Numerical Model and Simulation Analysis of Composite Stringer Docking Structures

Jingchao Wei*, Gang Wang, Su Cao and Xiangming Chen

Aeronautics Science and Technology Key Laboratory of Full Scale Aircraft Structure and Fatigue, Aircraft Strength Research Institute of China, Xi’an 710065, China

*Corresponding author

Abstract. Due to the manufacturing restrictions or design requirements, composite structures are usually connected in the form of butt joint near the wing rib or fuselage frame to solve the problem of discontinuity of load transfer. In this paper, the finite element model of butt joint structure is established by simulating the engineering model of metal fasteners and common joint connected by beam element under the action of in-plane load, and the mechanical simulation analysis of typical butt joint configuration is carried out. In the engineering model, the allowable stress value is used to predict the failure of composite material and the classical strength theory is used to predict the fracture failure of metal fasteners. The result show that the strength prediction obtained by the engineering model is in good agreement with the test results, and the application of this method can improve the calculation efficiency of connection strength with complicated multi-fastened composite structures.

Keywords: numerical model; simulation analysis; strength prediction; composite structure.

1. Introduction

Composite structure has been widely used in a variety of main/secondary load bearing structures of aircraft, and composite stringer due to manufacturing, transportation, cost and other considerations or restrictions, usually adopts the segmented design and docking mode. The connection of multiple parts is mainly realized through mechanical fasteners, whose connection strength directly affects flight safety and aircraft service life. Due to the importance of connection design, a large number of scholars have conducted extensive research on the connection strength of composite laminates. The three-dimensional cumulative damage calculation can vividly and objectively reflect the damage generation and evolution process at the connection, which is the current mainstream computational simulation method. Xiao et al. established a two-dimensional damage accumulation model based on the nonlinear shear theory of composite materials and Hashin, yamada-sun failure criterion. The nonlinear material term and the degradation mode of the failure layering were included in the stress analysis of the model, and the finite deformation and the contact boundary conditions of the nail holes were considered. Wei et al. used three-dimensional solid element model to simulate the single bolt loading and structural progressive failure process through friction contact between bolt and hole. Due to the structural characteristics of composite laminates, it is necessary to use nonlinear finite element method to calculate the damage and extension repeatedly, which makes the calculation of the connection strength large scale and long time. For large-scale composite structures, a simple and fast finite element analysis method is needed. Based on the beam element joint method, this paper establishes an engineering model of the connection structure, which can quickly judge the weak links and failure locations of the structure and better predict the failure strength of the structure.
2. Composite Structure Design and Finite Element Model

2.1. Configuration of Composite Structure
The composite stringer docking structure refers to the butt-joint area of stringer near the wing root of the aircraft structure. The test specimens are designed symmetrically without considering the influence of the back Angle on the outer wing. In order to avoid the early failure of the test pieces in the loading area, the stringer flange is widened in the clamping area. In the test pieces, the actual structure of the cross joint is simplified into a t-joint, and the web of the t-joint is perpendicular to the edge strip. Both sides of the stringer are connected by two diagonal boxes and horizontal cross joint, and the web of the stringer is obliquely cutting in the root; The corner boxes is connected with two tensile bolts, and the corner box is not connected with the web. There are four rows of nails along the span. The first three rows of nails connect the corner box, reinforced siding and horizontal cross joint, while the fourth row of nails only connect the reinforced siding and horizontal cross joint.

2.2. Material Property
The test pieces are made of carbon fiber reinforced epoxy resin based prepreg (as shown in Table 1), and the stringer and the skin are made of co-bonded technology. Corner box and cross joint material is titanium alloy Ti-6Al-4V, after forging and forming and rib material is aluminum alloy 7050.

| Property          | Value 1 | Value 2 | Value 3 | Value 4 |
|-------------------|---------|---------|---------|---------|
| Longitudinal modulus $E_{11}$ / MPa | 178000  | 8260    | 5200    | 0.34    |

2.3. FE Model
Shell element is used to simulate the structure of skin, stringer, butt joint, corner box, cross joint and rib. For the girders and webs, the shell element nodes are not biased and located on the middle plane of the structure. For the flat plate connected with the stringer such as corner box, cross joint and trident joint, the shell element node is positioned on the outer surface close to the skin and the long truss, and the element is set with corresponding bias. For the vertical plates of rib webs, cross joints and trident joints, the shell element nodes are located on the middle plane of the structure, and the element is not biased. All fasteners are simulated with Beam element. In order to ensure equal displacement loading, generate a node outside the structure for loading, apply a 10kN tensile load to the point, and couple the node with the end node of the test piece with constraints of Coupling.

2.4. Results of Calculation

2.4.1. Distribution of Fastener Load. The fastener load is basically measured in the rib position. In order to describe the fastener Numbers on the side of the test piece, fasteners no. 1 to no. 16 endure
cutting load on the long girder strip, and fasteners no. 20 to no. 23 endure pulling load on the corner box joint, as shown in Figure 2.

![Figure 2. Schematic diagram of fastener number in the finite element model.](image)

It can be seen from the table 1 that the shear load distributed by fasteners no.6, no.7, no.14 and no.15 is relatively large, accounting for 9.21% and 6.92% of the total shear load respectively. The maximum single shear force is 525N, and the maximum double shear force is 921N. The ratio of tensile load transmitted through the cross joint and corner box is about 2.3 : 1.

Table 2. Shear load on fasteners.

| No. | Shear load between skin and cross joint / N | Shear load between stringer and angle box / N | Total shear load / N | Percentage |
|-----|-------------------------------------------|---------------------------------------------|---------------------|------------|
| 1   | 413                                       | /                                           | 413                 | 4.13%      |
| 2   | 428                                       | /                                           | 428                 | 4.28%      |
| 3   | 428                                       | /                                           | 428                 | 4.28%      |
| 4   | 413                                       | /                                           | 413                 | 4.13%      |
| 5   | 416                                       | 361                                         | 777                 | 7.77%      |
| 6   | 453                                       | 468                                         | 921                 | 9.21%      |
| 7   | 453                                       | 468                                         | 921                 | 9.21%      |
| 8   | 416                                       | 360                                         | 776                 | 7.76%      |
| 9   | 369                                       | 165                                         | 534                 | 5.34%      |
| 10  | 408                                       | 252                                         | 660                 | 6.60%      |
| 11  | 408                                       | 252                                         | 660                 | 6.60%      |
| 12  | 369                                       | 164                                         | 533                 | 5.33%      |
| 13  | 487                                       | 89                                          | 576                 | 5.76%      |
| 14  | 525                                       | 167                                         | 692                 | 6.92%      |
| 15  | 524                                       | 168                                         | 692                 | 6.92%      |
| 16  | 486                                       | 87                                          | 573                 | 5.73%      |
| Total | 6996                                    | 3001                                        | 9997                | 100.00%    |

2.4.2. Composite Strain. The x-direction strain of the composite material is mainly tensile strain, which is prone to stress concentration due to extrusion along the edge of hole. Therefore, when the strength are checked, the edge of the composite material hole adopt the design allowable values method of single/double shear stress, and the design allowable values of strain are checked at the
location away from the hole. The maximum stress value of the double shear hole edge is located near the hole of fastener No.6 and 7 on the edge strip, and the maximum stress value of the single shear hole edge is located near the hole of fastener No. 2 and no. 3 (as shown in Figure 3). The maximum strain value away from the edge of the hole is located at the straight section of the tensile necking root with a strain value of 47\(\mu\)ε. The maximum stress value of the double shear hole edge of the skin is located near the holes of fasteners No. 5 to No. 8 on the edge strip, and is 5.7MPa. The maximum stress value of the single shear hole edge is located near the holes of fasteners No. 1 to No. 4, and is 5.7MPa. The maximum strain value away from the edge of the hole is located at the straight section of the tensile necking root with a strain value of 49\(\mu\)ε.

![Figure 3.](C:\Users\asus\AppData\Local\Youdao\DictBeta\Application\7.1.0.0421\resultui\dict\stress of stringer)

![Figure 3.](C:\Users\asus\AppData\Local\Youdao\DictBeta\Application\7.1.0.0421\resultui\dict\stress of skin)

3. Strength Prediction

3.1. Strength of Composite Structures

The material strength of composite structure is checked by the structural main strain. The maximum tensile strain, compressive strain and shear strain of FE model are compared with tensile strain allowable value, compressive strain allowable value as well as shear strain allowable value of composite material, and the strength on the side of composite hole are checked by bearing stress and single/double shear strength. Strength margins are calculated by equations (1) - (5).

Tensile strength margin of composite materials:

\[ M.S. = \frac{\varepsilon}{\varepsilon_{\text{allow}}} - 1 \]  \hspace{1cm} (1)

Compression strength margin of composite materials:

\[ M.S. = \frac{\gamma}{\gamma_{\text{allow}}} - 1 \]  \hspace{1cm} (2)

Shear strength margin of composite materials:

\[ M.S. = \frac{\sigma_{\text{shear}}}{\sigma_{\text{allow}}} - 1 \]  \hspace{1cm} (3)

Single-lap bearing strength margin of composite materials:

\[ M.S. = \frac{\sigma_{\text{single}}}{{\sigma} - 1} \]  \hspace{1cm} (4)
3.2. Strength of Composite Structures

The tensile strength of fasteners is checked by the tensile load of bolts. The maximum bolt tension in the structure is compared with the tensile stress allowable value of bolts, and the strength margin is calculated according to equation (5). The shear strength of fasteners was checked by the shear load of bolts. The maximum single shear force of bolts in the structure was compared with the single shear allowable value of bolts, and the strength margin was calculated according to equation (6).

\[ M.S. = \frac{F}{F_{\text{allow}}} - 1 \]  
\[ M.S. = \frac{Q}{Q_{\text{allow}}} - 1 \]

3.3. Structural Failure Mode

The strength margins of composite structures are obtained through finite element analysis and strength check, and the failure mode of the structure is estimated. Among them, the composites mainly consider the tensile/compression strength margin and pin-hole bearing strength margin, while the bolts mainly consider the tensile strength margin and shear strength margin, which serve as a reference for the prediction of structural failure mode. By comparing the above strength margin values, the tensile strength margin of bolts is the minimum (M.S. = 2.05).

It can be seen that the possible failure mode is tensile failure of No.21 and No.22 bolts, with the initial failure load of about 726kN, and the failure load of about 1088kN if the failure is estimated to be 1.5 times the allowable value of the design.

4. Conclusion

In this paper, the finite element analysis and strength prediction of composite stringer docking structure are carried out. According to the structural characteristics, loading and clamping mode, an engineering finite element model is established, and the stress, strain and bolt load distribution of the structure are obtained through linear static analysis. The margin analysis of the material strength, bolt tensile strength and bolt shear strength of the composite stringer butt-joint test pieces is carried out, and the strength margin of each part of the structure is obtained, and the failure load and possible failure mode of the structure are estimated by linear extrapolation. Although this article is based on linear analysis, the material design allowable values as a benchmark are adopted in the analysis, rather than material real strength value, structure progressive failure process cannot be simulated. However, the application of engineering experience and simplified model can predict the failure position and failure load of structure well and quickly, and greatly improve the efficiency of connection calculation in engineering applications.

References

[1] Aviation research institute of China 2004 Handbook of Composite Structure Design (Beijing: Aviation industry)
[2] Xie M J 2011 Composite material connection (Shanghai: Shanghai jiao tong university)
[3] Sun HT, Qing X, Chang F-K. The response of composite joints with bolt-clamping loads, part II: model verification. J Composite Material 2002; 36(1): 69-91.
[4] Binnur Goren Kiral. Effect of the clearance and interference fit on failure of the pin-loaded composites. Materials and Design 2010; 31: 85-93.
[5] Irisarri F -X, Laurin F, Carrere N, Marie J -F. Progressive damage and failure of mechanically fastened joints in CFRP laminates - Part I: Refined Finite Element modeling of single-fastener joints. Composite Structures 2012; 94: 2269-2277.
[6] Yi Xiao, Takashi Ishikawa. Bearing strength and failure behavior of bolted composite joints (Part II: modeling and simulation). Composites Science and Technology 2005; 65: 1032-1043.
[7] Wei JC, Jiao GQ, Liu FL, Yan ZM. Bearing strength of composite joints interference-fitted with blind bolts. Acta Aeronautica et Astronautica Sinica 2013; 34: 1627-1635.