EXPERIMENTAL AND NUMERICAL INVESTIGATION ON SHEARING STABILITY OF CURVED STIFFENED COMPOSITE PANELS

Tianliang Qin [1], Lei Peng [2], Bo Ma [3], Zizi Lu [4], Chaobo Xin [5], Yanan Chai[6] and Jifeng Xu [7,*]

[1,2,3,4,5,7] Beijing Key Laboratory of Commercial Aircraft Structures and Composite Materials, Beijing Aeronautical Science & Technology Research Institute of COMAC, Beijing, 102211 P.R. China;
[6] China Aircraft Strength Research Institute, Xi'an, 610113 P.R. China
[*] Corresponding author (xujifeng@comac.cc)

Keywords: Composite structures; Buckling; FE analysis; Mechanical testing

ABSTRACT

The stiffened composite panel are the main structural components to build the aircraft fuselage. The shearing stability of the curved stiffened composite panel is investigated experimentally and numerically in this paper. The D-box experiment setup is used to apply shearing load on the specimens. The buckling and postbuckling behaviours are observed using Digital Image Correlation (DIC) technique and strain gauges. The damage process is recorded using high-speed camera. The loads in different directions are applied to research the effects of the shear stress direction on the buckling and postbuckling load. Meanwhile, the FE method is used to analyze the stability and damage process of the curved stiffened composite panel under shearing load. The nonlinear FE analysis is carried out with Riks method to investigate the specimen's buckling and postbuckling behaviours. Then progressive damage model is implemented in the FE model to investigate the damage process. The numerical and experimental results have good agreement.

1 INTRODUCTION

As the aircraft fuselage panels withstand dramatic shearing loads, the shearing stability is an important concerned problem for the researchers and designers. Most reported works mainly focus on the buckling and postbuckling behaviours of flat composite panels [1, 2]. Some researchers studied the compressive stability of curved composite panels [3]. However, rare works are about the shearing stability of complex curved composite panels which have both stringers and frames. This paper uses the experimental and numerical methods to investigate the shearing buckling and postbuckling behaviours of curved stiffened composite panels with seven hat stringers and four frames. A D-box experiment fixture is used to apply the shearing loads on the curved composite panels. Meanwhile, the nonlinear FE analysis using Riks method is carried out in this paper.

2 EXPERIMENT

The configuration and dimensions of curved stiffened composite panel are shown in Fig.1. The curved stiffened composite panels have four frames and seven hat stringers. The skin, stringers and frames are all made of carbon/epoxy composite materials. The ply sequences of skin, frames and hat stringers are $[\pm 45/0/0/+45/90/-45/0]_s$, $[\pm 45/0/0/90/0/0/\overline{\pm 45}]_s$, and $[\pm 45/90/\pm 45/0/0/\overline{\pm 45}]_s$ respectively. The stringers and the skin are jointed using adhesive bonding technique, and the frames and the skin are jointed using bolt joint technique. The four edges of the specimens are connected to the experiment fixtures, and are reinforced using composite laminates. There are three specimens in the experiment.

The shear loads are applied to the curved stiffened composite panel using a D-box experiment setup. The D-box experiment fixtures include the platform, a C metal panel, a loading fixture and some L jigs. The specimen and the fixtures form a D-box. Two hydraulic actuators put a moment on

the box as shown in Fig. 2. The moment can produce uniform shear stress in the curved stiffened composite panel.

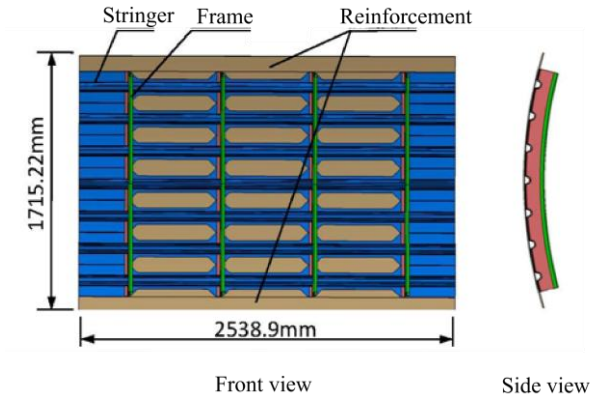


Fig.1 Configuration and dimensions of curved stiffened composite panel

Each specimen is loaded to buckling in clockwise and anti-clockwise directions respectively to observe buckling behaviors of the curved stiffened composite panel and the shearing direction effects on the buckling load. Further, two specimens are loaded to failure by anti-clockwise load and one by clockwise load.

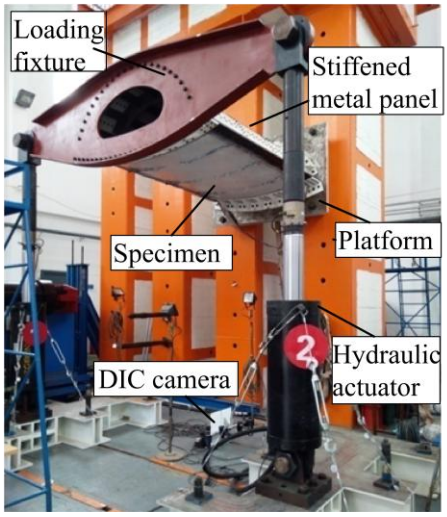


Fig.2 Experiment setup

The DIC technique is a non-contact optical technique for measuring the strain and displacement of a structure. It can provide the deformation and strain field of the specimens visually. This paper uses DIC technique to observe the buckling mode and strain distributions of the skin. The outer surface of the skin is painted white strewn with black spots as shown in Fig. 2 for the DIC measurement. The strain gages are used as well to measure the strains of the skin, stringers. The back-to-back strains of the skin are used to monitor the buckling in the experiment. Additionally, the high-speed photography is used to find out the failure process of specimens.

3 NUMERICAL ANALYSIS

The FE stability analysis of the curved stiffened composite panels under shearing load is carried out in Abaqus. To obtain accurate loading and boundary conditions acting on the curved composite panel, the experiment fixtures are modeled in the FE model. All the composite parts of the specimen are modeled using S4 shell elements with composite shell sections, as shown in Fig.3. The fixtures are modeled using S4 shell elements with conventional shell sections. The bolted joints are simulated with

combination of B31 beam elements and coupling elements.

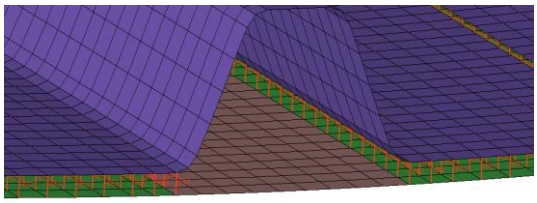


Fig.3 Detailed FE model of the stiffened panel

The fixture end which is fixed to the wall is fully constrained by constraining all the displacements of the nodes on the end, as shown in Fig. 4. Pair of concentrate forces is applied to the loading fixture model to simulate the experiment. The geometrically nonlinear FE analyses are carried out using the modified Riks method.

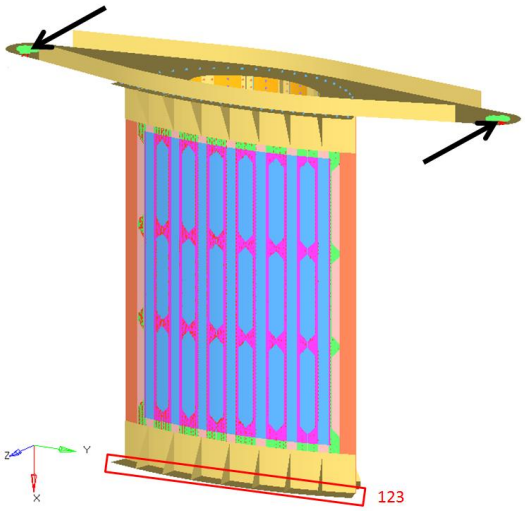
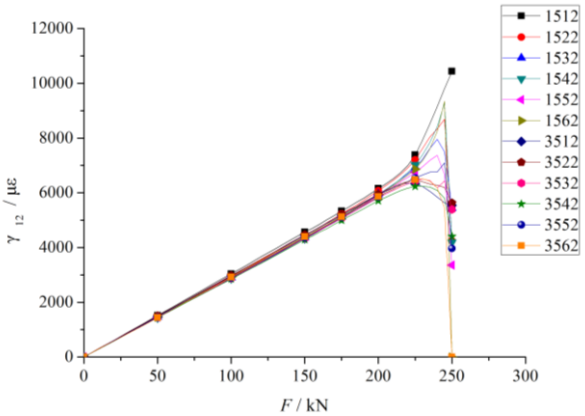


Fig.4 Loads and constraints of the FE model

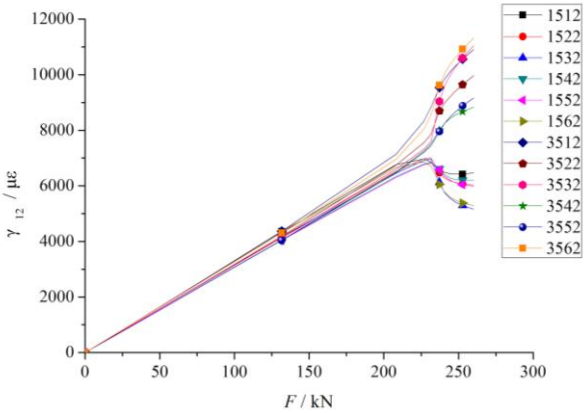
Two different models are established in the paper. One is a simple model for a fast estimate of the buckling load and ultimate failure load. In the model, the adhesive bonded joints between the skin and stringers are simulated with tie constraints. The ultimate failure is predicted by maximum strain criterion. The other model is a progressive damage model to investigate the damage process in the postbuckling stage. In the progressive damage model, the adhesive bonded joints are simulated using cohesive elements. The Hashin criteria and linear damage evolution law are used to predict the damage process of the composite laminates in the specimens. The progressive damage model is only used in the anti-clockwise load case as it is quite time-consuming.

4 RESULTS AND DISCUSSIONS

Fig.5 provides the experimental and numerical load-strain curves of the skin under anti-clockwise load. The strains increase linearly before about 200 kN in the experiment. After 200 kN, the back-to-back strain curves depart from each other. It indicates the skin becomes buckling. With the load increasing, some strains decrease, while the others increase rapidly. The specimen fails at the load of 250 kN. The numerical strain curves are similar with the experiment results. The predicted buckling load by numerical model is 210 kN, which is 6.6% higher than the average experiment load, as shown in Table1. The predicted ultimate failure load using the maximum strain criterion is 270 kN, which is 7.1% higher than the experiment results.



(a) Experiment



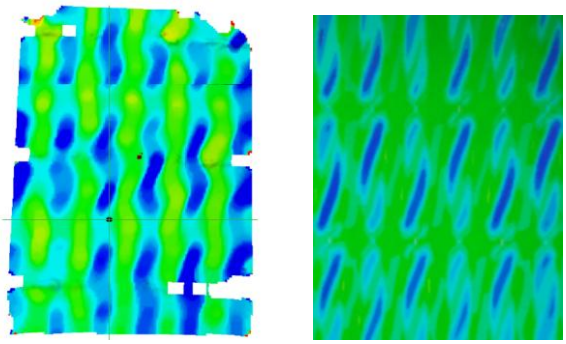
(b) Numerical

Fig. 5 Load-strain curves of the skin under anti-clockwise load

	Clockwise /kN		Anti-clockwise /kN	
	Buckling	Failure	Buckling	Failure
Spec.1	-	-	205	250
Spec.2	228	274	192	-
Spec.3	222	-	194	254
Aver.	225	275	197	252
Num.	240	300	210	270
Error	6.7%	9.5%	6.6%	7.1%

Table1 Experimental and numerical buckling and failure loads under shearing loads

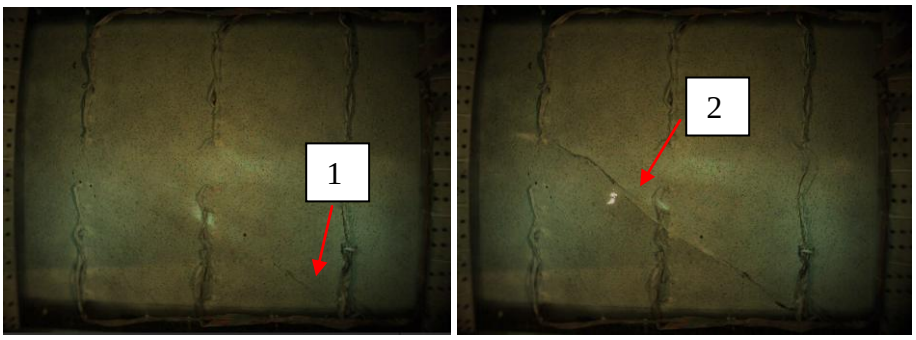
Fig. 6 shows the typical shearing buckling mode of curved stiffened composite panel under clockwise load. The buckling waves exist in the skin between the stringers. They are long and inclined as shown in the Fig. 6. It is caused by the compressive component of the shear stresses. Due to the constraints of hat stringers, the wave lines are not exactly perpendicular to the compressive stress component. The numerical model predicts the same buckling mode.



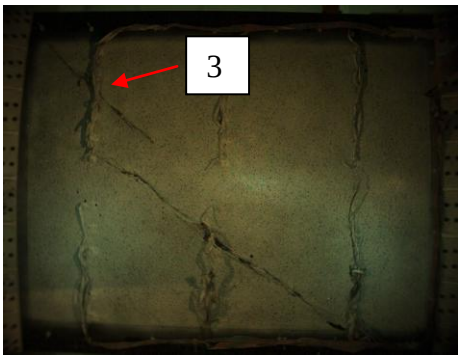
(a) Experiment (b) Numerical

Fig.6 Shearing buckling mode under anti-clockwise load

Fig. 7 gives the damage photos of the skin under clockwise load recorded by high-speed camera. The left edge is loaded by the hydraulic actuators in Fig.7. The skin close to the edge marked as 1 in Fig. 7(a) is first observed to bulge. The crack occurs in the same area at the same time, as shown in Fig. 7(a). The crack develops rapidly almost perpendicular to the compressive stress component, as shown in Fig. 7(b). Then a new crack occurs near the other edge marked as 3 in Fig. 7(c). The damage process is completed in one second. Meanwhile, large sounds are emitted from the specimen.



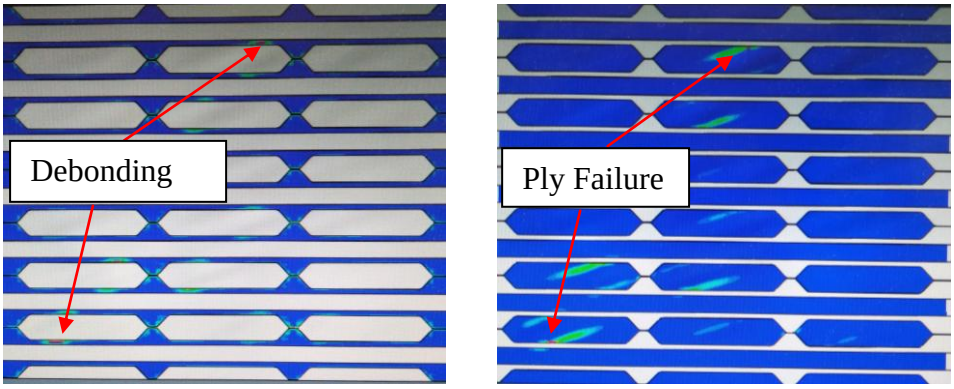
(a) Initiation of first crack (b) Development of first crack



(c) Appearance of second crack

Fig.7 Damage process of the skin under anti-clockwise load recorded by high-speed camera

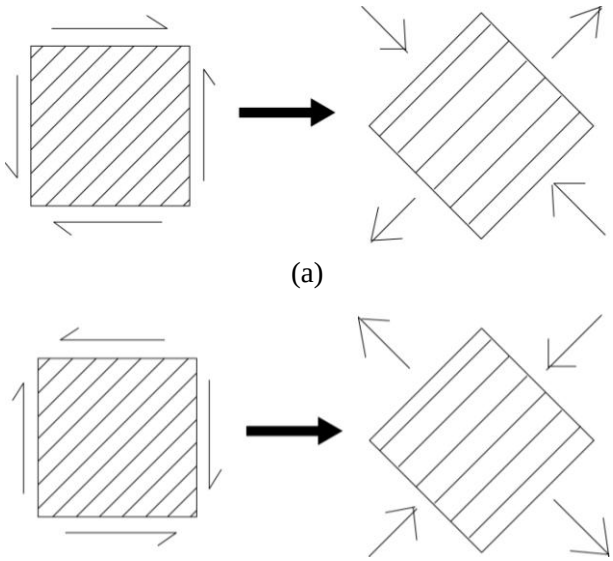
Fig. 8 provides the predicted damages by the progressive damage model. When the load reaches 245kN, the adhesive near the regions of 1 and 3 in Fig. 7 becomes to debonding. When the load reaches 252kN, the composite laminates around the bebonding regions start to damage. The damage places, shapes and direction are similar with the experiment observation. The numerical analysis indicates that the debonding between the skin and the skin is the early damage mode when the curved stiffened panel under shearing load, and it triggers the subsequent damage in the skin.



(a) Delamination, 245kN (b) Ply failure, 252 kN

Fig. 8 Damage predicted by progressive damage model under ainti-clockwise load

Fig. 9 illustrates the effects of shear stress direction on the buckling of composite laminates. In the case of Fig. 9(a), the minimum principle stress is perpendicular to the fiber, and the maximum principle stress is along the fiber. The composite laminate is in compression in the transverse direction, and in tension in the fiber direction. At this time, the buckling load is mainly affected by the bending stiffness in the transverse direction. In the case of Fig. 9(b), the minimum principle stress is along to the fiber. The buckling load of composite laminate is mainly affected by the bending stiffness in the fiber direction. When the differences of the bending stiffness in the two directions are great, the buckling load may be significantly influenced by the shear stress direction.



(a)

(b)

Fig.9 Influence of shear stress direction on the buckling of composite laminates

For the specimens in this paper, the stress states of the outer plies are similar with the one in Fig. 9(a) when the load is anti-clockwise, and are similar with the one in Fig. 9(b) when the load is clockwise. The bending stiffness in compression under the anti-clockwise load is lower than under the clockwise load. Therefore, the buckling load in anti-clockwise case is lower than that in clockwise case. The buckling load in anti-clockwise case is 12.4% lower than clockwise one in this experiment, as shown in Table 1. The ultimate failure load in anti-clockwise case is 8.4% lower than clockwise one. The numerical analyses give the same predictions. The buckling line is nearly perpendicular to the compressive stress under shearing load. As a result, the crack direction changes with the stress direction changing, as shown in Fig. 10.

(a) Clockwise (b) Anti-clockwise

Fig.10 Failure morphologies

5 CONCLUSIONS

The buckling and post buckling behaviours of the curved stiffened composite panel are investigated using a D-box experiment setup. The buckling loads are monitored by the strain gauges. The buckling modes are observed with DIC technique. In addition, the damage process is recorded using high-speed camera. The clockwise and anti-clockwise loads are applied on the specimens respectively to investigate the shear stress direction effects on the buckling and postbuckling behaviours. The results indicate that the buckling and postbuckling loads under anti-clockwise load are 12.4% and 8.4% lower than the ones under clockwise load. The nonlinear FE analysis is also carried out. The error of predicted buckling load is less than 6.7%. The error of predicted post-buckling load is less than 9.5%.

REFERENCES

[1] A.C. Orifici, *et al*, Compression and post-buckling damage growth and collapse analysis of flat composite stiffened panels, *Composites science and technology*, 68, 2008, pp 3150-3160.

[2] C.W. Kong, *et al*, Postbuckling and failure of stiffened composite panels under axial compression, *Composite Structures*, 42, 1998, pp 13-21.

[3] C. Bisagni, Numerical analysis and experimental correlation of composite shell buckling and post-buckling, *Composites: Part B Engineering*, 31, 2000, pp 655-667.