Research on Buckling and Post-buckling Characteristics of Composite Curved Stiffened Fuselage Panel under Hoop Bending load

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Abstract. In order to study the buckling, post-buckling and failure modes of composite fuselage structures under circumferential bending loads, innovative four-point bending tests technology was developed and performed on composite curved stiffened fuselage panel (CSFP) specimens with two frame configurations of C-section and Z-section. Meanwhile, the stability engineering analysis and estimation based on plate buckling theory and simplified boundary were carried out, and the finite element (FE) models based on Hashin failure criterion were established to simulate the buckling, post-buckling and failure modes of CSFP specimens. The tests and analysis results show that the buckling modes and failure modes of C-section and Z-section specimens are different under positive bending loads. Specifically, the buckling of C-section specimens firstly occurs in the middle of the frame, then local buckling occurs at both ends of the frame, leading to fracture. For Z-section specimens, only local buckling occurs in the middle of the frame, which directly leads to fracture. By comparing the three methods, the results of FE analysis and engineering calculation are in good agreement with the test results. Among them, the prediction of instability mode and failure mode by FE method is very accurate, and the buckling strain calculated by engineering method can provide a good reference for structural design.

1. Introduction
In order to develop the lightweight structure and reduce the fuel consumption of future aircraft, the interest in composite materials for the design of aircraft structures has been steadily growing over the last few decades. New commercial aircrafts such as Boeing 787 and Airbus 350 are the first commercial aircrafts to feature composites in primary structures such as fuselage and wing. It turns out that the extensive use of composite structures can greatly improve economic efficiency of flight [1-3]. Therefore, in the design of modern aircraft, the all-composite fuselage becomes a sought-after object.

The all-composite fuselage structure is similar to the traditional fuselage structure composed of skins and supporting airframe that consists of circumferential frames and axial stringers [4-6]. The primary role of the airframe is to bear a major part of internal axial loads and circumferential loads, come from the external loads such as lift, thrust, drag, and gravity in addition to cabin pressurization. It acts as a skeleton for the fuselage structure and stiffens the skin against buckling and instability [7-9]. Therefore, the stability of the fuselage frame and cross-section are critical to the fuselage.

During the development of a new aircraft, the crash behaviour is of high importance for passenger safety. The performance of novel aircraft designs under survivable crash landing conditions is typically assessed and demonstrated in vertical drop tests of aircraft fuselage sections, to evaluate
strength and safety of fuselage section [10-13]. The flexural properties of the fuselage section or the frames are the most important factors in maintaining structural integrity under static conditions or crash conditions [14, 15]. Therefore, it is the first step in the design of the fuselage to study the bending performance of the fuselage section and the frame, and to evaluate its instability mode and failure mode under the annular bending load [16-18].

At present, it mainly focuses on the study of the tensile properties or the pressure filling performance in the experimental research of the curved fuselage panel, as well as the bending performance of the fuselage frame is mostly performed on single frame [19-22]. It is not effectively evaluated the stability of frame in the actual structure and overall stability of fuselage as a whole structure.

In this paper, the study of stability of frame and buckling of skin performed on composite curved stiffened fuselage panel (CSFP) under bending condition. The experiment results combining with engineering analysis (EA) and finite element analysis (FEA), exactly predict the actual instability mode and failure mode of the structures.

2. Experiment

2.1. composite curved stiffened fuselage panel (CSFP)

In this tests, generic specimens of composite CSFP, representing conventional aircraft fuselage design, with skin, seven stringers, one shear-clip and one frame, were used for the tests. The picture of specimen is shown in Figure 1. All components were manufactured by IMA/M21E composite material, a unidirectional carbon fibre/epoxy prepreg, nominal ply thickness of 0.19 mm and curing temperature of 180℃. The elastic and strength properties of this material were taken from data sheets and are given in Table 1. The skin was a straight curved panel, had a radius of 2960mm, span of 28.455° (horizontal length was about 1455mm), width of 620mm and thickness of 2.28mm, made from 12 plies of the same prepreg material described before, with a stacking sequence of [45/-45/-45/90/45/0]s where the 0-direction was oriented in flight direction (stringer direction). The cap-stringer had a height of 31.5mm and a thickness of 1.71mm with the following 9 plies: [45/0/0/-45/90/-45/0/45]. The shear-

| Elastic properties | Value  | Strength properties | Value  |
|--------------------|--------|---------------------|--------|
| E_{11}             | 154GPa | X_T                 | 2610MPa|
| E_{22}             | 8.5GPa | X_C                 | 1450MPa|
| G_{12}             | 4.2GPa | Y_T                 | 55MPa  |
| ν_{12}             | 0.35   | Y_C                 | 285MPa |
|                   |        | S_{12}              | 105MPa |

Table 1. Material properties of IMA/M21E composite.
clip had a height of 67mm and a thickness of 2.66mm with an order of the layers of [45/-45/0/90/-45/45/0/0/45/-45/90/0/-45/45]. The C-section and Z-section frame both had a web with height of 80mm and a flange with width of 28mm as shown in Figure 2, and a thickness of 1.9mm with stacking sequence of [45/-45/0/90/45/-45/90/0/-45/45].

2.2. Four-point bending test

Frames are circumferential stiffeners of the fuselage shell and its instability and breaking is one of the major failure modes of fuselage structure, but the skin plays a great role in the load transmission and bearing of the fuselage. Therefore, the bending test of the CSFP with frame is a correct method to assess their structural performance for global fuselage loading analyses [21, 22]. In the test, the pure bending loading of composite CSFP was performed on testing machine by the four-point bending loading technology, as shown in Figure 3. The major components of the test device were the huge rigid support and loading platform, support and loading base, strengthening components of specimen as shown in Figure 4.

Figure 3. Four-point-bending test device of CSFP specimen.

Figure 4. Section sketch of strengthening components

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Figure 5. The (a) front view, (b) top view and (c) detail view A of Strain gauge position on specimen.

The support platform and loading platform were respectively fixed on the lower and upper fixed supports of the test machine. Special metal strengthening components and devices such as loading pad, reinforcement box, supports pad and wedge cushion block for both ends of the specimens were developed and attached by screw connection to avoid local damage and instability of the composite
material by direct load introduction through the supports. The horizontal distance L between the support base and the loading base was 307mm. If the force loaded by test machine was F, the bending moment M was F·L/2.

The four-point bending tests were performed on Instron8804 (500kN) universal testing machine, with loading accuracy of level 0.5. The loading speed was 1mm/min. There were 30 strain gauges on each specimen for capturing local strain and identifying buckling mode, and all strain gauges were back-to-back pasted, as shown in Figure 5, where the number 22-24 pieces were pasted on the flange of the middle of frame along the cross-section. The strain measurement system was ST-16 strain acquisition system, with range of ±20000µε and measurement accuracy of 0.5%FS.

3. Analytical estimation

3.1. Engineering analysis (EA)

In the four-point bending tests of CSFP, there are tensile loads in the skin and compressive loads in the shear-clip and frame. The buckling easily occurs in the frame, especially in the upper flange and outward buckling of the web because of compression. Therefore, Euler-instability theory and plate buckling theory based on simplified boundary can be used for evaluating the overall instability and local buckling.

Euler-instability easily occurs in the frame, cause of the longer compressive segment. For cross-section of frame, the instability mode is lateral instability [23, 24], as shown in Figure 6. The boundary of frame is simplified into a Euler-rod that one of the lateral edges with elastic support, and the lateral instability stress shown in Equation.1[24], in which, the C=1 is support coefficient, the L is assessment section length of frame, the A is section area of frame and Iy is section bending stiffness of frame.

\[ \sigma_{lat,cr} = \frac{\pi^2 \cdot EI_y}{L^2 \cdot A} \]  

(1)

When local buckling occurs in the upper flange, the boundary of flange is simplified into a rectangular plate that one of the lateral edges with simply support and two loading edges clamped, as shown in Figure 7 (a). Local buckling load of flange is shown in Equation.2, in which, the b is width of the flange and the D11, D66 is stiffness of flange.

\[ N_{scr} = \frac{\pi^2}{L} D_{11} + \frac{12}{b_f^2} D_{66} \]  

(2)

Buckling boundary of web with compression is simplified into a rectangular plate that two lateral edges with simply support and other two loading edges clamped, as shown in Figure 7 (b). Local buckling load of web is shown in Equation.3, in which, the b is height of the web and the D11, D22, D12, D66 is stiffness of web.

\[ N_{scr} = \frac{2\pi^2}{b_w^2} \left[ \sqrt{D_{11}D_{22}} + (D_{12} + 2D_{66}) \right] \]  

(3)

![Figure 6. Lateral instability of frame.](image)

![Figure 7. Buckling boundary of (a) flange and (b) web.](image)
The local buckling stress and strain is shown in Equation 4 and Equation 5, in which, the \( t \) is local thickness of plate and the \( E_{11} \) is local axial elastic module of plate.

\[
\sigma_{cr} = \frac{N_{cr}}{t} \tag{4}
\]
\[
\varepsilon_{cr} = \frac{\sigma_{cr}}{E_{11}} \tag{5}
\]

3.2. Finite element analysis (FEA)

All simulation works of this study were performed with Abaqus/CAE, and the global aim was to obtain the instability mode and failure mode. The FE model assembled according to the actual connection between the sample and the device is shown in Figure 8. Connections were modelled by means of "connection" and "interaction". Four-node simplified integrated shell element of type S4R was used to model composite fuselage and metal reinforcement. The other devices such as cushion blocks, platforms and bases were modelled by C3D8R Solid element. The composite material model was based on Hashin failure criteria for damage initiation and on fracture energies for damage evolution up to ply. Once all layers failed, the whole element is removed from the calculation. The support and load introduction parts were also modelled as meshed parts to allow for contact friction. The resulting force-displacement curves of FEA as shown in Figure 9 show that the results of simulation exactly matched the experiments.

**Figure 8.** Four-point-bending loading of fuselage frame.

**Figure 9.** The load-displacement curves of (a) C-section, (b) Z-section specimen.

4. Results and discussion

4.1. buckling and post-buckling of positive bending

The resulting force-displacement curves of specimens in positive bending condition are shown in Figure 9. For C-section specimens, the initial phase of test is linear elastic with compressive load in the frame and tensile load in the skin. After the load of approx. 18kN, the force-strain curves of three strain gauges (22, 23, 24) arranged laterally on the flange show inflection points as shown in Figure 10, resulting a non-linear trend of the force-displacement curves (Figure 9(a)). The inflection points of this curves are the lateral buckling point of the frame, and the corresponding lateral buckling strain is 1875µε. Compared with the non-linear results of the finite element method, as shown in Figure 12 (a), lateral buckling of the upper flange and outward deformation of the web can be visually observed. However, at this point, since the curve shown in Figure 10 is still linear, no local buckling occurs on the flange and web. Then, the force-strain curves of back-to-back strain gauges (20, 120) on the upper flange close to ends of frame appears inflection point at the load of level of approx. 20kN, as shown in Figure 10. This inflection point indicates local buckling on the upper flange, as visually shown in Figure 12(a), the corresponding local buckling strain is 3120µε. However, there is no obvious local buckling on the web, as shown in Figure 10. At the load level of 24kN, the local buckling position of the upper flange near the load point is damaged, as shown in Figure 10 and Figure 13, resulting in force drop and test stopping.
The force-displacement curves of Z-section specimens shown in Figure 9(b) is near to linear elastic throughout the phase, and there is no inflection point on the force-strain curves of lateral strain gauges on the flange, which indicate that no obvious overall instability or lateral buckling occurs in the whole process, as shown in Figure 11. This is obviously different from the C-section specimen. At the load level of 23.5kN, the force-strain curves of back-to-back strain gauges (23, 123) on the upper flange appears inflection point, showing that the local buckling occurs in the flange and web in the middle of frame, and corresponding strain is 3500\(\mu\varepsilon\) and 2507\(\mu\varepsilon\) respectively. This local buckling mode is intuitively displayed in the FE method calculation result graph, as shown in Figure 12(b). Under the load of approx.28kN, brittle failure of the compressively loaded flange and web occurs in the specimen center, as shown in Figure 14, leading to a force drop to the zero.

### 4.2. Results Comparison

Based on the above analysis, the buckling mode and failure mode of C-section and Z-section is distinct due to the difference of cross-section configuration of frame. The buckling load and buckling strain of Z-section is 23.5kN and 3500\(\mu\varepsilon\), respectively 32% and 86.7% higher than C-section. The failure load of Z-section is 28kN, with 16.7% higher than the C-section. Therefore, the stability and strength performance of Z-section is better than C-section. Table 2 lists the buckling strains obtained from the test, FEA and EA. It can be seen from the table that the error between the results of the two analytical methods and the test results are within the acceptable range, and the comparisons proved good correlation and correct representation of analytical methods. Differently, the FEA results are close to the test results, but larger than the test results; but the EA results and the test results have relatively large errors, and the results are more conservative.
Figure 13. Failure mode of C-section specimen (a) simulation result, (b) experiment result

Figure 14. Failure mode of Z-section specimen (a) simulation result, (b) experiment result

Table 2. Comparison of FEA results, EA results and test results

| Configuration | Part       | Type       | Experiment | Simulation | Error | Engineering | Error |
|---------------|------------|------------|------------|------------|-------|-------------|-------|
| C-section     | Frame      | Initial buckling | 1875με    | 1950με | 4.0%  | 1752με    | -6.6% |
|               | Flange     | Local buckling | 3120με    | 3200με | 2.5%  | 2852με    | -8.6% |
| Z-section     | Flange     | Initial buckling | 3500με    | 3815με | 9.0%  | 2852με    | -18.5% |
|               | Web        | Local buckling | 2507με    | 2830με | 12.9% | 2215με    | -11.6% |

5. Conclusion
The four-point-bending test technology investigated in this paper has successfully carried out the bending tests of composite CSFP on the test machine, avoiding local damage and instability of load segment. Based on four-point-bending test technology, the experimental and numerical study has conducted to generate a method for the validation of composite structure models for aircraft fuselage design. The following conclusions could be drawn:

- In the tests of C-section specimens, lateral buckling and outward deformation firstly occurs in the middle of frame, causing local buckling and fracture at the end. However, for Z-section specimens, no lateral buckling occurs, only local buckling and fracture occur in the middle of the frame.
- The buckling load and failure load of Z-section specimen are both higher than C-section, and the stability and strength of Z-section specimen are excelled the C-frame.
- The FEA results and EA results are close to the experiment results, validating against the correctness of simulation and engineering analysis.

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