EFFECTS OF COMPRESSION-SHEARING LOAD ON STABILITY OF CONFIGURED COMPOSITE PANELS

Jifeng Xu[1,*], Tianliang Qin[2], Lei Peng[3], Caoning Su[4], Mufeng Duan[5], Lingwei Tang[6], and Yanan Chai[7]

[1,2,3,4,5,6] Beijing Key Laboratory of Commercial Aircraft Structures and Composite Materials, Beijing Aeronautical Science & Technology Research Institute of COMAC, Beijing, 102211 P.R. China.
[7] 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 composite materials have been widely used in the main structures of the airplane such as fuselages and wings. The stability of configured composite panels under compression-shearing loads is an important problem for the fuselage and wing design. This paper investigates the compression-shearing buckling and postbuckling behaviors of complex flat stiffened composite panels experimentally and numerically. A new test setup is designed, on which the compression and shearing loads could be applied by the vertical and horizontal loading fixtures in coordination to implement arbitrary ratio of compression-shearing loads. The compression-only, shearing-only and combined compression-shearing loads of 8:1, 3:1, 2:1, 1:1 and 1:2 are applied to survey the compression-shearing interaction effects on buckling modes and loads of the stiffened composite panels. Further, the ultimate failures are studied under compression-only, shearing-only and compression-shearing loads of 2:1 respectively. Meanwhile, the buckling and postbuckling behaviors of these panels are analyzed using FE methods in Abaqus. The nonlinear FE analyses are carried out using Riks method. The maximum strain criterion is used to predict the ultimate failure. The experimental and numerical results of the buckling modes, buckling load, and ultimate failure are compared in different load cases. The numerical analysis method is also validated by the experimental results.

1 INTRODUCTION

With the applications of composite materials on airplane fuselages and wings, the stability of stiffened composite panels have drawn great attention [1,2]. The fuselage and wing panels usually withstand combined loads of compression and shearing. However, rare researches are reported on the stability of stiffened composite panels under compression-shearing loads, especially for the complex stiffened composite panels with multiple stringers and frames. Most of them are about the stabilities of simple composite panels under compression or shearing loads [3-5]. This paper studies the buckling and postbuckling behaviors of configured composite panels under compression-shearing loads experimentally and numerically for the understanding of complex stiffened panel stabilities and for the validation of numerical analysis methods. A new experiment setup is designed to apply loads with arbitrary compression-shearing ratios on the flat stiffened panels. During the experiment, the measurements are performed by the DIC technique, strain gages as well as cameras to record the deformations and damages. The detailed experimental results under different loads are compared to investigate the compression-shearing interaction effects on the stability of configured composite panels. The experimental results are used to validate the numerical analysis technique for the complex composite panels.

2 EXPERIMENT

The stiffened composite panel consists of the skin, seven hat stringers and three fames, as shown in Fig. 1. All parts are made of carbon/epoxy composite materials. The ply sequence of skin is [±45/0/0/90/0]s. The ply sequences of frames are [±45/0/0/0/90/ ±45]s. The hat stringer is formed with an Ω laminate of [±45/0/0/0/90/±45]$_s$ and an inner U laminate of [±45]. The stringers are adhesive bonded to the skin. The frames are fastened to the skin using titanium alloy bolts. The left and right sides of the skin are connected with the shearing fixtures. The connection regions are reinforced using two pieces of laminates. The top and bottom ends of the stiffened panel are potted in aluminum boxes filled with resin. The potted ends are used to implement uniform compressive load to the panels. Three same panels were used in the experiment.

A new experiment setup has been designed for the compression-shearing experiments, as shown in Fig. 2. The vertical loading element acts on the top and bottom edges of the panels and creates compressive loads. The horizontal loading element and the specimen form a self-balancing system. When the hydraulic actuators works on the left and right edges of the panels, the counterforce produces shear load to the top and bottom ends of the panels. The vertical and horizontal loading elements of the experiment setup can apply compression and shearing loads in coordination. Arbitrary ratio of the mixed compression-shearing loads could be applied on the panels using this experiment loading system.

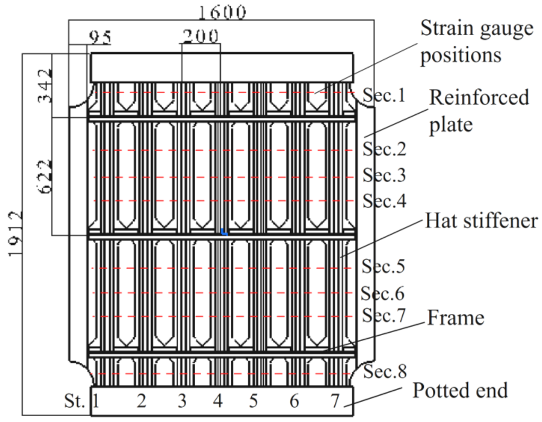


Fig.1 Configuration and dimensions of stiffened composite panel

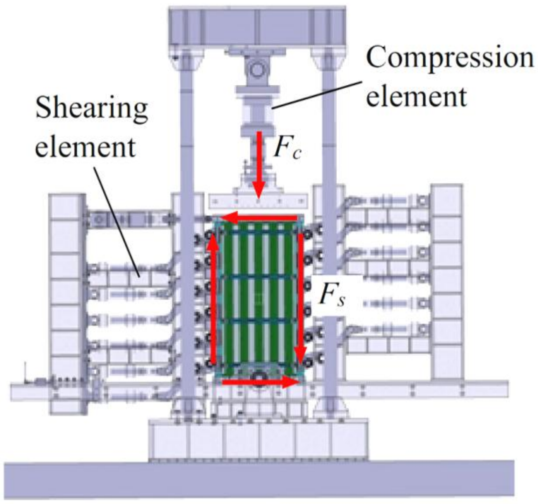


Fig.2 Experiment loading system for arbitrary compression-shearing ratio

In the experiment, the bottom ends of the specimens are fixed to the experiment platform using two L-fixtures and several bolts. The top ends are connected to the left columns of the shearing setup using two metal plates, as shown in Fig. 2. The setup of compression-shearing experiment is shown in Fig. 3.

To investigate the compression-shearing interaction effects on buckling modes and loads of the configured composite panels, the panels are loaded to the appearance of buckling under seven load conditions, including compression-only, shearing-only and combined compression -shearing loads of 5:1, 3:1, 2:1, 1:1 and 1:2. Further, the three panels are loaded to failure under compression-only, shearing-only and combined compression-shearing loads of 2:1 respectively for the postbuckling studies.

The DIC technique is used to monitor the displacement and strain responses of the skin. It is a non-contact optical technique for measuring the strain and displacement by comparing digital photographs of a test piece at different stages of deformation. The outer surface of the skin is painted white strewn with black spots as shown in Fig. 3 for the DIC measurement. The strain gages are used as well to monitor the strains of the skin and stringers. The strain gages are placed on eight sections as shown in Fig. 1. Five 0° strain gauges are bonded on each section of the hat stringers. The strain rosette gauges are placed on the skin front and back. The sounds and damages in the experiment are recorded with digital videos for the analysis.

Fig.3 Experiment setup of stiffened composite panels

3 FINITE ELEMENT ANALYSIS

The FE analyses are conducted in Abaqus. All composite parts of the specimen are modeled using S4 shell elements in Abaqus. The fixtures for shear loading are also modeled with S4 shell elements. The tie constraints are used to simulate the adhesive bonded joints. The bolts are simulated using B31 beam elements. The beam element nodes are connected to the shell elements using distributing coupling elements. The finite element model mesh is shown in Fig. 4.

The supported end is completely fixed in the FEM. The out-of-plane displacements of the top elements are constrained. A concentrated compressive force is applied on a reference point, which is coupled with the top end nodes using the MPC. Six same forces are applied to the shearing fixtures on each side. A total shearing force is applied to the end of the metal plates at the top end of the stiffened panel. The forces on the shearing fixtures and that on the metal plates make a moment balance.

The anisotropic properties of composite materials lead to complex responses of composite panels, such as the bending-extension coupling effects in unsymmetrical laminated plates. In addition, the stability of the complex stiffened composite panels with multiple stringers and frames are quite complicated due to their complex configurations. Various local buckling patterns may occur before the global buckling for a stiffened panel. The bending-extension coupling effects and local eccentric loading in the stiffened panels may induce serious geometric nonlinearity. Therefore, the geometrically nonlinear analysis associated with the modified Riks method is carried out for the buckling and postbuckling process of the stiffened composite panel under different compression-shearing loads. A very tight convergence tolerance is set to prevent the load floating back because of the existence of local buckling. The ultimate failures are predicted using maximum strain criteria.

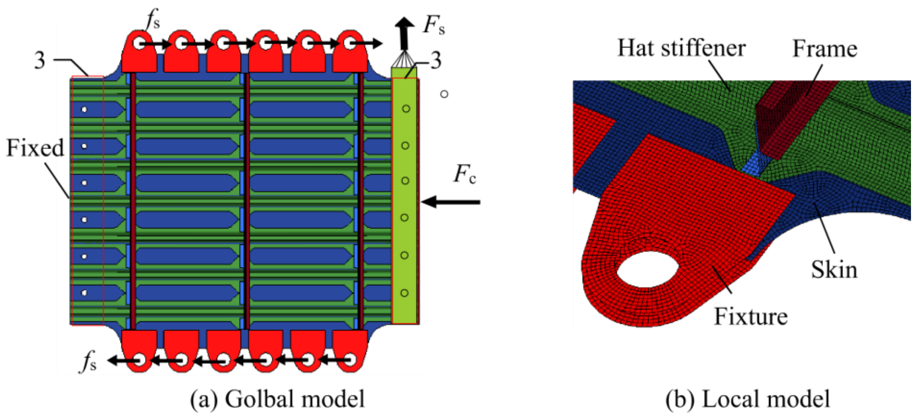


Fig.4 Finite element model, boundary and load of stiffened panel in compression

4 RESULTS AND DISCUSSION

When the composite plates are loaded by the combined compressive and shear forces, the effects of the compressive and shear stress combination on the composite plate stability are illustrated by Fig. 5. The composite plates are in compression in the minimum stress direction, while in tension in the maximum stress direction. Let the ratio of shear stress to compressive stress is *k*. The minimum stress is expressed as follows.

$$\sigma_{c2} = \frac{1+\sqrt{1+4k^2}}{2} \tag{1}$$

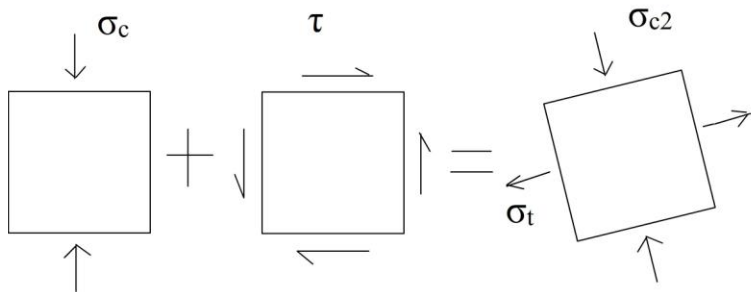


Fig.5 Combination of compressive and shear stresses

With the ratio of shear stress to compressive stress increases, the compressive stress increases. This is unfavourable for the stability of the panels. Besides, the stability of the panels is influenced by the bending stiffness. The ratio of shear stress to compressive stress will cause the minimum stress direction change. So the bending stiffness corresponding to the minimum stress changes if the composite laminates do not have the quasi-isotropic plies. In addition, the diagonal stresses affect the buckling load of the panels as well. The tensile diagonal stresses are good for the stability, while the compressive diagonal stresses are harmful. As a result, the effect of compression-shearing interaction on the composite panels is the integrative effect of the above factors.

Table 1 provide the experimental and numerical buckling loads of the stiffened panels under different compression-shearing ratios. The experimental results indicate that the compressive load decreases at the buckling when the shear load ratio increases. The effects of compression-shearing interaction are significant when compression-shearing ratio is between 1:2 and 5:1. When compression-shearing ratio is below 1:2, the buckling load reaches the shear-only one. When the ratio is above 5:1, the buckling load reaches the compression-only one. The numerical results show the similar trend. The maximum prediction error of buckling load is -14.8%.

Com-shear ratio	Com/shear load (kN)		Error
	Exp.	Num.	
0:1	0/360	0/325	-9.7%
1:2	175/350	153/305	-12.9%
1:1	305/305	260/260	-14.8%
2:1	430/215	410/205	-4.7%
3:1	585/195	579/193	-1.1%
5:1	600/120	565/115	-4.2%
1:0	610/0	600/0	-1.6%

Table 1 Buckling loads under different loads

Fig. 6 shows the typical buckling mode of the stiffened panels under different compression-shearing load. Under compression-only load, the buckling waves of the skin are regular among the stringers. When the compression-shear ratio is 2:1, fewer waves appear between two frames than that in compression-only experiment. The waves in the right diagonal are larger than ones in the left diagonal. And the buckling waves are slightly slant, which is caused by the shear stress. For shearing-only experiment, the out-of-plane displacements of the skin are along the stringers.

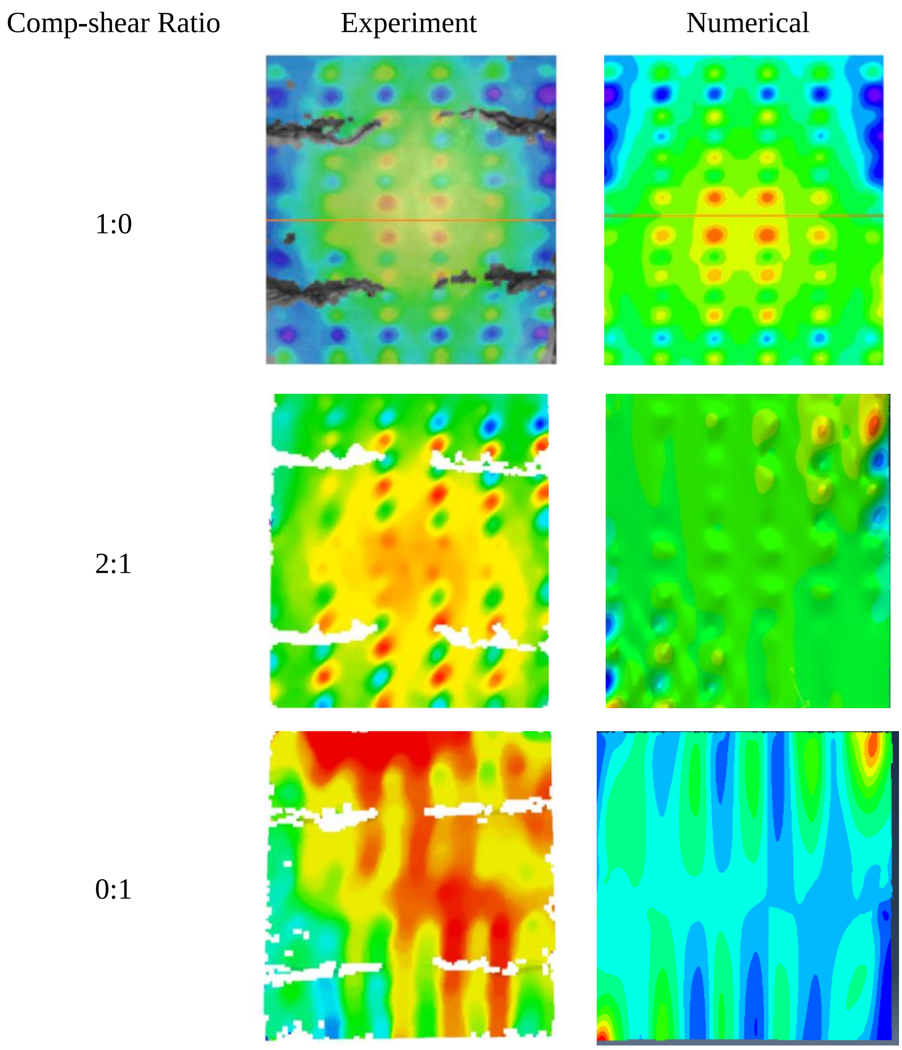
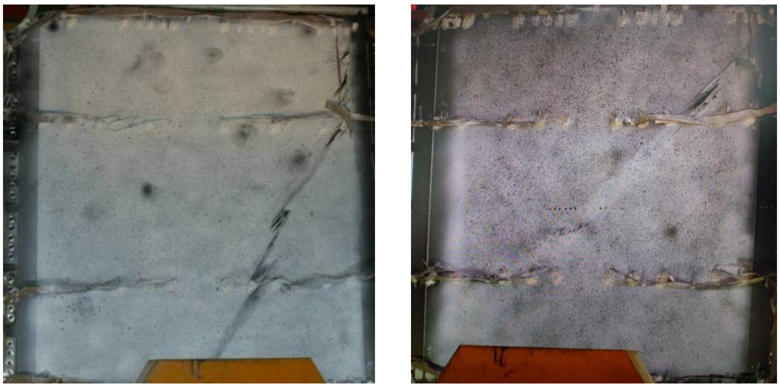


Fig.6 Buckling mode under different compression-shearing load

The ultimate failure under compression-only load occurs at the section between the lower potted end and the frame. In the shearing-only case, an inclined fracture appears in the skin, as shown in Fig. 7 (a). It is caused by the compressive stress component of the shear stress. Although the buckling wave shapes of the compression-shear ratio 2:1 are like the compression-only ones, its ultimate failure mode are like the shearing-only mode. However, the inclined angles of the fractures in compression-shear ratio 2:1 and shearing-only cases are different. The inclined angles between the fracture and stringer direction in compression-shear ratio 2:1 is larger than one in shearing-only case.



(a) Shearing-only (b) Comp-Shear ratio 2:1

Fig.7 Ultimate failure of the panels

Table 2 provide the ultimate failure loads of the stiffened panels under different compression-shearing ratios obtained experimentally and numerically. The ultimate failure load in compression-only experiment is 1490 kN, in compression-shearing 2:1 experiment is 840 kN of compressive load and 420 kN of shear load, and in shearing-only experiment is 510 kN. The maximum prediction error of failure load is -11.9%.

Com-shear ratio	Com/shear load (kN)		Error
	Exp.	Num.	
0:1	0/510	0/490	-3.9%
2:1	840/420	740/370	-11.9%
1:0	1490/0	1430/0	-4.0%

Table 2 Failure load under different loads

5 CONCLUSIONS

The buckling and failure behaviours of configured composite panels under different compression-shearing load are studied in this paper. The experiments are conducted on a new experiment setup. The DIC technique and strain gauges are used to record the deformations and strains of the specimens. The results indicate that the compression-shearing interaction influence the buckling load, buckling modes and ultimate failure significantly. With the shearing proportion increasing, the compressive buckling load decreases. When the compression-shearing ratio is smaller than 1:2, the buckling load becomes close to the shearing-only results. When the compression-shearing ratio is larger than 5:1, the buckling load becomes close to the compression-only results. The ultimate failure mode in compression-shearing 2:1 is similar with the one in compression-only experiment, but has different inclined angles. The maximum prediction error of buckling load is -14.8%. The maximum prediction error of failure load is -11.9%.

REFERENCES

[1] Z. Lei, R. Bai, W. Qiu, L. Zhan, Optical evaluation of the buckling behavior of stiffened composite laminates, *Composites: Part A*, **43**, 2012, pp 1850-1859.

[2] H. Hosseini-Toudeshky, J. Loughlan, M. Kharazi, The buckling characteristics of some integrally formed bead stiffened composite panels, *Thin Walled Structure*; **43(4)**, 2005, pp 629-445.

[3] A.C. Orifici, I.O.Z. Alberdi, R.S. Thomson, J. Bayandor, Compression and post-buckling damage growth and collapse analysis of flat composite stiffened panels, *Composites science and technology*, **68(15–16)**, 2008, pp 3150-3160.

[4] T. Gabriella, P. K. Laszlo, Buckling of axially loaded composite plates with restrained edges, *Journal of Reinforced Plastics and Composites*, 29(23), 2010, pp 3521-3529.

[5] P. Dash, B.N. Singh, Buckling and post-buckling of laminated composite plates, *Mechanics Research Communications*, 46, 2012, pp 1-7.