Numerical and experimental study of buckling behavior of a composite hat-stiffened panel under in-plane shear

Zhenya Sun, Zhenkun Lei*, Ruixiang Bai#, Cong Zhang

State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China

*E-mail: leizk@dlut.edu.cn and bairx@dlut.edu.cn

Abstract. The in-plane shear buckling behavior of a composite hat-stiffened panel is studied by the combination of experimental and numerical analysis. The buckling morphology changes of the hat-stiffened panel during in-plane shearing were monitored and measured by using the fringe projection profilometry and 3D digital image correlation. The in-plane shear buckling load, buckling modes, and failure load of the hat-stiffened composite panel were predicted by using the finite element numerical simulation. The buckling evolution process and failure mechanism of the composite hat-stiffened panel under in-plane shear can be effectively revealed by numerical and experimental investigation.

1. Introduction
The stiffened composite panel is one of the most widely used structural forms that can reflect the design concepts of high strength and light weight. And it is primary structural component in marine, aircraft and aerospace vehicles [1]. The buckling and various types of damages induced by buckling are the typical failure modes of the composite stiffened panels [2].

To study the failure behavior of the composite stiffened panels, researchers carried out a large number of numerical and experimental investigations. Lanzi [3] studied the structural compressive behavior of composite stiffened flat panels by numerical and experimental investigation. Bai et al. [4] studied the shear behavior of a stiffened composite panel with J-shaped stiffener by the combination of numerical and experimental investigation. Kong et al. [5] studied the detailed compressive buckling behavior and failure modes of stiffened panels by the combination of experimental and numerical investigation.

The development of buckling modes of composite stiffened plane can be monitored by noncontact optical techniques, such as the shadow moiré [6], fringe projection profilometry [7-8] and 3D digital image correlation [9-10].

In this paper, the buckling and post-buckling behaviors of a composite hat-stiffened panel under in-plane shear were studied by the in-plane shear test and finite element (FE) numerical analysis. Firstly, the shear behavior of the hat-stiffened panel was simulated by FE method. Finally, a diagonal tensile test realized the in-plane shear test of the composite hat-stiffened panel. In the test, the strain state of the specimen surface was measured by the strain gauge, and the buckling evolution process of the specimen was monitored by the fringe projection profilometry (FPP) and 3D digital image correlation (3D-DIC). The results of experiment and FE numerical analysis were consistent.
2. Experiment

2.1. Specimen preparation

A typical hat-stiffened panel with five hat-type stiffeners is shown in Fig. 1. The width and length are both 1210 mm. The five stiffeners are equally spaced at 210 mm. The lay-up sequence is summarized in Table 1. The thickness of a single layer is 0.185 mm. The material properties are listed in Table 2. The in-plane elastic moduli in directions 1 and 2 are $E_1$ and $E_2$, respectively; $G_{12}$ is the in-plane shear modulus; $\nu_{12}$ is the in-plane Poisson’s ratio; the longitudinal strength parameters under tension and compression are $X_t$ and $X_c$, respectively; the transverse strength parameters under tension and compression are $Y_t$ and $Y_c$, respectively; the in-plane shear strength parameter is $S$.

![Fig. 1 Diagram of hat-stiffened composite panel](image)

Table 1 Lay-up information of specimen

| Lay-up for stiffener | Lay-up for skin |
|----------------------|-----------------|
| [45/0/0/-45/90/0/45] | [45/-45/-45/90/45/0] |

Table 2 Material parameters

| $E_1$ (GPa) | $E_2$ (GPa) | $G_{12}$ (GPa) | $\nu_{12}$ | $X_t$ (MPa) | $X_c$ (MPa) | $Y_t$ (MPa) | $Y_c$ (MPa) | $S$ (MPa) |
|-------------|-------------|---------------|------------|-------------|-------------|-------------|-------------|----------|
| 162         | 9.14        | 4.57          | 0.33       | 3071        | 1747        | 88          | 271         | 143      |

2.2. In-plane shear test

The in-plane shear test of hat-stiffened panel was carried out on a four column tester (CSS-100T, Changchun experimental machine company), and the loading scheme is shown in Fig. 2. The load and displacement were measured by force and displacement sensors.

In the experiment, the strain state of skin surface was monitored by strain gauge measurement, and the strain data was recorded by the strain device (DH3816, Jiangsu Donghua testing company). The strain gauge layout is shown in Fig. 1 (the blue dots represents the strain rosette). The strain gauges were pasted on the skin in "back-to-back" from top to bottom, from left to right. The coding method is shown in Table 3.

FPP was used to measure the deflection change of the stiffened side of the hat-stiffened panel in the in-plane shear test. The white paint was made on the front surface in order to ensure the image quality, improve the test accuracy and reduce the error. At the same time, 3D-DIC was used for the full-field strain measurement of the no stiffened side of the hat-stiffened panel, which was made the white and black paint speckles. Region of interest (ROI) measured by FPP and 3D-DIC is selected in the middle of stiffened panel, as shown in Fig. 1. The acquisition frame rate of the camera in the test is 1 fps.
3. FE analysis

3.1. FE model
The commercial software SIMULIA ABAQUS 2019 is employed for the FE analysis. An S4R element is adopted for the skin and stiffener, and the model seed size is 5 mm, as shown in Fig. 3(a). To simulate the test loading, two reference points were established on the diagonal of the FE model, and the grip sides were coupled to the points, as shown in Fig. 3(b). The load and constraint can be applied to the grip sides through the reference points.

3.2. Buckling analysis
A linear eigenvalue buckling analysis was implemented to derive the buckling eigenvalues. The buckling load values from the first and second order analyses are 457.02 and 465.02 kN, respectively.

3.3. Post-buckling analysis
To calculate the post-buckling capacity and large skin deformation of the hat-stiffened panel, the ABAQUS/Standard analysis was used to carry out in the FE numerical analysis. The initial and maximum increment sizes are both 0.01. The damage criterion was the Hashin criterion [11], and the material degradation model was the Camanho degradation model [12-13].

The calculation in this paper well converges without artificial damping. The out-of-plane displacements in ROI are shown in Fig. 4. The ultimate load simulated by the FE method is 766.8 kN. The material failure under ultimate load occurred in the diagonal regions along the tensile direction, which accompanied by large local buckling deformation, as shown in Fig. 5. The tensile damage to the matrix and compressive damage to the fiber are the main damage modes.
Fig. 4 The out-of-plane displacements: (a) 400kN, (b) 500kN, (c) 600kN, (d) 700kN, and (e) ultimate load

Fig. 5 Failure modes: (a) matrix tension damage, (b) matrix compression damage, (c) fiber tension damage, and (d) fiber compression damage

4. Results and analysis

4.1. Buckling analysis
The strain-load curves of strain gauges are plotted, as shown in Fig. 6. It can be seen that the shear strain on each line increases gradually with the load, and then a bifurcation phenomenon occurs on the "back-to-back" gauges. For example, when the load is 460 kN, a pair of strain values (No. 1141 and No. 1241) located in the assessment area firstly bifurcate. The moment of strain bifurcation corresponds to the initial shear buckling load, and then the hat-stiffened panel enters the post-buckling process. The buckling load of the specimen is 460 kN, which is within 1% of the FE method prediction error.

In order to observe the buckling mode of the panel, the full-field deflection was measured by the FPP and the out-of-plane displacement was measured by the 3D-DIC, as showed in Fig. 7. The local buckling instability occurred on the skin between stiffeners.

4.2. Post-buckling analysis
When the loading of the testing machine reaches 723 kN, the specimen can not continue to bear the load due to failure, which is defined as the shear ultimate load. The actual situation is shown in Fig. 8. The error of ultimate load predicted by FE method is within 6%.
Fig. 6 Strain-load curves

FPP:

3D-DIC:

Fig. 7 Buckling mode measured by FPP and 3D-DIC: (a) 400kN, (b) 500kN, (c) 600kN, and (d) ultimate load

Fig. 8 The final failure photo: (a) front and (b) back
5. Conclusions
In this paper, the in-plane shear buckling behavior of a composite hat-stiffened panel was studied by the combination of the FE numerical simulation and in-plane shear test. Compared to the in-plane shear test, the FE analysis can accurately predict the shear buckling load, ultimate load and shear buckling deformation. The evolution of shear buckling morphology can be effectively detected by the FPP and 3D-DIC. The material failure modes of the hat-stiffened panel mainly were the matrix tensile damage and the fiber compression damage, which occurred in the diagonal tensile regions with large local buckling.

Acknowledgments
The authors thank the National Natural Science Foundation of China (Nos. 11772081, 11972106).

References
[1] Kolanu NR, Prakash SS, Ramji M. (2016) Experimental study on compressive behavior of GFRP stiffened panels using digital image correlation. Ocean Engineering, 114:290-302
[2] Mo Y, Ge D, Zhou J. (2015) Experiment and analysis of hat-stringer-stiffened composite curved panels under axial compression. Composite Structures, 123:150-160.
[3] Lanzi L. (2004) A numerical and experimental investigation on composite stiffened panels into post-buckling[J]. Thin-Walled Structures, 42(12):1645-1664.
[4] Bai RX, Lei ZK, Wei X, Tao W, Yan C. (2017) Numerical and experimental study of dynamic buckling behavior of a J-stiffened composite panel under in-plane shear. Composite Structures, 166: 96–103.
[5] Kong X, Yang Y, Gan J, Yuan T, Wu W. (2020) Experimental and numerical investigation on the detailed buckling process of similar stiffened panels subjected to in-plane compressive load. Thin-Walled Structures, 148:106620.
[6] Barbero EJ, Dede EK, Jones S. (2000) Experimental verification of buckling-mode interaction in intermediate-length composite columns. International Journal of Solids and Structures, 37(29):3919-3934.
[7] Liu D, Bai RX, Wang R, Lei ZK, Yan C. Experimental study on compressive buckling behavior of J-stiffened composite panels. Optics and Lasers in Engineering, 2019, 120: 31–39.
[8] Bai RX, Bao SH, Lei ZK, Liu C, Chen Y, Liu D, Yan C. Experimental study on compressive behavior of I-stiffened CFRP panel using fringe projection profilometry. Ocean Engineering, 2018, 160: 382–388.
[9] Jin TL, Ha NS, Goo NS. (2014) A study of the thermal buckling behavior of a circular aluminum plate using the digital image correlation technique and finite element analysis. Thin-Walled Structures, 77:187-197.
[10] Masood SN, SrV, Gaddikeri KM. (2020) Composites Airframe Panel Design for Post-buckling: An Experimental Investigation. Composite Structures, 2020, 241:112104.
[11] Hashin Z. Failure Criteria for Unidirectional Fiber Composites. Journal of Applied Mechanics, 1980, 47(2):329-334.
[12] Camanho PP, Matthews FL. A Progressive Damage Model for Mechanically Fastened Joints in Composite Laminates. Journal of Composite Materials, 1999, 33(24):2248-2280.
[13] Liu PF, Gu ZP, Yang YH, Peng XQ. A nonlocal finite element model for progressive failure analysis of composite laminates. Composites Part B: Engineering, 2016, 86:178-196.