ATLANTIS PRESS
Advances in Engineering Research, volume 141
5th International Conference on Mechatronics, Materials, Chemistry and Computer Engineering (ICMMCCE 2017)

Finite Element Analysis of Multiple Bolted Connection between Composites and Metal Materials

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Key words: Composite; double-lap joints; pin-load distribution; finite element model

Abstract: Two finite element models based on PATRAN/ NASTRAN are carried out to determine the nail load distribution of double lap structure with composites and metal materials. And the results were compared with the classical stiffness algorithm to verify the simulation model is effectiveness to calculate pin load distribution. Results show that the pin load distribution of the double-lap joints is uneven. It has a similar shape to bathtub. The modeling method with CBUSH can be used in pin-load distribution and CGAP can be used in hole edge stress concentration of composite laminates. The conclusions have been obtained to offer useful engineering-oriented reference for the design of multi-fastener joints in laminated composite plates.

1. Introduction

In recent years, the usage of composite materials in aerospace structures has been increased rapidly for high modulus, high specific strength, good corrosion resistance, excellent fatigue resistance and outstanding designability characteristic[1]. At present, along with application of composites from non-bearing structure, secondary structure to primary structures such as wings and the fuselage, its usage has also become an important symbol of the aircraft advanced nature. Relative to metal structure, the application of composite materials improve the structural integrity in a certain extent, but there exist inevitably connection problems in structures due to the design, process and maintenance. However, connection parts are usually considered to be the weak links in static strength and fatigue strength of composites structural, so it have to be connection problem have to be good deal with to improve the efficiency of connection. And therefore must be very good to deal with connection problems to improve the connection efficiency.

At present, national and international scholars carried out a large number of analysis and research work about multiple nails connection structure of composites, including analytic method research, experimental study and finite element analysis [2]. The mathematical formula of analytic method owns complex derivation and large amount of calculation. It can only solve the simple and regular model, can't fully reflect the actual characteristics of the connection structure. Experimental study on the cost is large, and specimen processing is strict. Besides, it is difficult to study the many factors that affect the distribution and strength of nail load systematically, and the test result is decentralized. Therefore, with the development of large commercial finite element software, finite element method has been used to simulate the connection reality of fasteners. However, the key to simulate the squeeze relationship between fasteners and nail holes is whether finite element model is accurate.

There are many connection parts between composites and metal on the aircraft. In this paper, the MSC NASTRAN software is used to simulate the double lap connection between composites and metal with two simplified models. Afterwards, the analysis results are compared with the engineering algorithm-classical stiffness method, so as to obtain advantages and disadvantages of the two simplified methods.

2. Analysis method of composites connection

2.1. Engineering Algorithm of Composites Connection

Engineering algorithm - classical stiffness method is one of the main methods to solve the load distribution of composites, which is suitable for the structure of fasteners arranged more rules. The analytical method of the multi-row single-row nails connection used in this paper is based on the elastic statically indeterminate method, which takes into account the tensile stiffness of the connecting pieces, the diameter and pitch of the fasteners, but does not take into account the bending stiffness of the connected parts[3]. For the form of double lap connection by the 1 row×4 rows of nails (shown in Figure. 1), based on the coordination of deformation and force balance conditions, it can deduce the load equation of each fastener with classical stiffness method.

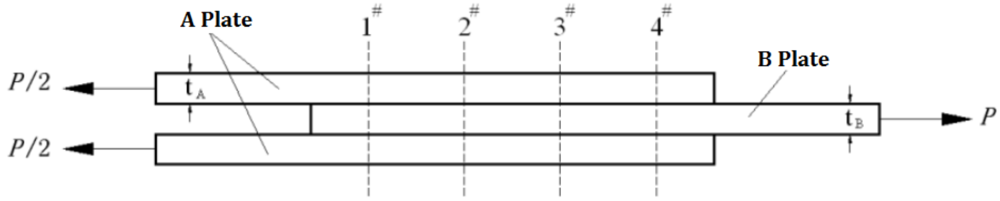


Figure. 1 Double lap connection by 1 row×4 rows

For the same upper and lower plates, the load of the fasteners is calculated as follows:

$$\{P_i\} = \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{Bmatrix} = [B]^{-1}\{C\} \tag{1}$$

In the formula:

$$[B] = \begin{bmatrix} \left(\frac{1}{K_1^S}+\frac{1}{K_{12}^A}+\frac{1}{K_{12}^B}\right) & \left(-\frac{1}{K_2^S}\right) & 0 & 0 \\ \left(\frac{1}{K_{23}^A}+\frac{1}{K_{23}^B}\right) & \left(\frac{1}{K_2^S}+\frac{1}{K_{23}^A}+\frac{1}{K_{23}^B}\right) & \left(-\frac{1}{K_3^S}\right) & 0 \\ \left(\frac{1}{K_{34}^A}+\frac{1}{K_{34}^B}\right) & \left(\frac{1}{K_{34}^A}+\frac{1}{K_{34}^B}\right) & \left(\frac{1}{K_3^S}+\frac{1}{K_{34}^A}+\frac{1}{K_{34}^B}\right) & \left(-\frac{1}{K_4^S}\right) \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{2}$$

$$\{C\} = \begin{Bmatrix} \frac{P}{2K_{12}^A} \\ \frac{P}{2K_{23}^A} \\ \frac{P}{2K_{34}^A} \\ \frac{P}{2} \end{Bmatrix} \tag{3}$$

P_i is the load of the i-th nail, P is the total load applied;

K_i^S is the shear stiffness of the i-th nail, $K_i^S = \frac{1}{\alpha}$, α is flexibility coefficient;

In the above formula, change A to B is the corresponding value of plate B.

2.2. The Simplified Method for Finite Element

2.2.1. CBUSH Method

The method uses combinatorial units to simulate the fastener. CBAR units are used to simulate the screw rod, but at the middle node add 2 CBAR units to simulate the nail or nut. Besides, CBUSH units are used to simulate lateral compression deformation between the plate and the nail, and simulate bending deformation due to the mutual sliding between the plate and the nail. What's more, RBAR units are used to ensure that there is no relative sliding between the plate and the fastener, and that the plate and the fastener have the same slope under the action of bending, as shown in Figure. 2.

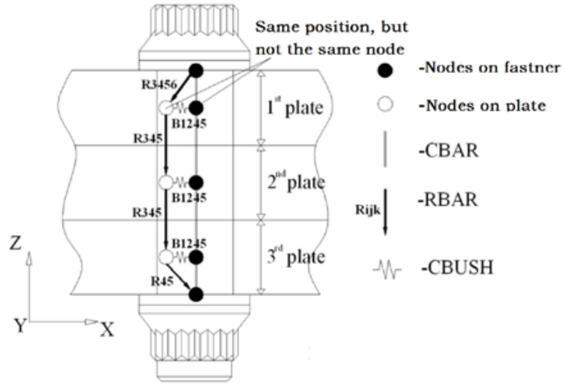


Figure. 2 Diagram of CBUSH method

The stiffness of the CBUSH unit consists of lateral extrusion stiffness and bending stiffness, where the lateral extrusion is due to the lateral compression deformation between the plates and the nails caused by the mutual sliding between the plates, whose stiffness is squeezed by the lateral extrusion stiffness of the plates and nails together. Bending extrusion is due to the relative rotation of the plate and the nail in the plate-nail section of the torque caused by the relative angle of change, the amount of change is determined by the rotational stiffness of the plate and the nail. The transverse extrusion stiffness S_{bi} is calculated as same as the formula (4).

$$S_{bi} = \frac{E_{cpi} \bullet E_{cf} \bullet t_{pi}}{E_{cpi} + E_{cf}} \tag{4}$$

In the formula: E_{cpi} is the elastic modulus of the connected parts; E_{cf} is the elastic modulus of the fasteners; t_{pi} is the thickness of the plate.

2.2.2. CGAP Method[4]

The method also uses combinatorial units to simulate the fastener. CBAR units are used to simulate the screw rod, but at the middle node add 2 CBAR units to simulate the nail or nut. Besides, CBUSH units are used to simulate lateral compression deformation between the plate and the nail, and simulate bending deformation due to the mutual sliding between the plate and the nail. What's more, RBAR units are used to ensure that there is no relative sliding between the plate and the fastener, and that the plate and the fastener have the same slope under the action of bending, as shown in Figure. 3.

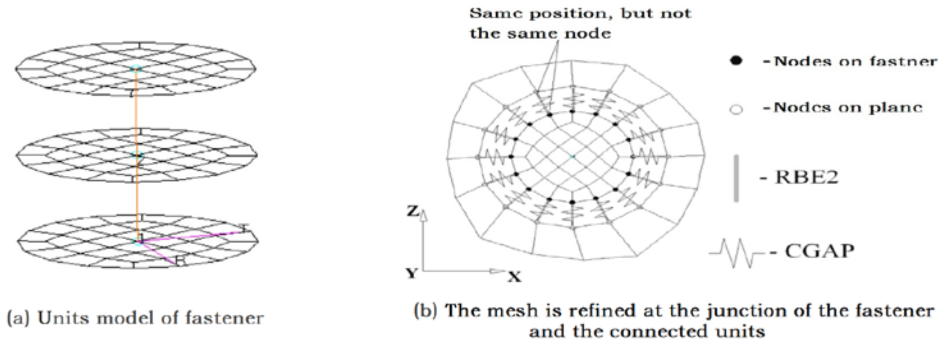


Figure. 3 Diagram of CGAP method

This method takes into account the contact relationship between the fastener and the plane, and establishes a one-to-one correspondence between the fastener node and the hole node. The fastener element is simplified as shown in Fig. 3, and simulated by CQUAD board unit. The open stiffness K_b and the closed stiffness Ka of the CGAP units are determined by the stiffness of the contact body, and the stiffness of the two contact bodies in the direction of the contact point x is $\widetilde{K_a}$ and $\widetilde{K_b}$, then the opening stiffness K_b and the closing stiffness Ka is:

$$K_\alpha \geq 1000 \times \max(\widetilde{K_\alpha}, \widetilde{K_b}) \tag{5}$$

$$K_b \geq 10^{-3} \times \min(\widetilde{K_\alpha}, \widetilde{K_b}) \tag{6}$$

3. Finite element calculation and analysis

Composites and metal double lap structure single row 4 rows nail connection form is shown in Figure. 4, where the upper and lower plane is the composite laminate which made of T300/QY8911(the total thickness is 4mm, single layer thickness is 0.125mm, a total of 32 layers by paving order $[\pm 45°/0°/90°]_{4S}$). The middle plane is made of aluminum alloy, the material is 7075-T651, the thickness is 4mm. Fasteners for the M hexagonal bolts, the material is 30CrMnSiA. In the calculation, the six degrees of freedom at the left end of the laminate plate were calculated, and the X-direction force was applied to the right end of the metal plate, and the total load was applied to 14 KN. The material properties are shown in Table 1.

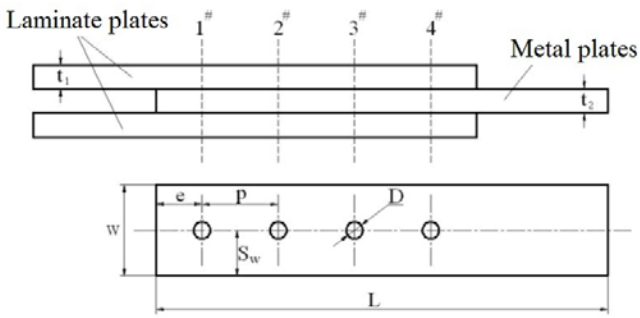


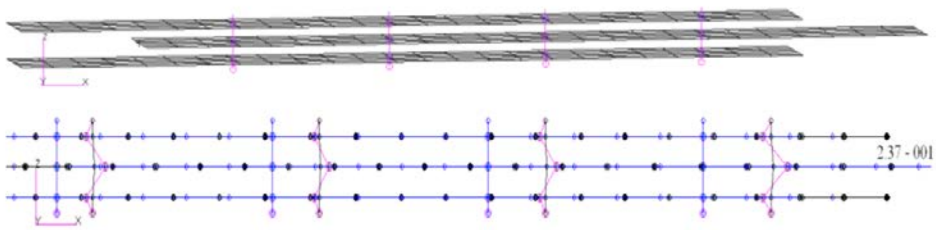
Figure. 4 Connection form diagram of double lap structure between composites and metal single row 4 row nail

In order to avoid the low-strength failure of splitting or shearing in the mechanical connection of the composite, the geometrical parameters of the connected plate generally follow the following principles[5]: W/D⩾4, e/D⩾3, P/D⩾5, S_w/D⩾2.5. Besides, plate is long enough to achieve a uniform stress σ_x before reaching the hole under the reaction force of the plate end node. In this paper, the diameter of the bolt hole of the connecting plate is 8mm, so take W=48, e=24, p=40, S_w=24, L=250.

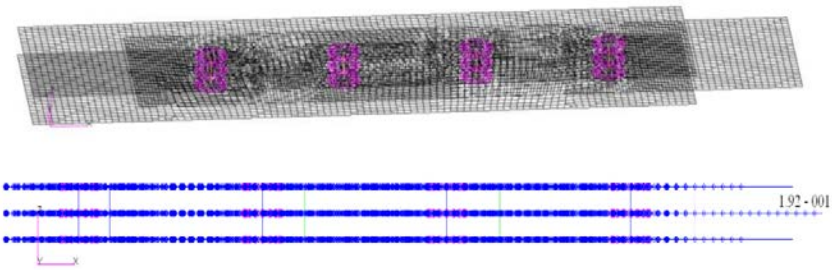
Table 1 Material properties

Material Name	E_{11}/Gpa	E_{22}/Gpa	G_{12}/Gpa	ν_{12}
Single plate	135	8.8	4.47	0.33
Laminate equivalent parameters	53.2	53.2	18.7	0.294
7075-T651	71		27	0.33
30CrMnSiA	196		75.5	0.3

The two kinds of simplified methods are used to calculate the pinning and distribution ratio of each fastener, and the results are compared with the classical stiffness method. In the calculation, the six degrees of freedom of the left end node of the upper and lower plate model were restrained, and the load distribution are imposed on the right end node of the middle plate model. The simplified model and the calculation result are shown in Fig. 5.



(a) CBUSH model and its deformation diagram



(b) CGAP model and its deformation diagram

Figure. 5 Finite element model of two methods and corresponding deformation diagram

Compared with the two calculation methods, we can find that the deformation diagram is basically the same, in which the finite element model of CBUSH is the most deformed because it takes into account the bending deformation and extrusion deformation of the fastener, while the other two methods only consider extrusion deformation. The plates in the CELAS2 method clearly have warping in the Z direction because the method assumes that the fasteners are consistent with the deformation of the plate, which will cause bending and mutual interference between the plates being connected, resulting in the actual structure, where is no additional stress. is shown in Table 2 and Fig. 6.

Table 2 The result comparison between the classical stiffness method and the finite element method

Analytical Method	Load ratio(%)				load error(%)			
	1#	2#	3#	4#	1#	2#	3#	4#
Classical Stiffness	27.2	19.0	20.7	33.2	0	0	0	0
CBUSH	25.8	20.0	21.9	32.4	-5.2	5.3	5.9	-2.5
CGAP	26.2	18.9	21.1	33.8	-3.7	-0.3	2.2	1.8

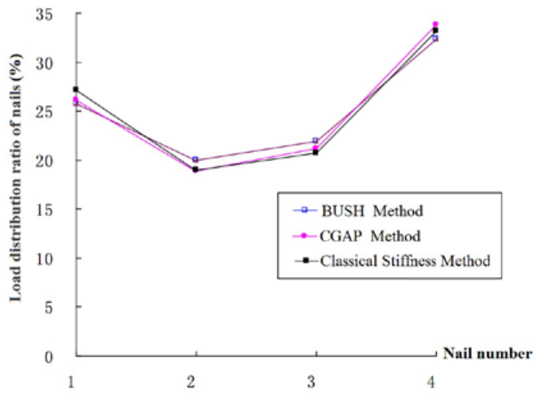


Figure. 6 Load distribution ratio of nails

Comparing Table 2 and Figure 7 to calculate the results, you can get the following conclusions:

1) The load distribution of the nails in the single row 4 row nails connection structure presents asymmetric "bathtub", the maximum bearing proportion of the nail is about 33%, the minimum bearing proportion is below 20%, the difference is very big.

2) Compared with the classical stiffness method, the CGAP method is the closest to the engineering algorithm. However, it is not appropriate to use the CGAP method to solve the nail load because the nail and the hole contact surface are unknown. The contact elements need to be set on the whole circumference, and the modeling work is large; What's more, the contact analysis needs more iterative calculation and more time.

3) If only the load distribution ratio between nails is calculated, all two finite element models are acceptable. However, when it is necessary to study the stress distribution around the nail hole, the simulate result is too large by the CBUSH method. The main reason is that the actual structure is to rely on nail hole compression surface to pass nail load, and these two methods rely solely on a node to pass the concentrated load. At this time, the CGAP method can be a good simulation of the nail around the contact surface and stress distribution.

4. Conclusion

In this paper, two kinds of finite element method are used to study the nail load distribution of the double lap structure between composites and metal materials. Besides, through the comparison between the results of the finite element calculation and the classical stiffness method, there are formed some conclusions as follows:

(1) The nail load distribution of single row 4 row nail connection structure is shown asymmetric "bathtub" shape;

(2) CBUSH method is appropriate to calculate the distribution of the nail load ratio;

(3) CGAP method is appropriate to calculate the stress details of the surrounding hole.

References

[1] Nagaraja Shetty , S.M. Shahabaz, S.S. Sharma. ete. A review on finite element method for machining of composite materials[J]. Composite Structures, 2017(176): 790-802.

[2] Longwei Zhou, Donghua Zhang, Libin Zhao, etc. Design and analysis of a novel bolted composite π joint under bending load[J]. Materials & Design, 2016(98): 201-208.

[3] P.J. Maljaars, M.L. Kaminski, J.H. den Besten. Finite element modelling and model updating of small scale composite propellers[J]. Composite Structures, 2017(176):154-163.

[4] Chao Zhang, Enock A. Duodu, Jinan Gu. Finite element modeling of damage development in crossply composite laminates subjected to low velocity impact[J]. Composite Structures, 2017(173): 219-227.

[5] Jingze Wang, Yanqi Li, Fuhong Dai. A micromechanical relaxation model of composite bolted connections based on viscoelastic theory[J]. Composite Structures, 2016(146): 14-25.