Calculation and analysis on braided carbon/carbon composite pull-through fastener threads load distribution

Tianya Bian¹, Wantao Guo and Xiang Li
Luoyang Ship Material Research Institute, China

¹E-mail: biantianya@vip.sina.com

Abstract. Braided carbon/carbon composites are widely used in the aerospace field due to their superior performance. However, because braided carbon/carbon composite materials have anisotropy characteristics, the distribution of screw loads in the fastener connection structure will differ from that of metal. In view of the particularity of the braided carbon/carbon composite fasteners' connection, this paper obtains the theoretical results of the load distribution of screw teeth through the homogenization of stiffness and establishes a finite element model for comparative verification. The trend of finite element results is the same as that of theoretical calculation results which can provide guidance for the engineering design of carbon/carbon composite fastener.

1. Introduction
In the future, spacecraft must be able to withstand high temperature and play a role in a wide range of temperature, so it is necessary to protect the structure by a thermal protection system with good performance. Braided carbon/carbon composites have high modulus-to-weight, high strength-to-weight, low density, wear resistance and other properties, and their modulus and strength have no obvious decline in high temperature environment [1-2], which has been widely used in aerospace field. Therefore, it is inevitable to use braided carbon/carbon composite fasteners in spacecraft thermal structure. At present, researches on composite fasteners include load distribution of multi pin connection [3-5], load calculation of fastener teeth [6-8] and failure mode analysis of fasteners [9-10]. Researchers have made study on the field of fastener threads load distribution. Zhou [11-12] analyzed the fastener threads load distribution by using the finite element method and the spring model respectively. Zhang [13] analyzed the load homogenization of nut thread. Zhao [14] studied the load distribution of metal thread and Hu [15] analyzed the load distribution of phenolic resin nut thread. However, due to the anisotropic characteristics of the braided carbon/carbon composite, the research on load distribution of the fastener teeth is not deep enough. In this paper, the elastic properties of fastener materials are homogenized, so that the calculation of load distribution law of this kind of fastener can follow the research theory of isotropic material fastener. In addition, the finite element model of fastener with different nut thickness is established to analyze the load distribution of screw teeth from the simulation point of view. Through the research of load distribution law of braided carbon/carbon composite fastener, it can provide guidance for the engineering design of this kind of fastener.
2. Theoretical analysis of load distribution of screw teeth

Yamamoto [16] and Sopwith [7] have conducted in-depth analysis and research on the load distribution of multi-screw engagement. Yamamoto ignores the angle of thread rising, regards the screw tooth as a tapered short beam, and then regards the axial deformation of the screw connection pair as the superposition of the following five types of deformation, including the deformation caused by the bending of the screw tooth $\delta_1$, the deformation caused by the shearing of the screw tooth $\delta_2$, the deformation caused by the inclination of the tooth root $\delta_3$, the deformation caused by the shearing of the tooth root $\delta_4$, and the deformation caused by the radial contraction of the bolt and nut body $\delta_5$, such as Figure 1. Finally, the load distribution along the thread is deduced according to the deformation coordination condition of the thread and the nut.

![Figure 1. Five kinds of axial deformation of screw teeth [16].](image)

This paper is still based on the above five types of axial deformation hypothesis, but the braided carbon/carbon composite fastener has anisotropic characteristics. In order to follow the theoretical framework of Yamamoto’s cone-shaped short beam theory, it is necessary to homogenize the characteristics of screw teeth. Liao [17] has done research in this direction and established extended Yamamoto’s method. This paper follows Liao’s way. Figure 2 shows that the screw teeth on one side perpendicular to the carbon cloth direction and the screw teeth on the other side parallel to the carbon cloth direction obviously have different micro geometry structures.

According to the calculation results of Yamamoto theory [16], the total axial deformation of bolt $\delta_b$ and nut $\delta_n$ in the screw connection pair are respectively

$$\delta_b = \delta_{b1} + \delta_{b2} + \delta_{b3} + \delta_{b4} + \delta_{b5} = \frac{k_{beq}}{E_{bt11}} \omega \cos \alpha$$

$$\delta_n = \delta_{n1} + \delta_{n2} + \delta_{n3} + \delta_{n4} + \delta_{n5} = \frac{k_{neq}}{E_{nc11}} \omega \cos \alpha$$

where: $E_{bt11}$ is the longitudinal tensile Young's modulus of bolt, $E_{nc11}$ is the longitudinal compressive Young's modulus of nut, $k_{beq}$ and $k_{neq}$ meet the following relations respectively.

$$k_{beq} = 0.034 \left(1 - \nu_{beq}^2\right)c_{1b} + 0.229 \left(1 - \nu_{beq}^2\right)c_{2b} + 1.08c_{2b} + 1.18 \left(1 - \nu_{beq}\right)c_{2b} + \left(1 - \nu_{beq}\right)\tan^2 \frac{\alpha p}{2} c_{1b}$$

$$k_{neq} = 0.073 \left(1 - \nu_{neq}^2\right)c_{1n} + 0.294 \left(1 - \nu_{neq}^2\right)c_{2n} + \frac{\left(D_0^2 + d_p^2\right)^2 + \nu_{neq}}{D_0^2 - d_p^2 + \nu_{neq}} + 1.15c_{2n} + 1.14 \left(1 - \nu_{neq}\right)c_{2n}$$

$$c_{1b} = \frac{E_{bt11}}{E_{beq}}$$

$$c_{2b} = \frac{E_{bt11}}{2G_{beq}}$$

2
\[
\begin{align*}
    c_{1n} &= \frac{E_{\text{eq}11}}{E_{\text{eq}}} \\
    c_{2n} &= \frac{E_{\text{eq}11}}{2G_{\text{eq}}}
\end{align*}
\]  
\(7\)

where: \(d_P\) is the bolt pitch diameter, \(p\) is the pitch, \(d_0\) is the nut outer diameter, \(E_{\text{eq}}\) and \(G_{\text{eq}}\) are the equivalent bolt Young's modulus and shear modulus after homogenization respectively, \(E_{\text{eq}1}\) and \(G_{\text{eq}1}\) are the equivalent nut Young's modulus and shear modulus after homogenization respectively.

\[
E = \cos^2 \psi E_2 + \sin^2 \psi E_3
\]  
\(9\)

where: \(E_2\) is the equivalent Young's modulus of carbon cloth in the parallel direction, \(E_3\) is the equivalent Young's modulus of carbon cloth in the vertical direction.

The equivalent Young's modulus of bolt and nut can be obtained from Equation (10):

\[
E_{\text{eq}} = \left( \frac{2}{\pi} \int_0^{\psi} E_x(\psi) d\psi \right)
\]  
\(10\)

It can be calculated from Equation (10)

\[
E_{\text{eq}} = \left( E_2 + E_3 \right) / 2
\]  
\(11\)

For the equivalent shear modulus of bolt and nut, due to the particularity of the microstructure of braided carbon/carbon composite, the following decomposition is carried out in this paper. As shown in Figure 2, the screw thread is mainly supported by out-plane shear modulus at the end parallel to the carbon cloth direction (Area A), while at the end perpendicular to the carbon cloth direction (Area B), it is mainly supported by in-plane shear modulus. Assuming that the load is uniformly distributed on the surface of the screw tooth, the equivalent shear modulus needs to be weighted and averaged according to the area of Area A and Area B, as shown in Equation (12):

\[
G_{\text{eq}} = \frac{2}{3} G_{12} + \frac{1}{3} G_{13}
\]  
\(12\)

where: \(G_{12}\) is the equivalent in-plane shear modulus and \(G_{13}\) is the equivalent out-plane shear modulus.

In this way, the homogenization of Young's modulus and shear modulus of the braided carbon/carbon composite fastener is completed.

Table 1 shows the mechanical properties of braided carbon/carbon composites.


Table 1. Elastic parameters of braided carbon/carbon composite [18].

| Elastic parameters                        | Value   |
|-------------------------------------------|---------|
| In-plane Young’s modulus $E_{11} = E_{22}$ (GPa) | 58.4    |
| In-plane Poisson’s ratio $v_{12}$          | 0.0105  |
| In-plane shear modulus $G_{12}$ (GPa)      | 5.41    |
| Out-plane Young’s modulus $E_{33}$ (GPa)   | 12.2    |
| Out-plane Poisson’s ratio $v_{13} = v_{23}$ | 0.18    |
| Out-plane shear modulus $G_{13} = G_{23}$ (GPa) | 7.44    |

Figure 3 shows a threaded connection pair, and the bolt rod is subject to the pull force $F_b$.

\[
F = C_1 \cosh \lambda_{eq} x + C_2 \sinh \lambda_{eq} x
\]

(13)

\[
\lambda_{eq} = \sqrt{\frac{1}{A_b} + \frac{1}{E_{eq11} A_b}}
\]

(14)

where: $C_1$ and $C_2$ are indefinite integral constant coefficients; $\beta$ is the helix angle; $A_b$ is the equivalent area of bolt and $A_n$ is the equivalent area of nut.

\[
A_b = \frac{\pi d_p^2}{4}
\]

(15)

\[
A_n = \frac{\pi \left(D_0^2 - d_p^2 \right)}{4}
\]

(16)

The boundary condition is

\[
F |_{x=0} = 0
\]

(17)

\[
F |_{x=L} = F_b
\]

(18)

If $C_1$ and $C_2$ are determined according to the boundary conditions, then Equation (13) becomes

\[
F = C_1 \cosh \lambda_{eq} x + C_2 \sinh \lambda_{eq} x
\]

(19)
The distribution of the axial force $F$ of the nut can be obtained by Equation (19), and then the load borne by a circle of thread can be obtained by the difference between the two shafts of the section whose distance is equal to the pitch.

The braided carbon/carbon composite fastener studied in this paper has ISO metric thread, and the specific geometric dimensions are shown in Table 2.

**Table 2.** Geometric parameters of braided carbon/carbon composite fastener thread.

| Geometric parameters            | Value |
|--------------------------------|-------|
| Bolt polished rod diameter(mm) | 10    |
| Pitch(mm)                      | 1.5   |
| Screw tooth apex angle(°)      | 60    |
| Bolt pitch diameter(mm)        | 9.026 |
| Nut outer diameter(mm)         | 18.9  |

**Table 3.** Load distribution of thread under three nut thicknesses conditions.

| Screw tooth serial number | L=10mm | L=15mm | L=25mm |
|---------------------------|--------|--------|--------|
| 1                         | 0.2198 | 0.1996 | 0.1940 |
| 2                         | 0.1835 | 0.1624 | 0.1565 |
| 3                         | 0.1557 | 0.1327 | 0.1263 |
| 4                         | 0.1352 | 0.1092 | 0.1020 |
| 5                         | 0.1209 | 0.0908 | 0.0824 |
| 6                         | 0.1123 | 0.0766 | 0.0666 |
| After 6                   | 0.0726 | 0.2287 | 0.2722 |

Combined with the braided carbon/carbon composite mechanical parameters and fastener geometric parameters, the nut thickness $L$ is set as 10,15,25mm, respectively. According to the above calculation process, the load distribution of the screw teeth under the three nut thickness conditions is obtained. The specific results are shown in Table 3, which lists the load distribution proportion of the first six cycles of screw teeth and the total load distribution proportion of the screw teeth after the sixth cycle. It can be seen from Table 3 that the load distribution proportion of the first round of screw teeth is the highest, about 1/5 of the total load, and the load distribution proportion of the subsequent screw teeth decreases in turn. With the increase of the nut thickness (engagement distance), the load distribution ratio of the first ring of the screw teeth decreased to some extent, while the total load distribution ratio of the screw teeth after the sixth ring increased gradually, indicating that with the increase of the nut thickness, the load distribution of the braided carbon/carbon composite fastener gradually tended to be uniform.

Generally, the larger the $\lambda_{eq}$ is, the more uneven the thread load distribution is. For braided carbon/carbon composite materials, the value of Equations (5) to (8) are generally larger than those of metal, so $\lambda_{eq}$ is smaller than that of metal bolts with the same geometric parameters, that is, the load distribution of each engagement thread in the braided carbon/carbon composite fastener is more uniform. Taking steel as an example, its modulus is 206GPa and Poisson's ratio is 0.3. Under the same geometric parameters, the load distribution of the first thread of the braided carbon/carbon composite fastener and steel fastener with three nut thicknesses is shown in Table 4. Under the three nut thicknesses, the load distribution of steel head screw is 30.1%, 39.3% and 42.8% higher than that of carbon/carbon composite respectively. It can be concluded that under the same geometric parameters, the load distribution of steel fastener is more uneven, and with the increase of nut thickness, the difference between the two materials increases gradually.
Table 4. First tooth Load ratio of carbon/carbon composite and steel fasteners.

| Material                  | L=10mm | L=15mm | L=25mm |
|---------------------------|--------|--------|--------|
| Carbon/carbon composite   | 0.2198 | 0.1996 | 0.1940 |
| Steel                     | 0.2859 | 0.2781 | 0.2771 |

Researcher [17] has studied the influence of the relative rotation of the bolt and nut on the load distribution in the anisotropic composite screw connection. The conclusion is that the relative angle of the bolt and nut has little effect on the load distribution, so it is considered that the load distribution of the thread mainly depends on the average stiffness of the one-circle thread and has little relationship with the local fit of the bolt and nut, which to some extent supports the homogenization of the stiffness of the one-circle thread of the braided carbon/carbon composite in this paper.

3. Numerical simulation

Finite element models are established by using ABAQUS software. There are three kinds of finite element models of multi thread fastener, among which the thickness of nut is 10mm, 15mm and 25mm respectively, and the number of thread rings of three kinds of nut is $6\frac{2}{3}$, 10 and $16\frac{2}{3}$ circles respectively. In order to save the calculation cost, only a quarter of the actual fastener shape is established for the multi thread model, as shown in Figure 4. Steps of finite element simulation include building a geometric model, assigning material properties, assembling selecting calculation method, creating boundary conditions and dividing elements. The finite element model uses three-dimensional solid reduction integral element with six degrees of freedom. Dynamic explicit method is used during calculation.

The modeling assumptions of screw drawing finite element model include:

1) When the screw model moves upward, the nut is restrained, thus forming the mutual extrusion movement of the screw and the nut;
2) The normal displacement of the left and right sides of the 1/4 model is limited to ensure that the screw and nut only move in the direction parallel to the axis;
3) The contact surface between the screw and the nut adopts normal hard contact and tangential non friction contact conditions.

During the finite element calculation, the upper surface of the nut adopts the fixed boundary condition, and the upper surface of the bolt adopts the displacement loading, as shown in Figure 5. Among them, there are 248968 bolt elements and 11685 nut elements in the finite element model of fastener with 10 mm nut thickness, 343075 bolt elements and 11685 nut elements in the model of fastener with 15 mm nut thickness, 443871 bolt elements and 22140 nut elements in the model of fastener with 25 mm nut thickness. The main purpose of multi screw fastener model is to explore the load distribution law of multi screw engagement by finite element method.

![Figure 4](image-url)
Figure 5. Displacement boundary conditions of multi thread finite element model: (a) bolt boundary conditions; (b) nut boundary conditions.

Figure 6. Axial force of screw tooth boundary section.

4. Results and discussions

4.1. Comparison between the result of FEM and analytical method
The axial force values of each screw tooth are counted in the finite element calculation results. The difference between the axial force of the adjacent boundary section is the load of the screw tooth, as shown in Figure 6. Using this method, the screw load distribution of fastener with 10mm, 15mm and 25mm nut thickness is calculated respectively and compared with the theoretical calculation results, as shown in Figures 7~9. It can be seen that the overall trend of the finite element calculation results and
the theoretical calculation results is the same: the load distribution proportion of the first ring of the screw teeth is the highest, and the load distribution proportion of the subsequent screw teeth decreases in turn; with the increase of the nut thickness, the load distribution of the screw teeth of the fastener tends to be uniform gradually. However, it can also be seen that in the calculation results of load distribution ratio of fasteners with the same nut thickness, the finite element calculation results are generally larger than the theoretical calculation results for the load distribution ratio of the first round of screw teeth, while the latter is generally smaller than the theoretical calculation results. In the finite element method, in order to ensure the convergence of the model, there are certain deformation constraints, resulting in a certain degree of additional stiffness of the finite element model, so the fastener finite element model shows higher rigidity characteristics, that is, the load distribution proportion of the screw teeth calculated by the finite element method is more uneven.

Figure 7. Comparison between theoretical and finite element calculation results of thread load distribution law of fastener with 10mm nut thickness.

Figure 8. Comparison between theoretical and finite element calculation results of thread load distribution law of fastener with 15mm nut thickness.

Figure 9. Comparison between theoretical and finite element calculation results of thread load distribution law of fastener with 25mm nut thickness.

Figure 10. Comparison between the anisotropy result and isotropy result.

4.2. Comparison between the anisotropy result and isotropy result
Take the test piece with 15mm nut thickness as the research object, compare the calculation results of the finite element model of isotropic material and anisotropic material, as shown in Figure 10. It can
be seen that the difference between the two results is not big, but the calculation results of isotropic materials will be more even.

4.3. Grid independence verification for the finite element model
Take the test piece with 15mm nut thickness as the research object, and compare the calculation results under the conditions of nominal grid size of 0.5mm, 0.25mm and 0.125mm, as shown in Figure 11. It can be seen that when the nominal size of the grid is less than 0.5mm, the calculation results do not depend on the density of the grid, and the calculation results in this paper have grid independence.

![Figure 11](image_url)

**Figure 11.** Comparison between finite element calculation results of thread load distribution of fastener with different nominal grid sizes.

5. Conclusions

1) Based on the anisotropic characteristics of the braided carbon/carbon composite fasteners, the equivalent Young's modulus and shear modulus of the screw teeth are calculated, and the load distribution law of the screw teeth is predicted theoretically.

2) The finite element model of fastener is established, and the calculation and analysis of screw load distribution are completed from the view of numerical simulation, which is compared with the theoretical prediction results. The trend of finite element results is the same as that of theoretical calculation results which can provide guidance for the engineering design of carbon/carbon composite fastener.

References

[1] Sheehan J 1993 *Carbon-carbon materials and composite* 223-66
[2] Bian T, Guan Z and Liu F 2018 Compressive experiment and numerical simulation of 3Dcarbon/carbon composite open-hole plates *Archive of Applied Mechanics* **88** 913-32
[3] Johan E and Schon J 2008 Finite element modeling and optimization of load transfer in multi-fastener joints using structuralelements *Composite Structures* **82** 245-56
[4] Gray P and McCarthy C 2010 A global bolted joint model for finite element analysis of load distributions in multi-bolt composite joints *Composites Part B* **41**(4) 317-25
[5] McCarthy C, McCarthy M and Lawbor V 2005 Progressive damage analysis of multi-bolt composite joints with variable bolt–hole clearances *Composites Part B* **36**(4) 290-305
[6] Eramo M and Cappa P 1991 An experimental validation of load distribution in screw threads Experimental Mechanics 31(1) 70-75
[7] Sopwith D 1948 The distribution of load in screw threads Proceedings of the Institution of Mechanical Engineers 159(1) 373-83
[8] Kenny B and Patterson E 1985 Load and stress distribution in screw threads Experimental Mechanics 25(3) 208-13
[9] Mu J, Guan Z, Bian T, Li Z, Wang K and Liu S 2014 The Experiment and Numerical Simulation of Composite Countersunk-head Fasteners Pull-through Mechanical Behavior Applied Composite Materials 21(5) 773-87
[10] Guan Z, Mu J, Su F, Bian T, Huang Y and Kang J 2015 Pull-through mechanical behavior of composite fastener threads Applied Composite Materials 22(3) 251-67
[11] Zhou X, Sun Y and Zhang E 2008 Analysis of axial load distribution trend for transmission screw by FEM Machinery Design & Manufacture 2008(1) 16-8
[12] Zhou X, Sun Y, Wei L and Zhang E 2007 Spring set model for the axial force distribution fo transmission screw thread Journal of Machine Design 24(6) 30-3.
[13] Zhang Y, Zhang Z, Sun Y, Huang F, Zhang G and Li J 2014 Load equalization analysis for stepped construction of transmission screw nut tooth Forging & Stamping Technology 39(3) 67-72
[14] Zhao H 1996 A numerical method for load distribution in threaded connections Journal of Mechanical Design 118(2) 274-9
[15] Hu X, Lu H and Huang S 2004 Research of loading distribution of nut made by phenolic resin in siral drive Chinese Journal of Mechanical Engineering 40(4) 185-9
[16] Yamamoto 1984 Theory and calculation of screw connection 45-52
[17] Liao Q, Lu Z, Yang Z, Feng X, Zhang Z and Feng Z 2014 Study of load distribution in the threads of composite fasteners Acta Materiae Compositae Sinica 31(1) 213-19
[18] Bian T, Guan Z and Liu F 2017 Tensile test and numerical simulation for satin weave composite fastener Journal of Beijing University of Aeronautics and Astronautics 43(2) 311-18