Parametric Analysis on Three-Points Bending Test of Typical Skin-Stringer Structure

Zhe WANG 1*, Xiangming CHEN 1, Peng ZOU 1, Xinxiang Li 1, Qingxianglong LIANG 1, Junchao YANG 1

1 Aircraft Strength Research Institute of China, Xi’an 710065, China
E-mail: 798367673@qq.com

Abstract: Stringer-skin debonding was one of the most important failure models in stiffened composite panels. In this paper, three-points bending tests were performed on representative stringer-skin structure of composite wing to simulate the flange-skin interface behavior and to obtain the failure mode and failure load. A 3D finite element model was built by using ABAQUS software to simulate interface failure with cohesive zone model. The numerical results agree well with test data, which validate the rationality of the finite element model. Hence the influence of factors during manufacture、installation and test in three-points bending tests, such as off-axis displacement、inclination loading and span, is studied. Results show that the initial debonding load and failure load of specimen decrease as the displacement from loading axis to central axis increases. The load of specimen decreases as the span increases. The influence of inclination loading is insignificant when the inclination angle is less than 6 degree. However, the initial debonding load and failure load of specimen decreases in varying degrees as the inclination loads increases. Furthermore, the initial debonding load decreases rapidly.

1. Introduction
Composite materials have been widely used in the aircraft and aerospace fields due to their low weight, low cost, good designability, and manufacturability. As a typical structure of aircraft structure, the detailed design of stiffened composite panel plays a positive role in reducing the structure weight and improving the structure bearing capacity [1]. Debonding between stringer and skin is one of the main failure modes of stiffened composite panels. In engineering application, it is found that when the stiffened panel with thin skin is subjected to axial compression [4-6], shear [7-9] and combined loads, buckling first occurs in the skin. With the increase of load, the buckling deformation increases, and even the wave phenomenon appears. When the deformation reaches a certain degree, the edge of stringer flange and the interface of skinned panel begin to debond [10-13], and the panel gradually damaged with the further expansion of interface degumming. A.Riccio et al. [14-15] focused on the effects of a single reinforcement seam of stitches along the edge of a stringer foot in a stiffened composite panel, and analyzed the influence of skin thickness, the stitching technique, the pitch and the yarn diameter based on three points bending test . Carlos et al. [16] studied bearing capacity and failure mode of skin and stringer flange typical structure in three-point bending test, but did not consider the influence of other parameters in the installation and test. M.Giglio et al. [17] Studied on an experimental–numerical methodology of three point bending test on sandwich panels with Al skins and Nomex™ Honeycomb core, and the influence of various parameters such as friction and relative position of the puncher has also been evaluated. In order to avoid premature debonding failure between skin and stringer effectively,
the research on the debonding between skin and stringer has become a difficult problem in the postbuckling design of stiffened composite panels.

In this paper, postbuckling failure mechanism between skin and stringer of stiffened composite panels was studied by three-points bending tests. The influence factors during manufacture, installation and test in tests, such as displacement from loading axis to central axis, inclination loading and span were studied based on the numerical verification.

2. Test overview

2.1. Specimen and test method

The specimen were selected from the typical skin-stringer sections of upper and lower panels of composite wing, and the structure is shown in Fig.1. The material of specimen is X850. The thickness of a monolayer is 0.191 mm. The co-bonding process is adopted between the skin and stringer and the material of the adhesive film is CMS-AD-105.

The length of the specimen is 275 mm and the width of the specimen is 70 mm. The width of the stringer flange is 90 mm. The thickness of the stringer flange is 5.921 mm, and the lay-ups is \([\pm 45/0/90/0/\pm 45/0/\pm 45/0/\pm 45/0/90/0/\pm 45/0\]s. The thickness of skin is 8.404 mm, and the lay-ups is \([\pm 45/0/90/0/\pm 45/0/\pm 45/0/\pm 45/0/\pm 45/0/\pm 45/0/\pm 45/0/\pm 45/0\]s. The dimension information is given in Fig 2.

The experiments were conducted in Aircraft Strength Research Institute of China. The loading method is shown in Fig.3. The distance between the support sticks and the edge of the specimen is 30mm. The boundary condition of the specimen is simply supported and the displacement load is applied on the middle of skin. The loading speed was set at 2mm/min. Strain measurement and displacement measurement were carried out in the test. The general configuration of the strain gauges is shown in Fig. 4.
2.2. Test results
The test results are shown in Table 1. Fig.5 shows the typical failure mode of the specimen. Debonding occurs at the edge of the interface between the skin and stringer.

Table 1. The test results of specimen

| Specimen number | Failure loads/kN | Displacement/ mm | Strain/µε |
|-----------------|------------------|------------------|-----------|
| S01             | 3.749            | 2.797            | -3426 (gauge 101) |
| S02             | 3.541            | 2.629            | -2646 (gauge 101) |
| S03             | 3.734            | 2.596            | -3249 (gauge 101) |
| S04             | 3.543            | 2.451            | -3085 (gauge 101) |
| S05             | 3.438            | 2.402            | -3004 (gauge 101) |
| Average value   | 3.601            | 2.575            |           |
| Coefficient of variation | 3.75%        | 6.08%            |           |

Fig.5 The failure mode of specimen (debonding of skin and stringer)

3. Numerical results

3.1. Failure criterion
The cohesive zone model is used in the skin and stringer. The cohesive zone model is based on the continuously damage mechanism of the traction-displacement relationship between the connected elastomers. Bilinear Constitutive Equation is widely used in engineering field:

\[
\begin{bmatrix}
    t_n \\
    t_s \\
    t_t
\end{bmatrix} =
\begin{bmatrix}
    K_{nn} & \delta_n \\
    K_{ss} & \delta_s \\
    K_{tt} & \delta_t
\end{bmatrix}
\begin{bmatrix}
    \delta_n \\
    \delta_s \\
    \delta_t
\end{bmatrix}
\]  
(1)
Where, $n_t$ represents the normal nominal stress, $t_i$ and $t_j$ represent two different tangential nominal stress, $K_{nn}$, $K_{ss}$ and $K_{tt}$ represent stiffness coefficient corresponded with the direction respectively, according to the method refers to the reference[18], $K_{nn} = K_{ss} = K_{tt} = 10^6 \text{ N/mm}^2$. $\delta_n$ represents the normal nominal interface stress, $\delta_s$ and $\delta_t$ represent two different tangential nominal interface stress.

In order to simulate the initiation of interface damage accurately under complex stress, the quadratic nominal stress criterion is adopted in this paper

$$d = \left[\frac{t_n}{\delta_n}\right]^2 + \left[\frac{t_s}{\delta_s}\right]^2 + \left[\frac{t_t}{\delta_t}\right]^2 \begin{cases} d < 1 & \text{Non-failure} \\ d = 1, \text{failure} & \end{cases}$$

(2)

Where, $d$ represents the interface failure coefficient, when $d$ equals to one, the interface reaches failure. $t_n^0$ represents interface tensile strength, $t_s^0$ and $t_t^0$ represent interface shear strength.

The mixed failure mode was adopted in damage evolution of cohesive element

$$D = \left[\frac{G_{IC}}{G_{IC}}\right]^\alpha + \left[\frac{G_{II}}{G_{IC}}\right]^\alpha + \left[\frac{G_{III}}{G_{IC}}\right]^\alpha \begin{cases} D < 1 & \text{damage} \\ D = 1, \text{failure} & \end{cases}$$

(3)

Where, $\alpha$ represents material parameters, $\alpha$ ranges from 1 to 2. $D$ represents damage variable, $D$ ranges from 0 to 1, which characterizes the damage degree. When $D = 1$, the interface is damage completely. $G_{IC}$, $G_{II}$, $G_{III}$ represent strain energy release rate under three different modes respectively.

The three dimensional constitutive relation considering the initial damage and damage evolution of cohesive zone model is shown in Fig. 6.

![Fig.6 Bilinear mixed-mode softening law](image)

### 3.2. Numerical model

The finite element model is shown in Fig.7. The element type of skin and stringer is SC8R, and the interface element type is COH3D8. The interface is tied to the skin and stringer. The boundary of the finite element was given in Fig.7. The material properties of X850 composite and interface material are shown in Table 2 and Table 3.
Fig. 7 Finite element model and boundary conditions

Table 2 The material properties of X850

| Properties | Value  |
|------------|--------|
| $E_1$      | 180GPa |
| $E_2$      | 9.14GPa|
| $\nu_{12}$ | 0.33   |
| $G_{12}$   | 4.57GPa|
| $G_{23}$   | 1.5GPa |

Table 3 The material properties of CMS-AD-105

| Properties | Value  |
|------------|--------|
| $N$        | 10MPa  |
| $S$        | 20MPa  |
| $T$        | 20MPa  |
| $G_{IC}$   | 0.5N·mm$^{-1}$ |
| $G_{II}$   | 3.5N·mm$^{-1}$ |
| $G_{III}$  | 3.5N·mm$^{-1}$ |

3.3. Finite element analysis

Comparisons of the load-displacement curves obtained from FEM and the tests are illustrated in Fig. 8. Comparisons of the load-strain curves obtained from FEM and the tests are illustrated in Fig. 9. Table 4 shows the relative error between FEM results and the test results. It is obvious that FEM results agreed well with the test curves, which shows that the numerical analysis method is reasonable and effective. The strain on flange first falls down, which is due to the change of the transmission path caused by debonding of skin and stringer flange. Therefore, the flange no longer bears.

Fig. 8 Load-displacement curve between FEM and test
Fig. 9 Load-strain curve between FEM and test
Table 4: Comparisons between FEM and test

|                          | Average values of test | FEM results | Error (%) |
|--------------------------|------------------------|-------------|-----------|
| Failure load/kN          | 3.601                  | 3.628       | 1%        |
| Displacement/mm          | 2.575                  | 2.636       | 2%        |
| Strain of Gauge 101/με   | -3203                  | -3209       | 0%        |
| Strain of Gauge 102/με   | -3146                  | -3209       | 2%        |
| Strain of Gauge 201/με   | 2158                   | 2322        | 7%        |
| Strain of Gauge 202/με   | 1522                   | 1514        | 1%        |
| Strain of Gauge 203/με   | 1493                   | 1512        | 1%        |
| Strain of Gauge 204/με   | 1509                   | 1520        | 1%        |
| Strain of Gauge 205/με   | 1490                   | 1512        | 1%        |
| Strain of Gauge 206/με   | 2142                   | 2323        | 8%        |

The failure mechanism of the interface between skin and stringer simulated by the FEM is shown in Fig. 10. SDEG was characterized as the degradation degree of the interface stiffness of the cohesive layer. SDEG equals to zero means that the interface is intact, SDEG equals to one means that the interface has been completely destroyed. The initial debonding failure occurs at the outside of the stringer flange, and the interface failure gradually expands inward when loads increase. Debonding occurs at both sides separately during the test, which may be due to the fact that the co-bonding process between the skin and stringer flange cannot guarantee completely homogeneous or the rods cannot guarantee completely symmetry.

![Fig. 10 Debonding of interface under maximum load](image)

4. Parametric Analysis

4.1. The influence of support spans

The influence analysis of different support spans was obtained in Fig. 11. It can be seen from the curve that the initial debonding load and failure load decrease with the increase of support span. The initial debonding load decreases by 6.73% and the failure load decreases by 6.65% when the supporting rods on both sides move to the outside edge by 5 mm at the same time.
4.2. The influence of off-axis loading
Off-axis loading refers to the test error caused by the fact that the position of the indenter is not at the middle of the specimen. The influence analysis of different off-axis distances was obtained in Fig.12. It can be seen that the initial debonding load and failure load of the specimen decrease with the increase of off-axis distance. The initial debonding load and the failure load decrease by 3.58% and 4.33% respectively when the off-axis distance is 5 mm.

4.3. The influence of inclination loading
The influence analysis of different inclination loading angle was obtained in Fig.13. The influence of inclination loading is insignificant when the inclination angle is less than 6 degree. However, the initial debonding load and failure load of specimen decrease in varying degrees as the inclination loads increases. Furthermore, the initial debonding load decreases rapidly.
5. Conclusion
Postbuckling failure mechanism between skin and stringer of stiffened composite panels was studied by three-points bending tests in this paper. The influence factors during manufacture, installation and test in tests, such as displacement from loading axis to central axis, inclination loading and span were studied based on the numerical verification. Main conclusions are as follows,

1) The influence analysis of different incline loading angle was obtained in Fig.13. The influence of inclination loading is insignificant when the inclination angle is less than 6 degree. However, the initial debonding load and failure load of specimen decreases in varying degrees as the inclination loads increases. Furthermore, the initial debonding load decreases rapidly.

2) The initial debonding load and failure load decrease with the increase of the off-axis distance.

3) The initial debonding load and failure load decrease with the increase of the support spans.

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