Experimental research on four-point-bending loading of composite fuselage frame

Li Xiang^1a, Li Xingfu^2

^1China Southern Airlines Co, Ltd. Shenzhen Branch, Shenzhen 518000, China;
^2AVIC Xi’an Aircraft Industry Group Co. Ltd, Xi’an 710089, China
^a xiangleenwpu@aliyun.com

Abstract. A four-point-bending loading test device was designed for the pure bending loading of the composite fuselage curved frame. The reinforcing subplates, reinforcing frames, wedge-shaped blocks and other parts were installed in the load segment of test pieces to enhance the local stiffness, strength and torsional stiffness. Four-point-bending loading tests and nonlinear finite element calculation of C-frame and Z-frame pieces under the condition of positive bending was carried out. The calculated buckling mode was in good agreement with the test result, which provides a certain theoretical basis for the instability mode analysis of curved frames. The test and analysis results show that under the condition of positive bending and the middle section of C-frame has lateral instability and the end inner edge of the frame has the local buckling and damage. While the middle section of inner edge of the Z-frame has only local buckling and damage. The test results of two kinds of frame show that the stability and structural strength of Z-frame are better than that of C-frame.

1. Introduction

Composite materials have been used more and more widely in aircraft structure because of their excellent performance. Among which the most typical composite structure is the fuselage panel composed of skin, girder and frame, etc. The girder mainly sustain the action of axial tension and compression in the fuselage structure while the role of the frame is to increase the lateral stability of the fuselage. In other words, when the panel structure composed of skin and girder is partially buckling, the circumferential connected frame can still support the girder and avoid the overall instability of the fuselage panel. The fuselage is equivalent to a closed annular barrel segment and the aerodynamic load borne by the skin is transmitted to the frame through the girder and making the frame sustain a large bending load. Therefore, the stability of the frame is very important for the whole fuselage. It is of great significance for the fuselage design to study the circumferential stability of the frame and assess the instability mode of the frame [1].

At present, experimental studies in domestic on fuselage structure mainly focus on axial tension-compression performance and circumferential charging performance [2]-[3]. Most experimental studies on circumferential loading performance of fuselage frame are carried out by single-frame bending loading method [4]-[7]. Gao Binhua [5] used the three-point bending loading method to carry out dynamic loading on the J-type single frame of braided composite material. The section of the J-type frame was bent and twisted and the load contact surface at the edge of the frame was broken first. Current research mainly focuses on the bending loading of single or straight frames and the assessment objective is simple. The experimental support conditions are greatly different from the real fuselage structure. So it is difficult to verify the real instability mode of fuselage frame with circumferential
load. Moreover, the support stiffness of the frame is weak and problems such as roll-over, torsion and premature failure are easy to occur when the concentrated force is applied. The actual boundary condition of the frame is elastic support of skin and girder on one side and the instability mode of the frame is quite different from that of the single frame loading. In order to study the circumferential stability of the frame actually, we design a frame structure composed of skin, stringer, shear angle sheet and curved frame, using a four-point bending load and designing reasonable way of connection and support to avoid frame side lean, torsion and early damage during the process of loading and reaching the purpose of assessment of the frame of instability and failure. At the same time, the experimental results were analyzed with finite element calculation and the instability modes and failure modes of C-frame and Z-frame were obtained respectively and the optimal configuration was given through comparison, which is of great significance to the structure design of composite fuselage.

2. Test pieces

2.1. Test pieces configuration

The test pieces include frame, shear angle sheet, girder and skin, etc. The test section is 3 times girders length in the middle of frame and the load segment is 1.5 times girders length at both ends. The test section is same with the actual fuselage structure. The clamping fixture is considered in the design of the load segment. The original girder is removed and a layer of subplate is laid on the inner surface of the skin. The skin radius of the test pieces is 2960mm and the interception span is 28. 455° and the horizontal length is about 1455mm and the width is 620mm. The basic appearance is shown in Figure 1. The test pieces contains C-frame and Z-frame cross-section configurations. In which the skin, girder and shear angle sheet configurations are the same. As shown in Figure 2. The inner edge extension directions of the frame of the two cross-section configurations are opposite.

![Figure 1. Sketch of Fuselage Curved Panel](image1)

![Figure 2. Frame Section Configuration](image2)

2.2. Material of test pieces

Every part of the test pieces are made of M21E/IMA. Material properties is $E_{11}=154$GPa, $E_{22}=8.5$GPa, $E_{33}=8.5$GPa, $G_{12}=4.2$GPa, $\nu_{12}=0.35$. The thickness of the single layer is 0.184mm. Among them, the layer order of skin is $[45/-45/-45/90/45/0]$s. The layer order of cap stringer is $[45/0/0/-45/90/-45/0/0/45]$. The layer order of shear angle sheet is $[45/-45/0/90/-45/45/0]$s. The layer order of frame is $[45/-45/0/90/-45/90/0/-45/45]$. 

3. Test and calculation method
3. 1. Load method
In this test, four-point bending loading is adopted for pure bending loading and the schematic diagram of the loading scheme is shown in Figure 3. The two ends of the test pieces are placed on two support seats respectively and the two loading seats exert concentrated loads on both sides of the assessment section respectively. Wedge-shaped blocks are installed at the support and loading places to convert the curved surface into a flat so that the supporting force and the loading force are parallel so as to form a pair of force couplings of equal size and opposite direction and thus form pure bending load. In this test, the positive bending load is applied to the frame of the fuselage. So the support seat is at both ends of the test pieces and the loading seat is in the middle. Among them, the horizontal distance between the support seat and the loading seat is L. If the load applied by the loading seat is F/2, then the bending moment suffered by the assessment section is M=1/2F·L.

3. 2. Support strengthening method
As the local stiffness and strength of the frame and skin are weak, it is easy to be unstable or destroyed advanced under the action of concentrated load. So it is necessary to strengthen the stiffness and strength of the whole load segment. In this test, a variety of reinforcing frames and reinforcing subplates are connected in the load segment to form a set of strengthening components. The section combination is shown in Figure 4. In Figure 4, the left and right side of shear angle sheet connect C-reinforcing frames and L-type reinforcing frame 2. And in order to increase the support stiffness, L-type reinforcing frame 1 is placed on the right side of connections. In order to increase local stiffness and strength of web and inner of frame, the reinforcing blocks are connected at the top of the frame to increase the strength of contact surface. The support subplate connects at the bottom of skin to increase the local stiffness and strength of support surface skin. All the connecting surfaces adopt the form of surface matching and mechanical connection to ensure sufficient connection strength.
The reinforcing frames and reinforcing subplates connected in the load segment are not only increasing the supporting stiffness but also effectively increasing the torsional stiffness and stiffness symmetry of the section. In addition, the transverse support surface of the loading surface and support surface is large, which effectively increases the transverse support stiffness of the section. The loading seat and support seat are fixed on the test machine, so the transverse boundary support of the loading surface and support surface is similar to the fixed support, which effectively limits the torsion or deformation of the section (As shown in Figure 5.).

![Figure 3. Four-point bending loading diagram of fuselage curved panel](image)

![Figure 4. Section Sketch of Load Segment](image)
3.3. Test measurement and implementation

Four-point bending test of fuselage frame was carried out on instron500kn testing machine and the test photos are shown in Figure 6. Upper and lower chuck of testing machine fixed support platform and install the load seat close to inside and support seat close to outside on the upper and lower support platform respectively and test pieces placed on the support seat. The support platform and two load seats transfer load from testing machine to load points of assessment segment of test pieces on both sides to form bending load. The horizontal distance between the load point and the support point in the test was L=309mm. According to the description in section 2.1, if the load value of the testing machine is F (unit KN), then the actual bending moment of the testing section of the test pieces M=154.5F (KN-mm). The load method adopts displacement loading and the load rate is 1mm/min and the accuracy is level 0.5.

In order to measure the strain response of the test pieces during the loading process, a strain gauge is pasted on the concerned part as shown in Figure 7. Among them, 20-26 pieces are pasted on the inner surface of the inner edge of the frame. 27-31 pieces are pasted on the side of the web of the frame. 40-42 pieces are pasted on the side of the shear angle sheet. And 22-24 pieces are pasted on the side of the middle part of the inner edge of the frame. All strain gauges are pasted back to back along circumferential of the frame. The number of strain gauges on the back is +100. For example, the No. 20 piece is located on the inner surface of the inner edge of the frame And the No. 120 symmetrical pieces on the back is located on the outer surface of the inner edge of the frame. St-16 strain acquisition system is adopted for strain measurement with range of ±20000με and measure accuracy of 0.5% FS.
Figure 7. Strain Gauge Arrangement on Specimen

3.4. Finite element analysis method

Using ABAQUS software, the finite element calculation based on the actual connection relationship and boundary conditions and load conditions of the test is carried out to assist the analysis of the instability mode of the test pieces. In the finite element model, the test pieces and the reinforcing frames and the reinforcing subplates all adopt shell element. The wedge-shaped block and the supporting seat adopt solid element. The bolt connection adopt 3D beam element and node coupling mode while the support surface and the load surface adopt face-contact. When the boundary conditions were set two support seats were fixed and two load seats were loaded with vertical downward displacement. Symmetrical boundary constraints were set on the circumferential central of the test piece. The finite element model was shown in Figure 8. The finite element analysis verify the instability mode of the test pieces only. Thus only geometric nonlinear calculation is adopted and the calculation of material damage is not considered.

Figure 8. The Finite Element Model of Fuselage Curved Frame

4. Results and analysis

4.1. C-Frame test results analysis

When the fuselage frame is loaded with positive bending, the frame mainly sustain compression load, which will cause instability. The load-strain curve of the instability position drawn according to the positive bending loading test results of C-frame test pieces is shown in Figure 9. The abscess of the figure is the load F directly applied by the testing machine.

From Figure 9 (a), it can be found that c-frame test assessment within the inner edge of the middle around the lateral surface of three strain gauges (22, 23, 24) of the load and strain curve showed a trend of bending upwards of nonlinear. Based on literature [7] that the lateral buckling happened, it namely the lateral deformation instability along the inner edge of frame and not normal deformation instability. The lowest point of the intermediate strain gauge is defined as the lateral instability point, then the lateral instability load of the frame is 17.8kn and the instability strain is -1875με. It can be seen from Figure. 9 (b) that the load-strain curve of back-to-back strain gauges (pieces 20 and 120) at the inner edge of the frame at the end of the assessment section generated divarication and inflexion point at 19.8kn and the inflexion point is defined as the local buckling point, and the average value of back-to-back strain gauges is defined as the local buckling strain. The local buckling load at the inner
The edge of the end frame is 19.8 kN and the buckling strain is -3120 με. When the test was loaded up to 24 kN, failure occurred at the local buckling position (no. 20 and no. 120 pieces) at the inner edge of the end of the frame and the failure mode was shown in Fig 10. In summary, when the c-frame test pieces were positively flexed under loading, lateral instability occurred in the middle section of the test section first, and led to local buckling at the inner edge of the end frame. With the increase of load, fracture failure occurred at the local buckling part of the end.

The instability mode of c-frame test pieces under positive bending loading obtained by geometric nonlinear finite element calculation is shown in Figure 11. From the figure, it can be intuitively found that lateral instability deformation occurred in the middle section of the assessment section and local buckling deformation occurred at the inner edge of the end. The instability load-strain curves of the middle segment of the inner edge and the end of the c-frame calculated by the finite element are shown in Figure 12 and the strain collection site in the figure is completely the same with the test pieces. According to the analysis method of the test results, the lateral buckling load and buckling strain of the frame calculated by the finite element method are 20.5 kN, -1950 με. The local buckling load at the inner edge of the end frame is 22 kN and the buckling strain is -3280 με, which are close to the experimental results and the maximum error is less than 15%. It can be seen that the instability mode and results of finite element calculation are in good agreement with the test and the instability mode of the structure can be analyzed more intuitively.

The mid-section load-strain curve of Z-frame test pieces under positive bending loading obtained from the test is shown in Figure 13. It can be seen from Figure 13 (a) that the load-strain curves of the three lateral strain gauges (pieces 22, 23 and 24) at the inner edge of the middle section of the Z-frame do not show obvious non-linearity and indicate that lateral instability does not occur at the middle section of the inner edge. However, it can be seen from Figure 13(b) that the load-strain curves of back-to-back strain gauges (plates 24 and 124) at the inner edge of the middle section of the Z-frame show an

**Figure 9.** Test Instability Load-Strain Curves of C-Frame: (a) Lateral Instability; (b) Local Instability

**Figure 10.** Test Failure Mode of C-Frame

**Figure 11.** FEA Instability Mode of C-Frame

**4. 2. Z-frame test results analysis**

The mid-section load-strain curve of Z-frame test pieces under positive bending loading obtained from the test is shown in Figure 13. It can be seen from Figure 13 (a) that the load-strain curves of the three lateral strain gauges (pieces 22, 23 and 24) at the inner edge of the middle section of the Z-frame do not show obvious non-linearity and indicate that lateral instability does not occur at the middle section of the inner edge. However, it can be seen from Figure 13(b) that the load-strain curves of back-to-back strain gauges (plates 24 and 124) at the inner edge of the middle section of the Z-frame show an
obvious bifurcating trend and indicate that local buckling occurs here. The buckling load is 23.5 kN and the buckling strain is -3500 με (taking the average value of the back-to-back 24 and 124 plates). When the test was loaded up to 28 kN, the local buckling part of the inner edge of the middle section of the Z-frame was damaged and the failure mode was shown in Figure 14. It can be seen that initial buckling occurs at the local inner edge of the frame in the middle section of the test section when the Z-frame is loaded with positive bending and rupture occurs at the local buckling part of the inner edge of the frame in the middle section with the load increase.

**Figure 12.** FEA Instability Load-Strain Curves of C-Frame: (a) Lateral Instability; (b) Local Instability

The instability mode of Z-frame under positive bending loading obtained by finite element calculation is shown in Figure 15. It can be found from the figure that corrugated local buckling occurs along the normal direction at the inner edge of the frame in the middle section of the assessment section. It can be seen from Fig 16 that the variation trend of load-strain curve of Z-frame instability calculated by finite element method is in good agreement with the test results. According to the analysis method of test results, the buckling load calculated by finite element method is 22.5 kN and the buckling strain is -3806 με and the maximum error between the finite element calculation and the test is less than 10%.

**Figure 13.** Test Load-Strain Curves in The Middle of Z-Frame: (a) Lateral; (b) Instability

**Figure 14.** Test Failure Mode of Z-Frame

**Figure 15.** FEA Instability Mode of Z-Frame
4.3. Comparison of frame configurations
It can be found through tests and finite element analysis that when the frame of fuselage is under positive bending loading that the C-frame is prone to lateral bending and lateral instability due to the asymmetry of the section when it is subjected to the compression load brought by bending, which leads to the stress concentration at the inner edge of the end and fracture. The section of Z-frame is relatively symmetrical and it is not easy to bend laterally when subjected to the compression load caused by bending. Local buckling and failure only occur at the inner edge of the mid-section frame, which belongs to the ideal instability mode and failure mode. According to the test data analyzed in Section 3.1 and Section 3.2, it can be found that the initial buckling load, buckling strain and failure load of Z-frame structure are 32%, 86.7% and 16.7% higher than that of C-frame structure under positive bending condition respectively. Therefore, from the perspective of strength and stability of composite fuselage structure, Z-frame configuration of fuselage structure is better than C-frame configuration.

Figure 16. FEA instability load-strain curves of Z-frame

5. Conclusion
1) The four-point bending test technology of fuselage frame studied in this paper solves the problems of side lean, torsion, and advanced instability and damage in the loading section of frame and achieves the purpose of the instability and damage in the assessment section;
2) Under positive bending loading of C-frame, lateral instability first occurs in the middle section of the assessment section and leads to local buckling and fracture failure at the inner edge of the end. The initial buckling occurred at the inner edge of the frame in the middle section of the test section and was damaged at the local buckling position of the inner edge of the middle section when the Z-frame was loaded with positive bending;
3) Under positive bending condition, the initial buckling load, buckling strain and failure load of Z-frame are 32%, 86.7% and 16.7% higher than those of C-frame test pieces. In terms of structural strength and stability, Z-frame configuration is superior to C-frame configuration.

6. References
[1] Maher B., Tarek L., Mohamed S. Mechanical Response of a Hexagonal Grid Stiffened Design of a Pressurized Cylindrical Shell-Application to Aircraft Fuselage[J]. Thin-Walled Structures, 2018(127): 40-50.
[2] ZE L Y, PU X. Crashworthiness Study of Composite Fuselage Section[J]. Key Engineering Materials, 2016(725): 94-98.
[3] CHEN An, WEI Yu-long, LIAO Jiang-hai. Damage Tolerance Test of Stiffened Fuselage Panel Under Complex Load[J]. Acta Aeronautica ET Astronautica Sinica, 2017, 38(1): 420093 (in Chinese)
[4] XIN Ya-jun, XIAO Bo, CHENG Shu-liang. Experimental Study of Four-point Bending Performance of Aluminum Foam Sandwich Beam[J]. Journal of Experimental Mechanics, 2016, 31(5): 593-599(in Chinese)
[5] XIN Ya-jun, XIAO Bo, CHENG Shu-liang. Experimental Study of Four-point Bending Performance of Aluminum Foam Sandwich Beam[J]. Journal of Experimental Mechanics, 2016, 31(5): 593-599 (in Chinese)

[6] GAO Bin-hua, REN Yi-ru. Impact Dynamic Characteristics of Braided Composite Fuselage Frame[J]. Acat Material Composite Sinica, 2017, 34(8):1780-1787 (in Chinese)

[7] Lei Zhang, Gen-shu Tong. Lateral Buckling of Simply Supported C-Section and Z-Section Purlins with Top Flange Horizontally Restrained. Thin-Walled Structures, 2016 (99): 155–167.