The study on stability of composite panel structure under axial compression load

J Jiang¹²*, C Chen¹, X Zhang² and Z Yang²

¹ Shenyang University of Technology, Institute of Mechanical Engineering, Laboratory of Mechanical Reliability and Dynamics Research Center, Shenyang, China;
² Shenyang City University, Institute of Intelligent Engineering, Mechanical Design and Automation, Shenyang, China.

* sherojjj@163.com

Abstract. The axial compressive load test and finite element simulation are made to study the mechanical properties of aircraft stiffened composite panel. Firstly, the numerical simulation model of composite stiffened panel structure is constructed, the accuracy and feasibility of the simulation model are verified by calculating the value of MAC (Modal Assurance Criterion) between the computational free modal and experimental free modal. Then, the nonlinear post-buckling numerical simulation is carried out to extract the buckling load, the post-buckling load path and the failure load. Then, the axial compression test of the panel structure is carried out by the testing machine, and the load-displacement curve and the load-strain curve of the loading position are obtained. Finally, the correctness of the analysis method is proved by comparing the numerical simulation value with the experimental analysis value. The experimental research method of the mechanical properties of the composite stiffened panel under axial load is explored, which can be used as a reference for the study of the bearing capacity of the stiffened panel.

1. Introduction

Composite material is a new high-performance material, which developed to meet the needs of aviation, aerospace and other high-tech fields. Compared with metal materials in the traditional sense, it has the advantages of light weight, high specific strength and high rigidity [1, 2]. At the same time, it can be layered according to the needs of practical engineering products and the characteristics of bearing loads, and various curvatures and shapes can be stacked to give full play to the mechanical properties of composite materials. It has been widely used in aviation, aerospace, automobile and other industrial structures [3, 4].

However, when the composite stiffened panel structure is subjected to axial compression load, buckling instability often occurs and fails [5, 6]. At the same time, the post-buckling behavior is nonlinear, the analysis is complicated and the workload is heavy, so the initial buckling load of the
structure has always been taken as the design allowable load in actual engineering design. However, as we all know, the composite stiffened panel structure will not be destroyed immediately after buckling, but will enter the post-buckling stage, at which time the structure still has great bearing capacity \[7\]. Therefore, it is very necessary to study the post-buckling behavior of composite stiffened panel structure, including finite element analysis method and experimental analysis method, so as to fully explore and utilize the post-buckling bearing capacity of composite stiffened panel structure, not only effectively reduce the structural weight, but also improve the structural design, which has important economic and practical significance for modern engineering structural design \[8\].

Since advanced composite materials were put into aerospace applications, there have been three achievements worth mentioning. The first is an eight-seater commercial aircraft Learjet 2100 made of carbon fiber composite materials in the United States and successfully tested. The second is the Columbia space shuttle made of a large number of advanced composite materials. This space shuttle uses carbon fiber/Epoxy resin makes the main cargo door of 18.2 m in length and 4.6m in width, and various pressure vessels are made of Kevlar/epoxy resin. Resin, metal and ceramic matrix composite materials were used on this space shuttle, which represents the most cutting-edge technological achievements in modern times; the third part is the use of advanced composite materials as the main bearing structure to manufacture a large Boeing-767 capable of carrying 80 people Passenger aircraft not only reduces the weight, but also improves the various flight performance of the aircraft \[9\].

After nearly 40 years of development, composite materials for aircraft have developed from the original non-load-bearing component to the application of secondary load-bearing and main load-bearing components, which can achieve a significant effect of reducing mass (20% – 30%) \[10\]. At present, it has entered a mature application period, and there is no doubt that it can improve the technical and tactical level, reliability, durability and maintainability of the aircraft. Its design, manufacturing and use experience has become richer. So far, the composite materials used in fighter jets account for about 30% of the total materials used, and the new generation fighter jets will reach 40%; the amount of composite materials used in helicopters and small aircraft will reach (70% - 80%), and even full-composite aircraft will appear. 70% of the fuselage of the Comanche helicopter is made of composite materials, but it is still planned to reduce the weight of the aircraft by another 15% by reducing the mass of the lower front part of the fuselage and expanding the composite materials into the accessories and bearings \[11\]. In order to reduce the quality of the "Apache", composite materials will be used instead of the metal body.

2. Finite element modeling and analysis

2.1. Organization introduction

As shown in figure 1, a series of composite stiffened panel structure test pieces are manufactured, the overall dimensions of which are all 400 mm x 500 mm, and three T-shaped stringers are uniformly arranged on the flat panel skin, in which the skin and stringers are manually laid and then assembled together, and the autoclave co-curing molding process is adopted \[12\].

The allowance of 30mm shall be designed at both ends of all stringers, and the allowance of 3mm shall be designed for the web of T-stringer, so as to facilitate milling after co-curing and eliminate the boundary effect of test pieces.
Figure 1. Schematic diagram of composite stiffened panel structure.

The skin and stringer are made of CMS-CP-306 material and epoxy prepreg toughened by medium-sized high-strength carbon fiber, which is a unidirectional tape material. The thickness of each layer of unidirectional tape is 0.13 mm and Poisson's ratio is 0.31. The mechanical properties of the material are shown in table 1. See table 2 for the sequence of structural paving.

| Table 1. Material parameters of carbon fiber unidirectional tape compression (MPa). |
| Compression modulus $E_{11}$ | Compression modulus $E_{22}$ | Shear modulus $G_{12}$ | Compression strength $E_{xc}$ | Compression strength $E_{yc}$ | Shear strength $G_{xy}$ |
|-----------------------------|-----------------------------|----------------------|-----------------------------|-----------------------------|----------------------|
| 135000                      | 10000                       | 6280                 | 1100                        | 230                         | 136                  |

| Table 2. Structure layup sequence. |
|-------------------------------------|
| Region    | Laying sequence                  |
| Web       | [45/-45/0/-45/90/45/0] s         |
| Cap       | [45/-45/0/-45/90/45/0] s         |
| Skin      | [45/-45/0/90/45/-45/0] s         |

2.2. Verification of simulation model

The two-dimensional shell element is used to model the composite stiffened panel structure. Because the thin shell can calculate the "missing" film internal force of the thin plate when buckling and postbuckling analysis is carried out under compressive load, the composite stiffened panel model constructed by the two-dimensional shell element has higher authenticity and feasibility [13].

Under compression load, the ideal failure mode of composite clamped panel structure must be from the middle of stiffened panel, and all stringers and skin are broken together, so the part between stringer and panel is treated by common node in modeling to improve calculation efficiency. For the composite laminate structure, as long as it does not fail under load (that is, the laminate is not buckled), the strain value of each layer in the laminate is the same, but the stress of each layer is not the same [14]. Therefore, the allowable strain is used as the design limit value when designing composite structures.

The rationality and feasibility of the simulation model can be verified by comparing the finite element strain data and the test strain data and calculating the SAC value of the two.

The rationality and feasibility of the model are verified by comparing the values of finite element free mode and experimental free mode. The hammering method used in the experiment is a typical
single-point excitation method. Since the excitation device is not directly connected to the structure being tested, it will not add additional mass to the structure, so it will not affect the structure Dynamic characteristics. Fix the test piece on the testing machine, select several test points and one excitation point according to the structure, use the hammer to excite, and the data acquisition system picks up the vibration signal of the test point [15].

According to the modal assurance criterion [16]:

\[
MAC_{ti,fj} = \frac{\left(\phi_{ti}^T \times \phi_{fj}\right)^2}{\left|\phi_{ti}^T \times \phi_{ti}\right| \left|\phi_{fj}^T \times \phi_{fj}\right|}
\]

Where, \(\phi_{ti}\) is the \(i\) modal vector of the experimental analysis, \(\phi_{fj}\) is the \(j\) modal vector of the finite element analysis, \(MAC_{ti,fj}\) is the linear correlation between the \(i\) modal vector of the experimental analysis and the \(j\) modal vector of the finite element analysis.

It is generally considered that when it is \(MAC_{ti,fj} \geq 0.7\), it means that the two vectors have good consistency, the constructed finite element simulation numerical model can better reflect the real situation of the structure [17].

![Figure 2. Loading and testing strain value of test piece.](image)

As shown in figure 2, gauges are used to extract the data of stiffened panel structure. According to the comparison results of the two modes, it can be seen that the MAC values of the experimental and finite element modes are all greater than 0.7, indicating that the constructed finite element simulation model has a high approximation to the real situation, and the calculation and analysis model Reasonability and feasibility, that is, it can reflect the actual load status, and lay the foundation for further research.
2.3. Analysis of simulation model

In the finite element analysis, one end of the structure is clamped and restrained, and the axial compressive displacement load of 3mm is applied to the other end of the structure. Based on the finite element analysis software Patran/Nastran, the failure and failure of structural materials are determined by using Hoffman material progressive damage criterion.

There are five kinds of commonly used failure criteria for composite materials [18], which are maximum stress criterion, maximum strain criterion, Tsai-Hill criterion, Tsai-Wu tensor criterion and Hoffman criterion. Among them, the first two kinds of criteria think that once the strength limit of material stress and strain is reached alone, the material will be destroyed immediately, without considering the interaction between material and geometry, so the accuracy of calculation results is relatively low; Tsai-Hill criterion considers the combination form to judge the damage of materials, but it is more suitable for laminates with the same tensile strength and compressive strength in the main direction of materials; Based on Tsai-Hill criterion, Tsai-Wu tensor criterion considers the different tensile and compressive strengths of composite materials, but it can not give the damage evolution process of laminates, and then it can not be determined whether the damage of laminates comes from matrix failure or fiber fracture. Hoffman criterion takes into account the difference of delamination criterion and tensile and compressive strength in the main direction of composite materials. Compared with the test results, its analysis results are closer to the test values, which can accurately determine the failure load of materials. Its material failure criterion is as follows:

\[
f(\sigma) = \frac{\sigma_1^2 - \sigma_2 \sigma_{22} - \sigma_{11} \sigma_{22}}{\sigma_{11} \sigma_{11}} + \frac{\sigma_2^2 - \sigma_2 \sigma_{22} - \sigma_{22} \sigma_{11}}{\sigma_{22} \sigma_{22}} - \frac{\sigma_{11}^2 - \sigma_{11} \sigma_{22}}{\sigma_{11} \sigma_{11}} + \frac{\sigma_{22}^2 - \sigma_{22} \sigma_{11}}{\sigma_{22} \sigma_{22}} - \frac{\tau_{12}^2}{(\tau_{12})^2} \]

(2)

Extract the reaction force at the application point of displacement load and make its load-displacement curve, as shown in figure 3:

![FEM load-displacement curve](image)

**Figure 3.** Finite element analysis-load-displacement curve.

It can be seen from figure 3 that the load and displacement of the structure change linearly in the range of 0 ~ 66.8 kN; When the load is in the range of 66.8 kN ~ 187.6 kN, the structure enters the post-buckling state, and the structure still has great bearing capacity at this time. Among them, the failure
load value is about 3 times the buckling load value, which is also consistent with the engineering experience value.

Tracing back the post-buckling path of the composite stiffened panel structure, it can be seen that in the whole compression process, the composite skin structure first enters the local buckling state, and then with the compression load exceeding the buckling load and increasing, the structure enters the post-buckling state until it is destroyed, and the failure form is also ideal, which is from the middle of the stiffened panel, all stringers and skin are broken and destroyed together [19, 20].

3. Experimental analysis

3.1. Experiment product preparation

All the experiment product were laid by hand and co-cured, and the parts manufacturing tooling was designed. The triangular gap of stiffened panel structure must be filled with twisted strips, and the filling amount of twisted strips directly affects the molding quality of products. According to the experiment, the most reasonable dosage of twister sliver is the calculated value of gap theory, which is multiplied by the correction factor of 1.15. As shown in figure 4, the twister strip is made of 0° carbon fiber prepreg, which is flattened and compacted by a stringer die, then covered with a cover plate and compacted in vacuum. Then, after vacuum compaction for 24 hours, the test piece is sent into hot-pressing irrigation for co-curing, and then taken out of the can and demoulded, as shown in figure 5.

![Figure 4. Compaction of Twins and Vacuum Compaction of experiment product.](image1)

![Figure 5. Curing and molding of experiment product.](image2)

Check the thickness of the demoulded experiment product first to ensure that the thickness of the skin and stringer is uniform, and the tolerance is controlled within 5%. If it exceeds the test piece, it will be discarded. Then the test piece is milled to remove the allowance of 30mm at both ends of the stringer
and 3mm at the web of the T-shaped stringer, so as to eliminate the influence of boundary effect of the test piece on the test results.

### 3.2. Design of test fixture

According to the form of the Test Machine, the test fixture is as shown in figure 6. The Test Fixture is made of precipitation hardening Martensitic stainless steel plate with 15-5PH and its allowable compressive yield stress is 1034 Mpa, it is manufactured by machining.

![Figure 6. Schematic Diagram of test fixture.](image)

The clamping end is designed according to the size of the testing machine, which is 30 x 50 x 10 mm. The loader is used to load the experiment product, the clamp is used to fix the experiment product on the loader, the clamp and the loader parts are fixed by 6 bolts, and the loader parts are round holes, on the gripper is a long round hole, different configuration of the wall plate shape center position, so the position of the gripper relative to the loader is also different, the long round hole can make the gripper move in a certain range. In order to ensure the loading at the centroid position of the specimen in the test, the locating line is carved on the loader according to the centroid position of the wall plates of different configurations, which is convenient for the location of the specimen.

### 3.3. Design of test fixture

Before attaching the strain gauge, first draw a line and draw the edge of the strain gauge according to the size of the strain gauge to ensure that the center of the strain gauge is in the position of the test design. The strain gauge is pasted along the radial direction of the test piece, and the wire is thrown to the bottom of the test piece when the test piece is loaded. Prevent the strain gauge from being damaged; before sticking, wipe the position of the patch with a wiper moistened with acetone to ensure that the patch area is clean and tidy and free of dust. If the bond between the patch and the test piece is not good, use 5000 series sandpaper to gently rub, wipe with acetone and then paste it. At the same time, try to ensure the verticality of the strain gauge; when attaching the strain gauge, take out the strain gauge and hold the strain gauge Lead wire (be careful not to touch the strain gauge), put a drop of glue on the back of the strain gauge Lead wire, put the strain gauge on the drawing line, find the verticality, and squeeze the excess glue from left to right. Make the strain gauge and the test piece perfect bonding [21].
According to the result of finite element analysis of the experiment product, the deformation form of the experiment product is predicted, the dangerous section and position are found out, combining with practical experience, the key inspection position is finally determined, in order to work out the plan of the experiment product, the gage is numbered in combination with the channel sequence of the gage, as shown in figure 7.

Figure 7. The map of the positions of resistive strain gauge.

It should be noted that it takes a long time to paste the strain gauges, and it is necessary to debug whether each strain gauge is working properly after the pasting, especially the static test piece, which requires a lot of strain gauges, too many channels, dense wires, and difficulty in patching. It is very large, so each time a strain gauge is pasted, the wire must be fixed to prevent winding, and at the same time, be careful of the patch series, as shown in figure 8.

Figure 8. Location and theoretical number of the experiment product.
Using Model BX120-3AA, resistance 120, non-welding strain gauge, pasting at room temperature, the strain gauge must be firmly pasted on the tested point to ensure that the strain gauge and the tested object produce deformation together, as shown in figure 9.

When connecting the strain gauges, the wires of the strain gauges should be connected to the two binding posts AB according to the corresponding numbers (note that the numbers must be unified for subsequent test data processing), and the compensation plates should be connected at the same time. Because the resistance strain gauge is very sensitive to temperature changes. When the ambient temperature changes, because the linear expansion coefficient of the strain gauge is different from the linear expansion coefficient of the test piece, and the resistance value of the sensitive grid changes with temperature, the measured strain will include the effect of temperature change and cannot reflect actual strain of the test piece, therefore, must try to eliminate the influence of temperature change in the measurement.

![Figure 9. Strain gauge paste map.](image)

3.4. Axial compression test
First, connect the strain gauge. In this process, it is necessary to ensure that the theoretical number of the strain gauge is consistent with the number of the strain gauge to ensure the correctness of the test data processing.

At the same time, a compensation piece should be connected to the test piece before the test, because the resistance strain gauge used in the test is sensitive to the change of ambient temperature and humidity, the adverse effects of environmental changes on the test shall be eliminated by means of compensating plates of the same material as the test piece [22, 23].

Then, the specimen is fixed on the loading machine and preloaded with 50% buckling load, which is 33.4 kN axial compression load, to eliminate the initial torque and bending moment of the specimen. After debugging, load at the rate of 100 N/s, and destroy it.
When the load is 64.2 kN, local buckling of the skin takes place, and when the load is 177.1 kN, the specimen is completely destroyed, and the final failure form is as shown in figure 10, which fits the profile [24, 25].

4. Comparison of analysis results
According to the test loading data, the load-displacement curve is drawn, as shown in figure 11. The buckling load is 64.2 kN and the failure load is 177.1 kN.

![Figure 11. Test analysis-load-displacement curve.](image)
It can be clearly seen from table 3 that the error of buckling load and failure load calculated by finite element analysis is very small, which is in good agreement with the test value, that is, the finite element analysis method can truly reflect the stability of composite stiffened panel structure.

|                      | Post Buckling Analysis | Test Analysis | Error |
|----------------------|------------------------|---------------|-------|
| Buckling load (kN)   | 66.8                   | 64.2          | 4.0%  |
| Failure load (kN)    | 187.6                  | 177.1         | 5.9%  |

5. Conclusion
The general procedure, points for attention and relevant test standards for the study of the stability of composite stiffened panel structures under axial compression are summarized by using finite element method and test analysis method, in particular, the making, preparation, testing, mounting, loading test and data processing of the test pieces have an important role in guiding the study of related issues.

Comparing the results of finite element analysis and test analysis, the feasibility of Patran/Nastran finite element analysis software and correlation analysis method is proved. At the same time, the failure load of the two analysis methods is about 3 times of the buckling load, which shows that the composite stiffened panel structure still has a great potential. Considering the post-buckling load-carrying capacity in the design of composite structures will give full play to its light weight, high specific strength and high stiffness, which is of great practical significance to promote the use of composite structures.

Acknowledgments
The work was supported by the National Natural Science Foundation of China (Grant Nos. 51675350), and thanks to AVIC SAC Commercial Aircraft Co. Ltd for their supports in the manufacture of specimens and NDT inspection.

References
[1] Anandan A, Dhaliwal G, Huo Z, Chandrashekhar K, Apetre N and Iyyer N 2018 Applied Composite Materials 25 1155
[2] Maciej T, Ryszard B and Michal K 2017 Composites Part B: Engineering 109 238
[3] Konstantinos N and Nicholas G 2012 Applied Composite Materials 19 219
[4] Yang Z, Zhang J, Xie Y, Zhang B, Sun B and Guo H 2017 Applied Composite Materials 24, 1447
[5] Jia L 2017 Aeronautical Manufacturing Technology 15 102
[6] Chen W 2017 Large aircraft 10 14
[7] Jeevan K, Ramesh B and Ratnakar P 2014 Applied Composite Materials 21 259
[8] Qiao J and Brian H 2015 Composites Part B 69 13
[9] Chen N and Guedes S 2007 Reinf Plast Compos 26 1021
[10] Fernass D and Mircea C 2010 International Journal of Structural Stability and Dynamics 10 905
[11] Tang J 2013 Spacecraft Environment Engineering 30 352
[12] Huo S, Wang F and Wang P 2010 Chinese Journal of Applied Mechanics 27 423
[13] Wang F, Cui D and Xiong Q 2013 Journal of Beijing University of Aeronautics and Astronautics 39 494
[14] Xun W and Jonathan D 2018 Composites Part A 111 62
[15] Fuller J and Wisnom M 2015 Composites Science and Technology 112 8
[16] Liu C, Yue Z and Geng X 2015 *Journal of Experimental Mechanics* **30** 757
[17] Shen H 2002 *Post buckling Behavior of Plates and Shells* (Shanghai: Shanghai Scientific & Technical Publishers)
[18] Shen G and Hu G 2006 *Mechanics of Composite Materials* (Beijing: Tsinghua University Press),
[19] Orifici A, Thomson R and Degenhardt R 2008 *Composite Structure* **82** 217
[20] Wang H, Chen H and Lei A 2018 *Acta Materiae Composite Sinica* **35** 2014
[21] Kong B, Ye Q and Chen P 2010 *Acta Materiae Composite Sinica* **27** 150
[22] Bisagni C and Davila C G 2014 *Composite Structure* **108** 493
[23] Orifici A C, Thomson R and Degenhardt R 2009 *Journal of Composite Materials* **43** 3239
[24] Li L, Li S and Chang F 2016 *J. of Nanjing University of Aeronautics & Astronautics* **48** 563
[25] Tifkitsis K, Mesogitis T, Struzziero G and Skordos A 2018 *Composites Part A* **112** 383