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TEMPERATURE-INDUCED LOAD OF BOLTED HYBRID COMPOSITE/METAL JOINT

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Abstract

Due to the different thermal expansion coefficients between the metal and composites, temperature-induced load in some hybrid structure should be considered when the aircraft is in service at extreme temperatures. To calculate the temperature-induced load of bolted composite/metal joint, a theoretical formula has been derived based on the force method of static indeterminacy problem. In order to verify the formula, a three-row composite/metal joint is taken as an example. By the means of formula analysis and finite element analysis, bolt load of the structure has been calculated in the condition of 71℃ and - 51℃. A comparison between the results of the two methods has been done and the error is not more than 5%. The main factors such as adjacent bolts distance and the number of bolts, which affect the temperature-induced load value, are analyzed based on the formula. The distribution pattern is obtained and shown in the paper. This will provide some valuable reference for aircraft structure strength analysis.

Keywords: Force Method; Hybrid Joint Structure; Temperature-Induced Load; Thermal Expansion Coefficients; Finite Element Analysis

1. Introduction

Due to the advantages of high specific strength and specific modulus, fatigue resistance, high temperature resistance and excellent thermal stability and the significant reduction of manufacturing costs in recent years, carbon fiber reinforced plastics (CFRP) has been widely used in aviation industry [1-2]. The main structure of aircraft has been mainly composed of CFRP, aluminum alloy, titanium alloy and alloy steel. Therefore, it is inevitable to connect the composite component with the metal component. Mechanical joint is the most common connection type in hybrid composite/metal structure because of its small strength dispersion, strong bearing capacity and easy disassembly etc. such as the assembly parts composed of composite skin and metal frame, the stiffened panel composed of composite skin and metal stringer.

Aircraft structure is assembled at room temperature, in its service environment will encounter low temperature, high temperature and other extreme weather conditions. Due to the great difference of thermal expansion coefficients between carbon fiber composite and aluminum alloy, temperature-induced load will occur in the joint structure at extreme temperature. According to the environmental conditions of aircraft storage and operation, the temperature range of aircraft service can be determined. Based on the table of temperature variation range of high temperature and low temperature daily cycle in the world given in standard GJB 150A, this paper mainly studied the bolt load distribution of hybrid composite/metal joint at the temperature of 71℃and -51℃, which can provide some engineering reference for aircraft structural design.

2. Related Literature Review

Scholars at home and abroad have done a lot of research on the bolt load distribution and the static strength, fatigue strength of the hybrid joint structure at room temperature [3-5], however there are few studies considering the effect of temperature. In addition, scholars have carried out research on the thermal stress generated by composite patches in repairing aircraft metal structures [6-7]. In the study of temperature induced load of hybrid joint, the research is limited.

Krodinov et al. [8] used the complex potential theory to study the determination of hole edge stress, contact area of bolts and the distribution of bolt load in single lap and double lap joints at any position in composite laminates under mechanical load and uniform temperature change, the research is too complex to be applied to engineering problems. Kan Quanqing [9] studied the temperature induced load of ceramic matrix composites and metal hybrid joint structure at high temperature and its influence on the structural strength. The analysis aimed at higher temperature, up to 750℃. Chihdar Yang et al. [10] studied the temperature distribution and bolt load distribution of the hybrid panel structure composed of composite plate and aluminum alloy Z-beam under the condition of aircraft service temperature field. The calculation method of bolt load is based on the force method of elastic statically indeterminate problem, which is verified by experiments. The results show that the distribution law of thermal stress is approximately "U", which means high on both sides and low in the middle, but the specific value is not given. Aimed at that hybrid panel, Deng Wenliang [11] analyzed the thermal stress distribution law through finite element modeling method. In addition, the bolt load distribution of five bolts structure under different degrees of high and low temperature was studied [12]. Guo Jushang [13] studied the bolt load and stress distribution behavior of hybrid composite/metal joint structure in aircraft tail at 70℃ by finite element modeling (EFM) method.

3. Theoretical Formula for Temperature-Induced Load

Based on the force method of the elastic static indeterminate problem, this paper derived the theoretical formula for calculating the load of the multi-bolts hybrid composite/metal joint. The application of the formula was given through an example, and ABAQUS software was used to verify the accuracy of the formula.

For the bolted hybrid composite/metal joint shown in ‘Figure 1 - The diagram of bolted hybrid composite/metal joint’, plate A is composite material and plate B is metal. Number the bolts from left to right, and the loads of each bolt are P1, P2 、Pn. The load transferred between two adjacent bolts of plate A is shown as P_{12}^A 、 P_{23}^A 、 … 、 $P_{n-1,n}^A$, and P_{12}^B 、 P_{23}^B 、 … 、 $P_{n-1,n}^B$ stand for the load transferred between two adjacent bolts of plate B.

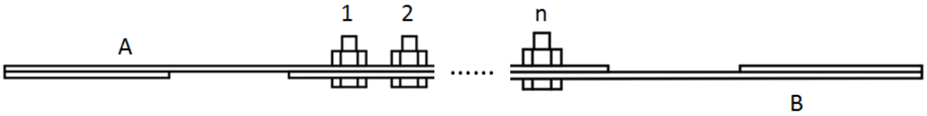


Figure 1 – The diagram of bolted hybrid composite/metal joint

Suppose the form of bolt load due to thermal stress is shown in ‘Figure 2 - The diagram of assumed structural load form’. The fit clearance between bolt and hole, friction between different assembly parts, bolt deformation caused by temperature, plastic deformation of aluminum alloy and the bending stiffness of the plate, etc. are not considered. The following equation can be obtained.

$$P_1+P_2+\cdots+P_n=0 \quad (1)$$

$$\left.\begin{array}{l} P_{12}^A=-P_1 \\ P_{23}^A=-(P_1+P_2) \\ \cdots \\ P_{n-1,n}^A=-(P_1+P_2+\cdots+P_{n-1}) \end{array}\right\} \quad (2)$$

$$\left.\begin{aligned} &P_{12}^{B}=P_1\\ &P_{23}^{B}=P_1+P_2\\ &\cdots\\ &P_{n-1,\mathrm{n}}^{B}=P_1+P_2+\cdots+\mathrm{P}_{n-1} \end{aligned}\right\} \tag{3}$$

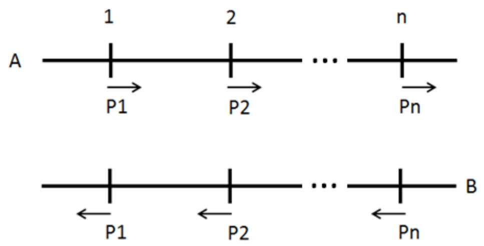
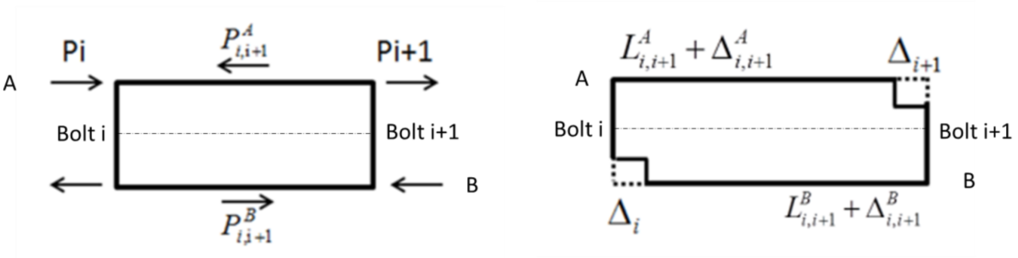


Figure 2 – The diagram of assumed structural load form

Take the adjacent bolts structures as a unit, the undeformed and deformed pattern are shown in 'Figure 3 - The diagrams of the undeformed and deformed pattern'.



(1) Undeformed pattern of a unit (2) Deformed pattern of a unit

Figure 3 – The diagrams of the undeformed and deformed pattern

$L_{i,i+1}^{A}$ and $L_{i,i+1}^{B}$ are the distance between two adjacent bolts, Δ_i is the shear deformation of bolts, the deformation between the two plates caused by thermal expansion and temperature-induced load are $\Delta_{i,i+1}^{A}$ and $\Delta_{i,i+1}^{B}$ respectively. The deformation compatibility equation of the unit is obtained as follows:

$$L_{i,i+1}^{A}+\Delta_{i,i+1}^{A}+\Delta_{i+1}=L_{i,i+1}^{B}+\Delta_{i,i+1}^{B}+\Delta_i \tag{4}$$

Because $L_{i,i+1}^{A}$ and $L_{i,i+1}^{B}$ are equal, the following equation can be obtained.

$$\left.\begin{aligned} &\Delta_1-\Delta_2=\Delta_{1,2}^{A}-\Delta_{1,2}^{B}\\ &\Delta_2-\Delta_3=\Delta_{2,3}^{A}-\Delta_{2,3}^{B}\\ &\cdots\\ &\Delta_{n-1}-\Delta_n=\Delta_{n-1,\mathrm{n}}^{A}-\Delta_{n-1,n}^{B} \end{aligned}\right\} \tag{5}$$

According to the definition of Δ_i , $\Delta_{i,i+1}^{A}$ and $\Delta_{i,i+1}^{B}$, those parameters can be expressed by equation (6)

$$\left.\begin{aligned} &\Delta_i=\frac{P_i}{K^D}\\ &\Delta_{i,i+1}^{A}=\frac{P_{i,i+1}^{A}}{K_{i,i+1}^{A}}+\alpha_A\Delta\mathrm{T}_A\,\mathrm{L}_{i,i+1}^{A}\\ &\Delta_{i,i+1}^{B}=\frac{P_{i,i+1}^{B}}{K_{i,i+1}^{B}}+\alpha_B\Delta\mathrm{T}_B\,\mathrm{L}_{i,i+1}^{A} \end{aligned}\right\} \tag{6}$$

The α_A and α_B are thermal expansion coefficients of two kinds of material consisted the plate along the tensile direction. The $\Delta\mathrm{T}_A$ and $\Delta\mathrm{T}_B$ are temperature change value of the two plates. K^D is the shear stiffness of the bolt. The $K_{i,i+1}^{A}$ and $K_{i,i+1}^{B}$ are the axial stiffness between the bolt i and i+1 in the two plates.

By substituting equation (6) into equation (5), the loads P_1、P_2、…、P_n can be calculated by formula (7). In formula (7), the parameters to be obtained mainly include the α_A, K^D, $K^A_{i,i+1}$ and $K^B_{i,i+1}$. An example is given to illustrate the application of the formula.

$$P=C^{-1}A \quad (7)$$

$$C=\begin{bmatrix} \frac{1}{K^D}+\frac{1}{K^A_{1,2}}+\frac{1}{K^B_{1,2}} & -\frac{1}{K^D} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{K^A_{2,3}}+\frac{1}{K^B_{2,3}} & \frac{1}{K^D}+\frac{1}{K^A_{2,3}}+\frac{1}{K^B_{2,3}} & -\frac{1}{K^D} & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{1}{K^A_{i,i+1}}+\frac{1}{K^B_{i,i+1}} & \frac{1}{K^A_{i,i+1}}+\frac{1}{K^B_{i,i+1}} & \cdots & \frac{1}{K^D}+\frac{1}{K^A_{i,i+1}}+\frac{1}{K^B_{i,i+1}} & -\frac{1}{K^D} & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{1}{K^A_{n-1,n}}+\frac{1}{K^B_{n-1,n}} & \frac{1}{K^A_{n-1,n}}+\frac{1}{K^B_{n-1,n}} & \cdots & \cdots & \frac{1}{K^A_{n-1,n}}+\frac{1}{K^B_{n-1,n}} & \frac{1}{K^D}+\frac{1}{K^A_{n-1,n}}+\frac{1}{K^B_{n-1,n}} & -\frac{1}{K^D} \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$$P=\begin{bmatrix} P_1 & P_2 & P_3 & \cdots & P_i & \cdots & P_n \end{bmatrix}^T$$

$$A=\begin{bmatrix} \alpha_A \Delta T_A L^A_{1,2}-\alpha_B \Delta T_B L^B_{1,2} & \alpha_A \Delta T_A L^A_{2,3}-\alpha_B \Delta T_B L^B_{2,3} & \cdots & \alpha_A \Delta T_A L^A_{i,i+1}-\alpha_B \Delta T_B L^B_{i,i+1} & \cdots & \alpha_A \Delta T_A L^A_{n-1,n}-\alpha_B \Delta T_B L^B_{n-1,n} & 0 \end{bmatrix}^T$$

4. Calculation Example

4.1 Problem Statement

The structure form of researched object in the example is shown in ‘Figure 1 - The diagram of bolted hybrid composite/metal joint’. The dimensions of composite plate and metal plate in the joint are shown in ‘Figure 4 - The dimensions of composite plate and metal plate’. The fiber orientations is [+45/-45/0/0-45/0/90/+45/0/-45/0/90+45/0]s. The thickness of single layer is 0.12mm and the reinforcing plate is made of aluminum with a thickness of 3mm. The metal plate is made of aluminum with a thickness of 3mm, and the reinforcing plate is made of aluminum with a thickness of 3.36mm. The material of bolts is 30CrMnSiA. ‘Tables 1 - The properties of composite material’, ‘Table 2 - The properties of aluminum alloy’ and ‘Table 3 - The properties of 30CrMnSiA’ show the properties of three materials.

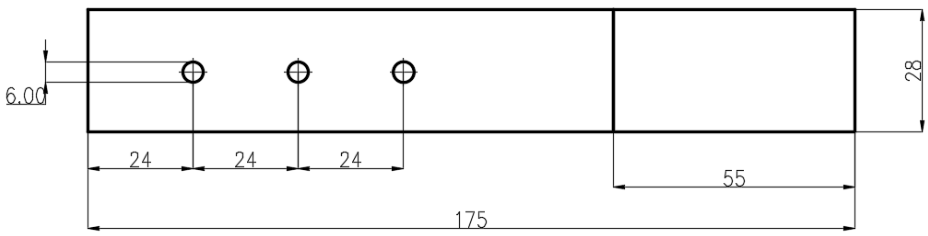


Figure 4 – The dimensions of composite plate and metal plate

Table 1 – The properties of composite material

Engineering constants	E_1/GPa	E_2/GPa	μ_{12}	G_{12}/GPa
	127	8.4	0.33	3.70
Thermal expansion coefficients	α1($10^{-6}K^{-1}$)	α2($10^{-6}K^{-1}$)	α3($10^{-6}K^{-1}$)	
	0.07	25.8	25.8	

Table 2 – The properties of aluminum alloy

E/GPa	μ	α($10^{-6}K^{-1}$)
71	0.3	23

Table 3 – The properties of 30CrMnSiA

E/GPa	μ	α($10^{-6}K^{-1}$)
210	0.3	8.8

4.2 Formula Parameter Calculation

4.2.1 Efficient of Thermal Expansion

A general formula to calculate the coefficient of thermal expansion of laminates is given in the reference [14]. In the case of symmetrical ply, the simplified calculation formula is shown as equation (8).

$$\begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix} = [A]^{-1} \cdot \sum_{k=1}^{N} [\bar{Q}]_k [T]_k \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{Bmatrix} \cdot (Z_k - Z_{k-1}) \tag{8}$$

In equation (8), [A] is the axial stiffness matrix of laminated plates, $[\bar{Q}]_k$ is the stiffness matrix of a single layer, $[T]_k$ is the conversion matrix of the coefficient of thermal expansion, same as the strain transformation matrix. By substituting the corresponding parameters, it can be concluded that the value of the coefficient of thermal expansion of composite is as follow.

$$\alpha_A = 0.95(10^{-6} K^{-1}) \tag{9}$$

4.2.2 The Axial Stiffness

Through material mechanics, the $K_{i,i+1}^A$ and $K_{i,i+1}^B$ in equation (6) can be calculated by equation (10)

$$\left.\begin{aligned} K_{i,i+1}^A &= E^A W^A t^A / L_{i,i+1}^A \\ K_{i,i+1}^B &= E^B W^B t^B / L_{i,i+1}^B \end{aligned}\right\} \tag{10}$$

E^A and E^B are the elastic modulus of the two plates along the tensile direction; W^A and W^B are the width of the two plates; t^A and t^B are the thickness of the two plates. Substituting the corresponding parameters, we can get the following results.

$$\begin{aligned} K_{i,i+1}^A &= 262.01(\text{kN}/mm) \\ K_{i,i+1}^B &= 248.50(\text{kN}/mm) \end{aligned} \tag{11}$$

4.2.3 The Shear Stiffness of The Bolt

The K^D in equation (6) can be calculated by finite element modeling. By establishing a single shear bolt joint finite element model, as shown in 'Figure 5 - The diagrams of single shear bolt joint finite element model', with the same structural form and the same width, hole diameter, thickness of the plate as the example.

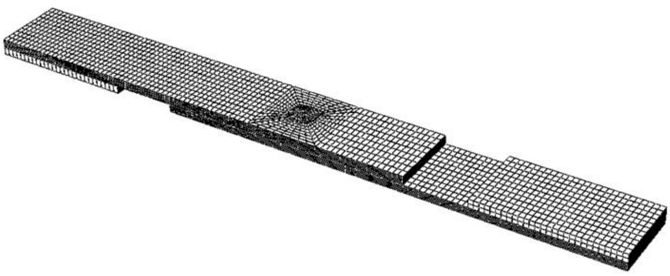


Figure 5 — The diagrams of single shear bolt joint finite element model

The shear deformation of bolts under different tensile loads is calculated respectively, furthermore, the shear deformation of bolts is defined as the relative deformation difference of two points in 'Figure 6 - The diagrams of the shear deformation of bolt'. The relationship between bolt load and shear deformation can be obtained, as shown in 'Figure 7 - The relationship between bolt load and shear deformation'. The slope is the shear stiffness K^D and the value is 28.517 kN/mm.

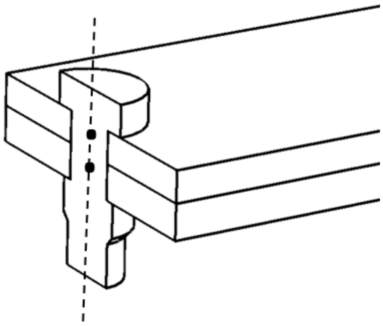


Figure 6 —The diagrams of the shear deformation of bolt

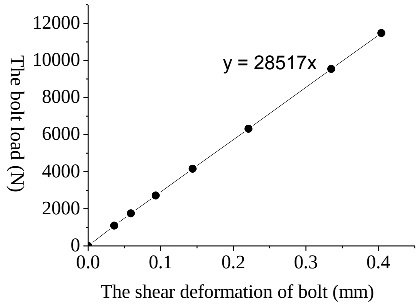


Figure 7 — The relationship between bolt load and shear deformation

4.3 The Result of Temperature-Induced Load

Taking the calculated parameters into formula (7), the load of the three bolts can be obtained, as shown in ‘Table 4 - The load value of the three bolts calculated by formula’. The accuracy of the theoretical analysis results is verified by the finite element modeling (FEM) simulation analysis.

Table 4 — The load value of the three bolts calculated by formula

Temperature condition	Bolt load (N)		
	Bolt1	Bolt2	Bolt3
71℃	629.01	0	-629.01
-51℃	-875.68	0	875.68

4.4 FEM Simulation Analysis of the Joint

With the development of FEM analysis technology, it has been widely used in structural stress analysis and strength prediction. In this example, the composite/metal three row single lap joint three-dimensional model is shown in ‘Figure 8 - The composite/metal three row single lap joint three-dimensional model’. The element type is set as C3D8R, with a total of 53505 elements. There are 13 contacts in total, including the contacts between the cylinder surface of three bolts and the surface of three circular holes in composite plate and aluminum alloy plate, the contacts between the surface of three gaskets and the surface of composite plate corresponding area, the contacts between the surface of three bolts’ head and the surface of aluminum alloy plate corresponding area, the contact between the lower surface of composite plate and the upper surface of aluminum alloy plate.

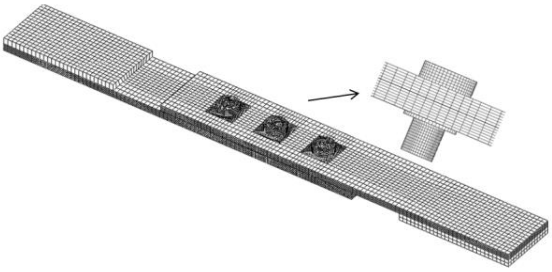


Figure 8 — The composite/metal three row single lap joint three-dimensional model

The initial temperature field of the model is set at 20 ℃, and the temperature fields of 71℃ and -55℃ are applied respectively. By reading the contact force in the model, the bolt load at high and low temperature can be obtained. The results of FEM analysis are shown in 'Table 5 - The load value of the three bolts calculated by FEM'.

Table 5 — The load value of the three bolts calculated by FEM

Temperature condition	Bolt load (N)		
	Bolt1	Bolt2	Bolt3
71℃	643.14	-3.64	-640.36
-51℃	-915.62	2.29	913.31

From the data, it can be seen that the results calculated by the theoretical formula are close to the results of the FEM analysis, and the relative calculation error of bolt load value on both sides is not more than 5%. It shows that the accuracy of the theoretical method can meet the needs of engineering calculation.

The 3D FEM analysis method can not only obtain the bolt load distribution and hole-edge stress, but also consider the influence of eccentric load, fit clearance and so on. However, accurate models often increase the complexity and consume a lot of computing resources. Especially for multi-bolt joints, not only the modeling workload is large, but also the increase of contact surface will bring the problem that the model is difficult to converge. Therefore, the parameters that affect the temperature-induced load of hybrid joint will be analyzed through the theoretical formula.

5. Analysis of parameters affecting temperature-induced load of hybrid joint

According to the formula (7), the main parameters affecting the load value include the material type of the joint; the stacking orientation of the composite; the structural form of the joint, such as the width and thickness of the composite plate and aluminum plate, the diameter of the bolt, the spacing of the bolt holes, etc. This paper mainly discusses the influence of the structural form of the joint on the temperature-induced load.

5.1 Parameter: adjacent bolts distance

Based on the structure form in the example, the distribution of bolt load under temperature field is shown in 'Table 6 - The distribution of bolt load when the distance between adjacent bolts is 48mm' when the distance between adjacent bolts increases from 24mm to 48mm.

Table 6 — The distribution of bolt load when the distance between adjacent bolts is 48mm.

Temperature condition	Bolt load (N)		
	Bolt1	Bolt2	Bolt3
71℃	1063.65	0	-1063.65
-51℃	-1480.77	0	1480.77

Continue to increase the adjacent bolts distance, the relationship between the increase multiple of adjacent bolts distance and the load value of bolts on both sides at 71℃ is shown in 'Figure 9 - The relationship between the increase multiple of adjacent bolts distance and the load value of bolts on both sides'. It can be concluded that the temperature-induced load of the structure is greatly affected before the adjacent bolts distance increases to 16 times, which means the adjacent bolts distance up to 384mm, and then the load value tends to be stable.

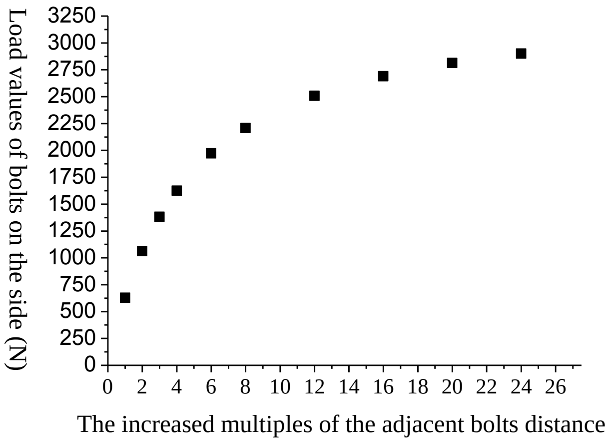


Figure 9 — The relationship between the increase multiple of adjacent bolts distance and the load value of bolts on both sides

5.2 Parameter: number of bolts

Based on the structure form in the example, there are two cases to consider.

1. When the total length of the joint increases, add the bolts with the fixed adjacent bolts distance
2. When the total length of connector is fixed, add the bolts with the decreasing adjacent bolts distance

In case1, the four row single lap joint is considered, which has the same structural style as the joint in the example, the bolt load distribution can be obtained from formula (7) as shown in 'Table 7 - The distribution of bolt load in case1'. Continue to increase the number of bolts, the relationship between the number of bolts and the load of bolts on both sides under 71℃ is shown in 'Figure 10 - The relationship between the number of bolts and the load of bolts on both sides'.

Table 7 — The distribution of bolt load in case1

Temperature condition	Bolt load（N）			
	Bolt1	Bolt2	Bolt3	Bolt4
71℃	842.60	261.40	-261.40	-842.60
-51℃	-1173.09	-363.91	363.91	1173.09

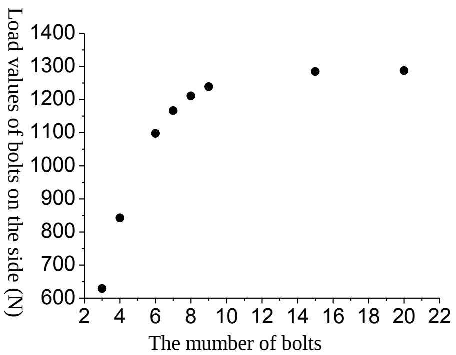


Figure 10 — The relationship between the number of bolts and the load of bolts on both sides

As can be seen from the figure, with the increase of bolt number, the load value of bolts on both sides is increasing, but the increasing range is decreasing and finally tends to be stable.

In case2, based on the three rows single lap joint with 384mm adjacent bolts distance, the relationship between the bolt number and bolt load was studied. When it adds to 4 bolts, the results of bolt load in two kinds of joint at 71℃ are shown in 'Table 8 - The results of bolt load in two kinds of joint at 71℃'. Continue to increase the number of bolts, the relationship between the number of bolts and the load of bolts on both sides, as well as the axial load on the plate near the middle can be obtained, and shows in 'Figure 11 - The relationship between the number of bolts and the load of bolts on both sides, as well as the axial load on the plate'.

Table 8 — The results of bolt load in two kinds of joint at 71℃

Structural form	Bolt load (N)			
	Bolt1	Bolt2	Bolt3	Bolt4
Three-bolt joint	2800.87	0	-2800.87	
Four-bolt joint	2672.06	492.78	-492.78	-2672.06

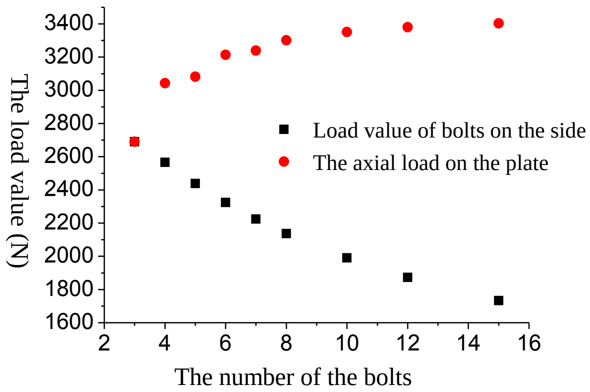


Figure 11 — The relationship between the number of bolts and the load of bolts on both sides, as well as the axial load on the plate

As can be seen in figure , with the increase of the number of bolts, the load value of bolts on both sides are decreasing, but the axial load on the plate are increasing .

6. Conclusions

Based on the theoretical formula for calculating the bolt load of bolted hybrid composite/metal joint in this paper, the parameters affecting the temperature-induced load of the structure are analyzed, including the adjacent bolts distance and the number of bolts. The conclusion is as follows.

1) In the hybrid composite/metal joint structures, the bolt loads caused by high or low temperature increases significantly with the increase of the adjacent bolts distance when the level is within a certain range. Once the distance exceeds to a certain value, the increase of the bolt loads will be very small and tend to be stable.
2) When the total length of the joint increases, in a certain range, with the increase of the number of bolts, the bolt loads will increases. Once the number exceeds to a certain value, the increase of the bolt loads will be very small and tend to be stable.
3) When the length of joints is fixed, with the increase of the number of bolts, the load value of bolts on both sides is decreasing, but the axial load on the plate is increasing.

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8. Copyright Statement

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