Finite Element Analysis of Short-edge Distance of Fastener Holes in Composite Laminates

Luchun Zhao and Zhiqin Zhao
Shanghai Aircraft Design and Research Institute, No.3115 Changzhong Road, Jing an District, Shanghai, China.
Email: 263360147@qq.com

Abstract. In the production process of aircraft structures, due to design defects or the accumulation of tolerances in part manufacturing and assembly, structural short margins appear at the mechanical joints of composite laminates. In this paper, the analytical method is used to analyze the hole edge stress of the composite material fastener, and the finite element analysis of the short edge distance of the fastener hole of the composite laminate structure is carried out. The hole edge stress and residual net of the structure after the short edge distance. The stress distribution of the cross-section is analyzed to discuss the changes of the stress and strain at the edge of the hole after the short margin of the composite laminate to determine the effect on the strength of the aircraft.

1. Introduction
Composite materials have received more and more attention in the field of materials today, especially in modern aircraft structures. With the continuous development of molding technology, the integrity of composite materials has been greatly improved. Modern airplanes generally use more than 25%, some even approach 35%, and their own weight loss efficiency is 30%. The application parts are almost all over the aircraft body, including: horizontal tail, vertical tail, fuselage skin, and wing wall and skin. Compared with general engineering materials, fiber-reinforced resin matrix composites have anisotropic strength and stiffness, low inter layer strength and low ductility, so the load redistribution ability in the stress or strain concentration area of the connection is weaker. According to some data, most of the damage to composite structures (60% -80%) also occurs at the joints. Therefore, the connection problem is one of the key technologies that affect the performance of the composite material. Solving the connection problem of the composite material structure is of great significance to improve the structural performance. In the manufacturing process, due to tolerance accumulation or artificial factors causing hole making errors, resulting in excessive hole margins of the fasteners of the composite material connection structure, which caused the failure mode of the composite laminate to change. The stress change of the hole edge after the short margin occurs, and the stress change of the remaining net section material at the short margin.

2. Mechanical Connection Requirements for Composite Laminates
The mechanical connection characteristics of composite materials are very different from the metal connection characteristics. First, the stiffness and strength of the composite laminate are related to the direction of the load; second, the composite laminate exhibits approximately linear elastic behavior until failure, and has little ability to redistribute the load. A general principle for the design of mechanical strength of composite materials is that the connected plates should be destroyed before the fasteners. The failure mode of mechanical connection is mainly related to its geometric parameters and
fiber laying. There are two types of failure modes: single type and combined type. The single type has seven kinds of failures such as extrusion, stretching, shearing, splitting, pulling off, and shearing and stretching of fasteners; the combined type is the combination of the above single types, such as pull-shear, pull-extrusion, extrusion-shearing, etc., are common failure modes of composite material laminate mechanical connection structures.

![Guidelines for fastener arrangement of composite materials](image1)

**Figure 1.** Guidelines for fastener arrangement of composite materials

In order to prevent the low-strength failure mode of the composite laminate mechanical connection and have a high strength, the margin / aperture $e/d \geq 2.5$ of the connected board is called short margin when the margin is less than 2.5$d$. Check the materials. Figure 1 shows the arrangement rules of the mechanically connected fasteners of the composite material structure. At present, there are two main methods for determining the hole stress of composite mechanical fasteners: analytical method and finite element method. The former is suitable for mechanical connections with relatively regular nail arrangement, and the latter is suitable for mechanical connections with complex shapes.

3. Analytical Calculation Method of Hole Edge Stress of Composite Laminate

The outstanding advantage of this method is that it can get the closed analytical expression of the stress at the hole. It does not need to assume the distribution type of the nail load. It can easily calculate and analyze the ply, plate width, friction coefficient, bypass load and load type. Influence of various parameters on stress distribution. The obtained displacement expression of the fastener can also be used to estimate the compressive strength by the maximum deformation criterion. When the nail loading force is inconsistent with the elastic main axis of the laminate, the angle between the displacement direction of the fastener and the load direction can be calculated conveniently and accurately, which is very important for the calculation of the load distribution of the multi-nail connection.

![Computation model of fastener](image2)

**Figure 2.** Computation model of fastener
When the $x$ and $y$ axes are consistent with the elastic principal axis of the plate, the stress expression for solving the hole edge is:

$$
\sigma_r = \frac{(C-1)u_0}{C_{gr0}} \cdot n(1-k) \cos 5\theta + \frac{u_0}{C_{gr0}} [(C+1) \cdot (3\nu_{12} - 3k - kn)] + \frac{(C-1)}{2} n(1-k) \\
\cos 3\theta = \left[ \frac{P}{\pi r_0} + \frac{(C-1)u_0}{2C_{gr0}} (2k-2\nu_{12}+nk+n) + \frac{(C+1)}{Cr_0} (k-\nu_{12}+n) \right] \cos \theta \\
\tau_{r\theta} = \frac{(C-1)}{C_{gr0}} u_0 \cdot n(1-k) \sin 5\theta - \frac{u_0}{C_{gr0}} \left[ (C+1) \cdot (k-\nu_{12}+nk+2n) \right] + \frac{(C-1)}{2} n(1-k) \\
\sin 3\theta + \left[ \frac{P}{\pi r_0} - \frac{(C-1)u_0}{2C_{gr0}} (2k-2\nu_{12}+nk+n) - \frac{(C+1)u_0}{C_{gr0}} (k-\nu_{12}+n) \right] \sin \theta
$$

Where:

$$
\begin{align*}
\{ & \begin{array}{c} 
    k = \left( \frac{E_x}{E_y} \right) \frac{1}{2} \\
    n = [2(k-\nu_{12}) + \frac{E_y}{E_x}]^2 \\
    g = \frac{1-\nu_{12}^2}{E_y} + \frac{k}{G} \\
  \end{array} \\
\end{align*}
$$

$$
C = \frac{B_1 - A_1}{A_1} \\
u_0 = \frac{gP}{\pi} \cdot \frac{B_1 - A_1}{2A_1(\nu_{12} - nk - k) - B_1(\nu_{12} + nk - k)} \\
A_1 = (19n + 11nk + 10k - 10\nu_{12}) + f(11n - 6nk + 15k - 16\nu_{12}) \\
B_1 = 10n(1 - k) + 10f(3k - 3\nu_{12} + 2nk + n)
$$

$E_x$, $E_y$, $G$, $\nu_{12}$ are the main elastic constants of orthotropic plates; $f$ is the friction coefficient between the fastener and the hole of the composite material.

The tangential normal stress at the edge of the hole can be divided into several partial stress superpositions, and the expression of the partial stress is:

$$
\sigma_{\theta \theta} = \frac{P}{\pi r_0} \frac{E_0}{E_x} \left[ -\nu_{12} \cos^4 \theta - (k^2 - 1 + 2\nu_{12}) \right] \cos^2 \theta \sin^2 \theta + (2 + 2k - \nu_{12} - n^2) \sin^4 \theta \cos \theta
$$
\[ \sigma_{\theta 2} = \frac{(C - 1)u_0}{Cgr_0} \frac{E_y}{E_x} \left( \frac{n}{2} \cos 2\theta - (\sin^2 \theta - k \cos^2 \theta) \right) \left[(1 + 2k)(k - \nu_{12} + n) \cos^2 \theta \right. \\
- (k\nu_{12} + n^2k - k^2 - n\nu_{12}) \sin^2 \theta \] \sin \theta \sin 2\theta \\
+ [\cos 2\theta (\sin^2 \theta - k \cos^2 \theta) + \frac{n}{2} \sin^2 2\theta] \\
[(k - n^2 - \nu_{12} + n\nu_{12}) \cos^2 \theta + (2 + k)(nk + k - \nu_{12}) \sin^2 \theta] \cos \theta \] \\
\] (2)

\[ \sigma_{\theta 4} = \frac{2(C + 1)u_0}{Cgr_0} \frac{E_y}{E_x} \left( \frac{n}{2} \cos 4\theta - 2 \cos 2\theta (\sin^2 \theta - k \cos^2 \theta) \right) \left[(1 + 2k)(k - \nu_{12} + n) \cos^2 \theta - \\
(k\nu_{12} + n^2k - k^2 - \nu_{12}) \sin^2 \theta \] \sin \theta \sin 2\theta + [\cos 4\theta (\sin^2 \theta - k \cos^2 \theta) + \frac{n}{2} \sin 2\theta \sin 4\theta] \\
[(k - n^2 - \nu_{12} + n\nu_{12}) \cos^2 \theta + (nk + k - \nu_{12})(2 + k) \sin^2 \theta] \cos \theta \] \\
\] (3)

\[ \frac{1}{E^0_{\theta}} = \frac{\sin^4 \theta}{E_x^0} + \left( \frac{1}{G} - \frac{2\nu_{12}}{E_x} \right) \sin^2 \theta \cos^2 \theta + \frac{\cos^4 \theta}{E_y} \] \\
\] (4)

\[ \sigma_{\theta 5} = \frac{C - 1}{2Cr_0} E_x u_0 \sin^2 \theta \] \\
\] (5)

\[ \sigma_{\theta 6} = \frac{E_y}{WE_x} \left[ \frac{u_0}{Cg} (C + 1)(k - \nu_{12} + nk) \sin 4\theta + \frac{u_0}{Cg} \right] \\
\frac{[(C - 1)(k - \nu_{12} + nk) + 2(C + 1)(k - \nu_{12})]}{P} \cdot [-k \cos^2 \theta + (1 + n) \sin^2 \theta] \] \\
\] (6)

4. Finite Element Model of Short Margin of Composite Material

In this paper, the Abaqus software is used to establish a finite element model, composite laminate T300 / 5208, the layup order is \([0/45/90/-45]_3\),, material properties \(E_1 = 181000MPa\), 
\(E_2 = 10300MPa\), \(\mu = 0.28\), \(G_{12} = G_{13} = 7170MPa\), \(G_{23} = 3780MPa\), design allowable strain 
[\(\varepsilon_c\)] = 3000\% , tensile stress 100MPa is applied at both ends, diameter \(d = 4.76mm\),
and pretension is applied at the edge of the hole. The end distance of the fastener is 3d, the distance 
between the fasteners in the vertical load direction is 5d, and the distance between the fasteners in the 
parallel load direction is 4d. The fastener margins are 1d, 1.5d, 2d, 2.5d, 2.5d + 1mm.And the 1d edge 
distance is shown as Figure 3. The hole side strain changes with different edge distance is shown as 
Figure 4. Figure 5 shows the stress changes at different edges of holes. Figure 6 shows the curve of 
stress distribution at holes.
5. Conclusion

1. In this paper, Abaqus is used to simulate the problem of short margin of composite laminates, and the hole edge stress and the residual net cross-section material strain and stress distribution are analyzed. From $e / d = 2.5$ to $e / d = 2$, the hole-side stress does not change significantly. When $e / d$ decreases to 1.5d, the hole-side stress increases significantly, and when $e / d = 1$, the hole-side stress 1.3 times when the margin is 2.5d + 1.

2. Lamination order is a unique parameter of composite materials that affects the mechanical properties of composite materials. For laminates with the same number of layers and ratios, there can be many kinds of layering sequence. Therefore, the interlayer stress will change, which will also have a certain impact on the mechanical properties of the laminate. When a short margin occurs, the failure mode also changes.

6. References

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