Interface damage analysis of composite hat-stiffened panels

Tao Wang, Ruixiang Bai*, Changlong Wei, Xiaodi Huang, Heshan Bai

State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China

*E-mail: bairx@dlut.edu.cn

Abstract. In order to reveal the mechanism of interfacial debonding damage of composite hat-stiffened panel, an eight-point bending model of single stiffened structure was designed. The finite element analysis was carried out by using the cohesive element to simulate debonding damage of interface between skin and rib. The deformation, interface stress and structural damage of the eight-point bending as well as the corresponding stiffened panel under axial compression were analyzed. The results showed that the initial debonding deformation was in good agreement with the interface stress distribution. For the eight-point bending model, although more damage appeared near the loading point due to stress concentration, it had little effect on the accurate prediction of interface damage behavior. The eight-point bending model can be used to evaluate the interface performance of corresponding multi-stiffened-panel during axial compression buckling by accurate simulation and parameter design, and it is helpful for the stiffness matching design of skin and stiffener.

1. Introduction

Composite stiffened panel is a kind of structure with high efficiency which is often used in aircraft structure, and it has considerable post buckling potential. When the panel is in the post buckling state, the local deformation of the stiffener and the skin can produce a large peeling force at the interface, which causes the debonding damage between the stiff and the skin [1-2]. Especially when the stiffened structure is subjected to a bending load, the load after skin buckling is transferred to the stiffeners, which makes the flange bear out of plane bending load, which easily causes debonding damage between the stiffeners and the skin, and will significantly reduce the bearing capacity of the panel.

Bertolini [3] and others studied the debonding behaviour of stiffeners and skin in hat stiffened structure under local buckling and global buckling by means of longitudinal three-point bending test and transverse four-point bending test of composite hat stiffened panel. The results showed that the debonding area of hat stiffeners changes according to structural parameters and load conditions. Koundouros M [4] studied the failure mode of stiffener skin interface of composite stiffened panels under axial compression, and pointed out three possible failure locations, among which the failure at the edge of the stiffener at the joint line and anti-joint line is the main one. Rijin J [5-7] and others designed a seven-point bending test to study the failure mechanism of stiffener skin interface in the post buckling stage, but it can not truly reflect the deformation of the joint line and anti-joint line in the post buckling stage.

Both the three and four-point bending test can be used to characterize the interface, but it is difficult to correspond with the post buckling deformation mode of multi-stiffened-panel. In this paper, based on the displacement of composite hat-stiffened panel under axial pressure, the eight-point
bending model of single stiffened panel was designed according to the wave peak and valley position. The corresponding relationship between the model and the post buckling deformation of multi-stiffened-panel was analysed. The results showed that the interface stress of the eight-point bending model in initial debonding of interface was in good agreement with that of multi-reinforced-panel. It is a feasible new way to evaluate the interface performance and the stiffness matching design of skin and stiffener of multi-stiffened-panel by single stiffener eight-point bending test.

2. Analysis method

2.1. Model description

Considering a typical composite hat-stiffened panel, the structural dimensions are shown in figure 1, and the unit of length in the figure is mm. The mechanical properties of the composite are shown in table 1, including elastic parameters and strength parameters. The stacking sequence of the skin and stiffeners is shown in table 2, and the nominal thickness of the single layer is 0.185mm. The x-axis is the longitudinal direction of the stiffener, and the z-axis is the out of plane direction of the skin and the stiffener.

![Figure 1. Structural dimensions of hat panels](image)

| Table 1. Material parameters |
|-----------------------------|
| E₁ (GPa) | E₂ (GPa) | G₁₂ (GPa) | G₂₃ (GPa) | V₁₂ | V₂₃ | V₃₄ | X₁ | X₂ | X₃ | Y₁ | Y₂ | Y₃ | S  |
|----------|----------|-----------|-----------|-----|-----|-----|----|----|----|----|----|----|----|----|
| 154      | 8.5      | 4.2       | 0.35      | 2610| 1450| 55  | 285| 105|

| Table 2. Lay-up information of specimen |
|----------------------------------------|
| Lay-up for skin                        |
| [45/-45/-45/90/45/0]                   |
| Lay-up for stiff                       |
| [45/0/0/-45/90/-45/0/0/45]             |

2.2. Cohesive theory

In present study, cohesive contact based on the tracing separation criterion was used to simulate the debonding process of the skin-stiffener interface.

\[
\left( \frac{t_0}{t_0^0} \right)^2 + \left( \frac{t_1}{t_1^0} \right)^2 + \left( \frac{t_2}{t_2^0} \right)^2 = 1
\]  

The quadratic nominal stress criterion was selected as the damage initiation criterion of the interface shown in equation (1). \( t_0^0, t_1^0 \) and \( t_2^0 \) represent the limit values of normal stress, first shear stress and second shear stress, respectively. When the sum of square of nominal stress ratio in each direction is equal to 1, the interface damage occurs, and then the damage evolution stage begins.
The energy criterion was used in the damage evolution stage, as shown in equation (2). \( G_1, G_II \) and \( G_III \) are the strain energy release rates of opening, staggering and sliding failure modes respectively, and \( G^C_1, G^C_II \) and \( G^C_III \) are the corresponding critical values. When \( D \) is equal to 1, the material will fail completely.

The interface performance parameters are shown in table 3.

| Table 3. Interface performance parameters |
|-------------------------------------------|
| \( E_n \) (MPa) | \( E_s \) (MPa) | \( E_t \) (MPa) | \( t^0_n \) (MPa) | \( t^0_s \) (MPa) | \( t^0_t \) (MPa) | \( G^C_n \) N/mm | \( G^C_s \) N/mm | \( G^C_t \) N/mm |
| 10000 | 1500 | 1500 | 10 | 15 | 15 | 3.34 | 1.165 | 1.165 |

2.3. Post-buckling analysis of multi-stiffened-panel under axial compression

Commercial finite element software ABAQUS was used to analyse the post-buckling deformation process of stiffened panels under axial compression. The reduced integral element for 8-node continuum shells (SC8R) was used to mesh the stiffeners and skin. The cohesive elements were applied to simulate the adhesive bonding between the stiffeners and skin. The nodes at both ends were coupled with the reference point, both the fixed boundary condition and the axial compressive displacement loading were applied at the corresponding reference point.

Figure 2 is the distribution of the out of plane displacement of the axial compression panel during the initial debonding. It can be found that the discontinuity of the lower flange causes local buckling of the skin in this area, which is more common in the hat-stiffened panels. Figure 3 is a partial enlarged view in figure 2, in which 1 #, 2 #, 3 #, 4 #, 7 # and 8 # are nodes, while 5 # and 6 # are anti-nodes.

2.4. Design of eight-point bending model for single stiffened panel

An eight-point bending test scheme was designed to simulate the local buckling mode of the skin during the post buckling deformation process for a multi-stiffened-panel. The distribution of wave crest and wave trough in post buckling is approximately simulated by setting the supported joint to limit its out of plane displacement and applying load at the opposite joint. The loading diagram is shown in figure 4, in which red points denote the support location, while blue point denotes the loading location. Specific location parameters of each point are shown in table 4.
Figure 4. The loading diagram of eight-point bending model

Figure 5. Finite element model of eight-point bending

Table 4. Specific location parameters of each point

| L   | H    | L₁ | L₂ | L₃ | L₄ |
|-----|------|----|----|----|----|
| 300mm | 210 mm | 120 mm | 60 mm | 48 mm | 210 mm |

The eight-point bending model of single reinforcement structure is shown in figure 5, and the unit of length is 2 mm x 2 mm. In order to ensure simultaneous loading, a reference point was set at the upper end of the hat top centre, and MPC constraint was established between the rigid body and the reference point. The support end keeps the out of plane displacement as zero.

3. Comparative analysis of deformation and interface stress of multi-stiffened-panel and single stiffened panel

It can be seen from figure 6 that the variation trend of out of plane displacement distribution of the eight-point bending model is similar to that of the axial compression panel. According to the time displacement curve of the two loading points, when the axial displacement \( U₁ \) reaches 4.5 mm, the interfacial damage occurs at the edge of the stiffener. When the displacement \( U₂ \) reaches 13.7 mm, the interfacial damage occurs at the edge of the stiffener, as shown in figure 7.

![Figure 6. distribution of out of plane displacement at initial damage](image)

It can be seen from figure 7 that the damage initiation positions of the axial compression panel and the eight-point bending model are the same, which are located at the intersection of the nodal line and the interface edge.
Figure 7. Comparison of initial damage at the interface

Figure 8 shows the interfacial stress along the left edge of the stiffeners at the initial debonding stage of the axial compression panel model and the eight-point bending model. It can be seen from the stress distribution curves that the interface stress distribution trend of the two model is basically the same. When the abscissa is about 0.3, the interface stresses are all small, indicating that the interface debonding has not occurred at this time. When the abscissa is about 0.7, $\sigma_{33}$ reaches the maximum value, and the shear stress at this time is very small, indicating that the interface debonding is mainly affected by the $\sigma_{33}$.

Figure 9 is the damage distribution of the structure under the initial debonding of the axial compression panel and the eight-point bending model. It can be seen that the axial compression panel has no damage at this time, indicating that the initial debonding of the interface occurs before the structural damage, while the eight-point bending model has some matrix tensile damage due to the stress concentration near the loading and supporting points. However, it can be seen from figure 8 that the damage of the eight-point bending structure does not affect the distribution of the interface stress during the initial debonding.
4. Conclusion

Through the comparative analysis of the integral axial compression panel and the eight-point bending, it was found that the deformation and stress distribution of the interface during the initial debonding were in a good agreement, which indicates that it is feasible to find the corresponding relationship between the interface stress and the interface damage based on the out of plane deformation. Due to the different loading methods of the two models, the stress concentration near the loading point lead to the damage of the eight-point bending model, but it did not lead to the failure of the structure. Meanwhile, the analysis also showed that the damage had little influence on the accurate prediction of interface debonding behavior. Therefore, the eight-point bending model can be used to evaluate the interfacial properties of the stiffened panel in the post-buckling process.

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