel.

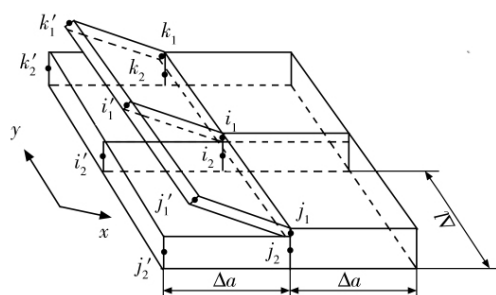


Fig. 8 Sketch map for the calculation of energy release rate

The present study makes a comparison between predictions of compressive strength for laminates with different delamination geometries according to FE analysis and the experimental results depicted in Fig. 9. For each tested specimen, five experiments are done, and the results were averaged. In this figure, the transverse represents the laminate type, and A, B, C represent these three kinds of laminates with different stick sequences. Also, 12 and 13 represent the delamination positions of $h/2$, $h/3$ respectively. Although the predictions of compressive strengths are consistently valued higher than the experimental results, agreement between FE analysis and experimental data is generally good, with the FE analysis results always standing within 10% error. In this figure, the predicted compressive strength of laminate A type with delamination in the position of $h/2$ makes the biggest difference. It may be the reason that for this laminate type, its thickness is thin, delamination position presenting to be symmetrical,

and the delamination being the smallest, and during the compressive course, the laminate is easy to buckle. Therefore, the difference reaches 9%.

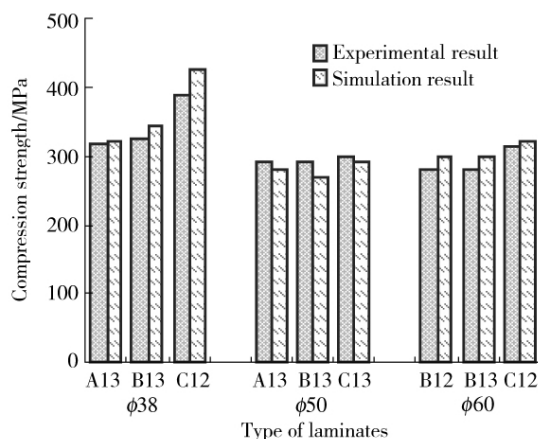


Fig. 9 Comparison between the experimental result and simulation result

5 Conclusions

According to the study of delamination distribution in the paper, it can be concluded that most of delaminations are distributed at the locations of $h/3$ and $h/2$ in terms of thickness. The same method is used for calculating the delamination sizes for delaminations of different geometric shapes so as to be consistent in analysis. And the results show that about 80% of delaminations are smaller than $\Phi 38\text{ mm}$.

Finite element model is employed to predict the compressive strength of laminates with delaminations of different sizes and thickness-oriented positions. A good agreement is reached between the results obtained from the experiments and the FE analysis. It is found that the compressive strength is highly influenced by the delamination size, while the thickness-oriented location of delamination exercises insignificant effect on the compressive strength.

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