Analysis on failure mechanism of CFRP double-tap interference-fit joint

Peng Zou¹, Hao Chen and Xue Bi

Full Scale Aircraft Structural Static/Fatigue Laboratory, AVIC Aircraft Strength Research Institute of China, Xi'an 710065, Shaanxi, China

¹ Email: zoupeng_0625@126.com

Abstract. Composite interference-fit joints have attracted much attention because they can effectively reduce the stress concentration around the holes during loading. In this paper, the load-bearing mechanism and strength of a typical double-lap structure under static load are studied through experiment and finite element method. In order to eliminate the influence of bending moment and other factors, a special fixture was designed to study the damage failure mechanism of CFRP interference fit joint under pure tension. The finite element model of CFRP interference fit double lap structure considering both intralaminar and interlaminar damages was established with ABAQUS user subroutine and cohesive element. The damage propagation mechanism during loading process is revealed and the ultimate bearing strength is predicted by comparing the results of experiment and finite element model.

1. Introduction

Carbon fibre reinforced plastic (CFRP) is widely used in aerospace industry because of its high specific strength, specific stiffness and good fatigue resistance. Although its usage is increasing gradually and its function is also changing from non-bearing to main-bearing parts, limited to cost and technical requirements, there are still a large number of mechanical joint structures, especially bolt joint, which is widely used because of its strong bearing capacity. However, it is also found that the stress concentration is easily caused during the loading process, which has a negative impact on the bearing capacity of the structure.

In order to solve this problem, relevant researchers introduced the metal interference fit style into the composite ones to reduce local stress concentration and improve bearing capacity. Li j et al. [1] studied the interface damage behaviour of titanium alloy/CFRP and titanium alloy/titanium alloy under different interference during the installation of CFRP/Ti alloy interference joint. They pointed out that the wear particles produced by CFRP damage around the hole have a certain lubricating effect. Aiming at the phenomenon of hole wall delamination in interference installation process, Zou P et al[2] established a critical delamination force model based on type I delamination, and predicted the critical delamination interference percentage. In reference[3], they further considered a variety of damage modes, and systematically analysed the hole wall quality under the influence of different interference percentages. During loading process, Liu LQ et al. [4] comprehensively analysed the influence of interference and bolt preload on the bearing capacity of the structure. Zou P et al. [5] analysed and predicted the loading failure mechanism and bearing strength of double lap structure. Literature[6,7] have studied the fatigue performance of the interference fit structure, found that reasonable interference can effectively improve the fatigue life. The optimal interference range was recommended.
From the above research, it can be found the relevant research mainly focuses on the selection of optimal interference by considering the installation, static loading and fatigue processes. Focusing on the failure mechanism, the research is rare. In fact, the bearing mechanism of composite is complex due to anisotropy and weak interlaminar strength. In the loading process, with the increase of external load, its response shows obvious nonlinear behaviour. As the damage gradually extends from the local contact area to the whole extruded surface, and from single-layer plate to whole composite plate, the structure eventually fails. In this process, the coupling and influence among fibre, matrix and interface are always accompanied, which makes the prediction of damage and failure difficult. Delamination leads to structural flexural instability and accelerates structural failure, which causes a significant decrease in the strength of the structure, especially under compression load. In loading process, the large-area matrix collapse in the extruded area accelerates the expansion of delamination, and the combination of the two causes the failure of composite structure[1]. For the interference structure, although it can delay the initiation and expansion of the damage around the hole to a certain extent, with the increase of load, its damage and failure are inevitable and become more complex.

The ultimate purpose of the research is to predict the bearing strength and optimize the interference based on the understanding of the damage mechanism. Therefore, this paper studied the double lap interference joint structure through the combination of experiment and simulation method. In order to eliminate the influence of bending moment, a special fixture was designed to study the damage failure mechanism of the joint under pure tension. The finite element model considering both intralaminar and interlaminar damages was established with ABAQUS user subroutine and cohesive element. While exploring the damage mechanism, the research predicted the effects of interference fit percentage on the ultimate bearing capacity of the structure.

2. Experimental research

2.1. Specimen preparation

As shown in Figure 1, the test piece is mainly composed of four parts: CFRP plate, 45# steel main plate, 45# steel side plates and two Ti alloy bolts (1 and 2 respectively). Among them, the main and side plates as well as Ti alloy bolt 1 constitute the fixture. There are two 6.1mm diameter holes on each side plate, one of which is used to connect with the main plate to form the fixture, and the other hole is used to connect with composite piece. In order to avoid the contact between the test piece and the fixture at the beginning of the test, the thickness of the 45# steel main plate is designed to be 5mm, while the thickness of the test piece is 4mm. The CFRP plate is placed between the two side plates. Because the boundary conditions and loading conditions of the test piece in the structure are completely symmetrical with respect to the middle plane, the damage expansion of the composite interference fit structure under the pure tensile load can be fully studied through the structure. The detailed dimensions of the test piece are shown in Figure 1. The laying sequence of composite materials is [0/±45/90]3s. Single layer thickness is 0.25mm. Material properties are shown in Table 1. Material properties are shown in Table 1. Titanium alloy bolt material is Ti-6Al-4V, material properties are shown in Table 2.

2.2. Experimental process

The static tensile test was completed on MTS criterion® Series 60 c64.305 static universal hydraulic testing machine. The test process is shown in Figure 2a). One end of the test piece is clamped by the chuck of the testing machine, and the other end is connected with the fixture. By applying displacement load, the force change is recorded. As shown in Figure 2b) in the figure, the elastic deformation of the two side plates occurs to some extent, which is mainly caused by the expansion extrusion in the thickness direction of the failed CFRP plate. The interference of the test is set as 0%, 0.4%, 0.8% and 1.2%. Each group of parameters were repeated for three times, and the loading speed was 2mm/min.
Table 1. Property of T700/BA9916.

| Property | $E_1$(GPa) | $E_2$(GPa) | $E_3$(GPa) | $G_{12}$(GPa) | $G_{13}$(GPa) | $G_{23}$(GPa) | $v_{12}$ | $v_{13}$ | $v_{23}$ |
|----------|------------|------------|------------|---------------|---------------|---------------|-----------|-----------|-----------|
| Value    | 114        | 8.61       | 8.61       | 4.16          | 4.16          | 3             | 0.3       | 0.3       | 0.45      |

| Property | $X_t$(MPa) | $X_c$(MPa) | $Y_t$(MPa) | $Z_t$(MPa) | $Y_c$(MPa) | $Z_c$(MPa) | $S_{12}$(MPa) | $S_{13}$(MPa) | $S_{23}$(MPa) |
|----------|------------|------------|------------|------------|------------|------------|---------------|---------------|---------------|
| Value    | 2688       | 1458       | 69.5       | 55.5       | 236        | 175        | 136           | 136           | 95.6          |

Table 2. Property of bolt.

| Material       | Modulus(GPa) | Poisson’s ratio | Tensile strength(MPa) | Yield strength(MPa) |
|----------------|--------------|-----------------|-----------------------|---------------------|
| Ti-6Al-4V      | 112          | 0.29            | 931                   | 862                 |
| 45# steel      | 210          | 0.3             | 625                   | 381                 |

Figure 1. Configuration and size of double lap structure.

Figure 2. Experimental process: a) loading process, b) specimen.

Figure 3. Finite element model.

3. Simulation research

3.1. Finite element model

In order to simplify the model and reduce the calculation requirement, the steel plate fixture is omitted in the model. The final model is shown in Figure 3, which is mainly composed of two parts: composite plate and Ti alloy bolt. There are 4320 C3D8R elements in each layer of composite plate, so 16 layers are composed of 69120 ones. The cohesive elements are embedded between layers, and there are 15 layers of 64800 COH3D8 elements. In order to improve the calculation accuracy, mesh subdivision is carried out in the area around the hole. The property of the contact pair between bolt shank and hole is set to limiting slip, and contact relationship is set to normal hard contact and tangential valve contact. The tangential friction coefficient is set to 0.1. In addition, a general contact is also added to define the contact relationship among the delaminated plies. In the model, the bolt is fixed, and a reference point is added and coupling with the right face of the plate. A displacement load is applied to the reference point.
3.2. Constitutive relationships

3.2.1. Intralaminar progressive damage model. The structure is loaded in an obvious 3D stress state, so the failure process considers both the failure of fibre and matrix in three directions and the shear failure of the fibre matrix interface. In addition, once the damage occurs, the corresponding properties also degrades. Therefore, the selection of failure criteria and degradation rule is the key to model building. Therefore, the modified Hashin failure criterion considering nonlinear shear stress-strain behaviour of materials[8] is used to predict the structure failure, as shown in Table 3 below.

| Table 3. The modified Hashin criteria considering nonlinear shear relationship. |
|---------------------------------------------------------------|
| Failure mode | criteria |
|---------------------------------------------------------------|
| Fiber failure | $\epsilon_p^f = \left[ \frac{\sigma_1}{X} \right]^c (\sigma_1 \geq 0)$ |
| Fiber failure | $\epsilon_p^c = \left[ \frac{\sigma_1}{X} \right]^c (\sigma_1 \leq 0)$ |
| Fiber-matrix shear out failure | $\epsilon_p^{s+} = \left[ \frac{\sigma_1}{Y} \right]^c + \frac{2\tau_{12}^f}{G_{12}} + 3\sigma_1 \epsilon_{12}^f + \frac{2\tau_{13}^f}{G_{13}} + 3\sigma_1 \epsilon_{13}^f (\sigma_1 \geq 0)$ |
| Matrix tensile failure | $\epsilon_p^{m+} = \left[ \frac{\sigma_1}{Y} \right]^c + \frac{2\tau_{12}^m}{G_{12}} + 3\sigma_1 \epsilon_{12}^m + \frac{2\tau_{13}^m}{G_{13}} + 3\sigma_1 \epsilon_{13}^m (\sigma_1 \geq 0)$ |
| Matrix compression failure | $\epsilon_p^{mc} = \left[ \frac{\sigma_1}{Y} \right]^c + \frac{2\tau_{12}^m}{G_{12}} + 3\sigma_1 \epsilon_{12}^m + \frac{2\tau_{13}^m}{G_{13}} + 3\sigma_1 \epsilon_{13}^m (\sigma_1 \leq 0)$ |

With load increase, the material is damaged and the stiffness begins to degrade, which eventually leads to the decrease of bearing capacity. In this paper, the degradation criterion proposed by Olmedo A and Santiuza C[9] is adopted, as shown in Table 4 below.

| Table 4. Property degradation rules. |
|-------------------------------------|
| Failure mode | $E_1$ | $E_2$ | $E_3$ | $G_{12}$ | $G_{13}$ | $G_{23}$ | $V_{12}$ | $V_{13}$ | $V_{23}$ |
|---------------------------------------------------------------|
| Fibre tension failure ($\sigma_1 \geq 0$) | 0.14 | 0.4 | 0.4 | 0.25 | 0.25 | 0.2 | 0 | 0 | 0 |
| Fibre compression failure ($\sigma_1 \leq 0$) | 0.14 | 0.4 | 0.4 | 0.25 | 0.25 | 0.2 | 0 | 0 | 0 |
| Fibre-matrix shear out failure ($\sigma_1 \leq 0$) | 0.25 | 0.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| In-plane matrix tension failure ($\sigma_2 \geq 0$) | 0.4 | 0.4 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| In-plane matrix compression failure ($\sigma_2 \leq 0$) | 0.4 | 0.4 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| Out-plane matrix tension failure ($\sigma_3 \geq 0$) | 0.4 | 0.4 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| Out-plane matrix compression failure ($\sigma_3 \leq 0$) | 0.4 | 0.4 | 0.2 | 0 | 0 | 0 | 0 | 0 |

3.2.2. Interlaminar delamination model. Cohesive element method based on fracture mechanics is used to simulate delamination damage[10]. The bilinear traction separation constitutive model characterizing delamination is shown in Figure 4 below. In the loading process, the secondary nominal stress criterion is used to predict the initiation of mixed mode delamination. When the traction stress rate meets the following criteria, delamination begins to occur,

$$\left\{ \frac{t_1}{t_c} \right\}^2 + \left\{ \frac{t_2}{t_c} \right\}^2 + \left\{ \frac{t_3}{t_c} \right\}^2 = 1$$ (1)
The symbol is Macaulay bracket. The use of this symbol indicates that the compressive load does not cause delamination expansion, and the effect of the compressive load on the interface layer is ignored.

Once the delamination initiation is met, the delamination begins to expand between layers. The interface stiffness also degenerates according to the softening law. With the degradation of the stiffness, the delamination displacement further increases, and the delamination fracture energy further consumes until the visible delamination finally occurs. In this paper, energy law[11,12] is used to define mixed mode delamination failure, as shown in the following formula,

\[
\left[ \frac{G_{n}}{G_{n}^{*}} \right]^{\beta} + \left[ \frac{G_{s}}{G_{s}^{*}} \right]^{\beta} + \left[ \frac{G_{c}}{G_{c}^{*}} \right]^{\beta} = 1
\]

Where \(G_{n}, G_{s}\) and \(G_{c}\) are the instantaneous fracture energy in three directions, respectively. \(G_{n}^{*}, G_{s}^{*}\) and \(G_{c}^{*}\) are the critical fracture energy of normal and two tangential stratification under a single mode. \(\beta\) is an empirical parameter, which is used to characterize the coupling degree of three stratified modes. 1 is obtained here[12-15].

\[
\text{Figure 4. The cohesive double linear constitutive model.}
\]

4. Result discussion

4.1. Verification of the simulation model
Failure in the loading process can be regarded as a process of gradual accumulation of compressive damage, which can be divided into three stages: local damage initiation, damage propagation and structural failure. Although micro damage such as fibre micro buckling and matrix cracking may occur in the first stage, the effect of these damages on the load displacement curve is relatively small, and the curve is still linear. When the damage accumulates gradually, a slight load decrease happens and it
enters the second stage, the micro damage area further expands. The nonlinear behaviour appears in the load displacement curve, which occupies most of the time of the structural bearing process. When the structure reaches the maximum load and causes the ultimate structural failure, the bearing capacity declines. The load displacement curve can express these three stages and predict the final extrusion strength. Figure 5 shows the comparison results of finite element and experiment till final failure at 0.8% interference. The trend and result of finite element and experiment are consistent, the final extrusion strength is 12.961kN and 13.297kN respectively, and the relative error is 2.6%, which shows the reliability of finite element model.

4.2. Effect of interference fit percentage on load-displacement curve

The load displacement curve and final extrusion strength under different interference (0.0%, 0.4%, 0.8% and 1.2%) are shown in Figure 6. It can be seen from the figure that the stiffness degradation of 0.0% and 0.4% interference is relatively early, while that of 1.2% interference is the latest. The obvious fluctuation at 1.2% interference indicates that the damage is more complex during loading. Under 0.8% interference, the bearing strength of the structure reaches the maximum value, followed by 1.2% interference, and the bearing strength of 0.0% fit is the lowest. The final strength at 0.8% interference is about 1.24 times that of tight fit(0.0%). It can be seen from the above that, compared with the clearance fit, an appropriate interference has a certain strength gain capability.

4.3. Damages around the hole

4.3.1. Intralaminar damage analysis. The influence of different interference on the damage around the hole is shown in Figure 7. It can be seen from the figure that the main failure mode is in-plane matrix compression failure, while the fibre matrix shear failure and in-plane matrix tensile failure are also serious. This phenomenon is mainly caused by the poor module and strength of the matrix. The fibre compression failure is relatively serious at 0° ply, indicating the ply bears lots of load. No fibre tensile failure occurs. This shows that the fibre bears most of the load, the bearing capacity of the matrix is weak. The distribution of various damage forms is generally consistent under different interference percentages. From the scope, the damage of 0.0% and 1.2% interference is relatively serious, while that of 0.4% and 0.8% interference is relatively light, which is especially obvious in out of plane matrix tensile and compression failure. Comparing 0.0% interference and 1.2% interference, the damage of 0.0% is more concentrated and accumulates in a large range in the direction of extrusion. However, the 1.2% interference is more widely distributed. For in-plane matrix tensile failure, there is also a certain degree of damage in the opposite direction of the extruded area (marked
area in the figure), which is mainly because the larger interference has caused damage in the installation stage and it maintains or even further expands in the loading stage.

4.3.2. Delamination damage analysis. With the propagation of fibre, matrix and interface damage, delamination damage also occurs. Compared with intralaminar damage, delamination is more seriously affected by the thickness direction. According to the damage expansion of delamination around the hole shown in Figure 8, the damage degree of each layer in the figure is different. The closer the layer is to the surface of composite plate, the more serious the delamination is, while the internal layer delamination is relatively less. It can be seen that in the case of lack of lateral restraint caused by bolt preload, the delamination damage around the hole occurs and expands rapidly in the area near the surface. In addition, it can be seen from the figure that the damage in and between layers reaches a relatively large range at this time, but a significant difference from the damage in Figure 7 is that the direction of each layer has no inevitable one-to-one correspondence with the direction of the upper and lower layers because the cohesive element is an independent layer between layers. Delamination mainly occurs in the range of ± 45 degrees in the direction of loading, which is also the main area of extrusion when the tensile strength is reached.

![Figure 7. Effect of interference fit percentage on intralaminar damage.](image)

![Figure 8. Delamination around the hole.](image)

The comparison of delamination damage under different interference fit percentages is shown in Figure 9 below. The deleted area in the figure indicates delamination, while the visible red area indicates delamination initiation criteria has been reached, but delamination has not yet occurred. It can be seen from the figure that the distribution area of delamination damage is basically the same, and the distribution range is also basically the same, although the 0.0% interference and 0.4% interference are relatively large, but the difference is very small. This is mainly because when the load...
is large enough, the deformation of the composite hole under load and the difference of contact state between the pin holes under different interference amount become smaller. When the delamination damage expands in a large range, it is difficult to see the obvious difference.

Figure 9. Effect of interference fit percentage on interlaminar delamination.

The sectional view of delamination expansion is shown in Figure 10, from which it can be seen that the composite delamination in the extruded area gradually occurs and expands during the tensile process. Delamination first occurs in the area close to the surface, as shown in figure a and b. With load increasing, delamination expands along the loading radial direction. Deflection caused by delamination happens and increases (c and d in the figure), and layers squeeze each other affecting deflection deformation. When load is large enough, the whole squeezed area suffers from local deflection instability, resulting in contact or separation areas larger (e, f in the figure). It can be seen that delamination is easy to occur without lateral restraint. Coupled with local deflection, it further aggravate the occurrence of intralaminar damage in the layer. In addition, it should be noted that when damage occurs in the middle layer of the model, elements will not be deleted, so the delamination can be easily seen. Practically, matrix in the layer can easily separate from the plate and be squeezed into the interlayer delamination area after being damaged, thus affecting the observation of delamination.

Figure 10. Delamination propagation in the extruded area around the hole.

4.4. Experimental result analysis
The cutting section of the test piece is shown in Figure 11. The delamination position is basically consistent with the simulation result. There are a large number of delamination on the upper and lower surfaces. A certain degree of matrix cracking can be found at the front of delamination, indicating delamination expansion is closely related to matrix damage, and the two promote each other. In addition, there are a lot of matrix cracking in the contact area, which results in fibre precipitation and extrusion. Matrix and fibres are squeezed into the interlaminar region, which not only leads to delamination, but also expands and bulges along the thickness direction intensifying damage coupling. In the practical loading process, crushed matrix not only is squeezed into the delamination interface, but also gathers around the hole wall. They are squeezed by the bolt, changing the contact property between bolt and hole. These factors cannot be considered in the finite element.
5. Conclusion

In this paper, the static load tensile test and finite element study of the interference fit of CFRP in double lap structure are carried out. The influence of the interference on damage expansion and strength of the structure is analysed. The main conclusions are as follows:

1) For the double lap structure, the stress around the hole is redistributed during the loading process, and the in-plane damage in the loading area is mainly matrix compression damage, whose distribution is affected by the lay direction and fibre/matrix strength. At the same time, different degrees of delamination damage occurs, but the direction of its expansion is not directly related to the direction of adjacent layers.

2) The load displacement curve of the double lap structure is obviously nonlinear. For the composite structure, the interference of 0.8% and 1.2% shows better bearing strength.

Acknowledgments

This work was supported by the Aviation Science Foundation of China (No. 2018ZE23011). The authors would like to be thankful for the supports.

References

[1] Li J, Li Y, Zhang K, Liu P, Zou P 2015 Interface damage behaviour during interference-fit bolt installation process for CFRP/Ti alloy joining structure Fatigue & Fracture of Engineering Materials & Structures 38 1359-71

[2] Zou P, Li Y, Zhang K, Liu P, Zhong H 2017 Mode I delamination mechanism analysis on CFRP interference-fit during the installation process[J] Materials & Design 116 268-77

[3] Zou P, Li Y, Zhang K, Cheng H, Li J Influence of interference-fit percentage on stress and damage mechanism in hi-lock pin installation process of CFRP[J] Journal of Composite Materials 0(0) 0021998316689601

[4] Liu LQ, Zhang JQ, Chen KK and Wang H 2014 Combined and interactive effects of interference fit and preloads on composite joints Chinese J Aeronaut. 27 716-29

[5] Zou P, Zhang K, Li Y, Liu P, Xie H 2016 Bearing strength and failure analysis on the interference-fit double shear-lap pin-loaded composite[J] International Journal of Damage Mechanics 1056789516671774

[6] Kim SY, Hennigan DJ, Kim D and Seok CS 2012 Fatigue enhancement by interference-fit in a pin-loaded glass fibre-reinforced plastics laminate P I Mech Eng C-J Mec. 226 1437-46

[7] Wei JC, Jiao GQ, Jia PR and Huang T 2013 The effect of interference fit size on the fatigue life of bolted joints in composite laminates Compos Part B-Eng. 53 62-8

[8] Camanho PP, Matthews FL 1999 A progressive damage model for mechanically fastened joints in composite laminates J Compos Mater 33(24) 2248–80

[9] Olmedo A, Santiuste C, Barbero E 2014 An analytical model for the secondary bending prediction in single-lap composite bolted-joints Composite Strucutre 111(1) 354-361
[10] Xiao Y, Ishikawa T 2005 Bearing strength and failure behavior of bolted composite joints (part I: Experimental investigation) Compos Sci Technol 65(7-8) 1022-31

[11] Zhao L, Gong Y, Zhang J, Chen Y and Fei B 2014 Simulation of delamination growth in multidirectional laminates under mode I and mixed mode I/II loadings using cohesive elements Compos Struct. 116 509-22

[12] Chen J-F, Morozov EV and Shankar K 2014 Simulating progressive failure of composite laminates including in-ply and delamination damage effects Composites Part A: Applied Science and Manufacturing 61 185-200

[13] Camanho PP, Davila CG, de Moura MF 2003 Numerical simulation of mixed-mode progressive delamination in composite materials J Compos Mater 37(16) 1415–38

[14] Riccio A, Caputo F, Di Felice G, Saputo S, Toscano C and Lopresto V 2015 A Joint Numerical-Experimental Study on Impact Induced Intra-laminar and Inter-laminar Damage in Laminated Composites Appl Compos Mater.

[15] Durao LMP, de Moura MF and Marques AT 2008 Numerical prediction of delamination onset in carbon/epoxy composites drilling Eng Fract Mech. 75 2767-78