Numerical Method on Load Sharing Problem of Thick Laminate Joints

LIU Long-quan* (刘龙权), CHEN Kun-kun (陈昆昆), ZHANG Jun-qi (张俊琪)
LIU Wu-xia (刘无瑕), WANG Hai (王海)
(School of Aeronautics and Astronautics, Shanghai Jiaotong University, Shanghai 200240, China)

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Abstract: Accurately and efficiently predicting the load sharing of multi-bolt thick laminate joints is necessary to quicken the optimization of the large-scale structures over various design variables, and a two-dimensional (2D) finite element method (FEM) is introduced to meet such a demand. The deformation contributions of the joint zone are analyzed and calculated separately, including the shearing deformation of the fasteners shank, the bending deformation of the fasteners shank, and the bearing deformation of the fasteners and joint plates. These deformations are all transferred and incorporated into the components of the fastener’s flexibility. In the 2D finite element model, the flexibilities of the beam elements and bush elements are used to simulate different components of the fastener’s flexibility. The parameters of the beam elements which include the bending moment of inertia and intersection area, and the parameters of the bush elements which include the stiffness in different directions, are all obtained through equalizing the fasteners flexibilities. In addition, the secondary bending effect introduced by the single-lap joints is also taken into account to verify the flexibilities of the fasteners in practical application. The proposed FEM is testified to be more accurate than the traditional 2D FEMs and more efficient than the three-dimensional (3D) FEM in solving load sharing problem of multi-bolt single-lap thick laminate joints. With the increase of joint plates’ thickness, the advantages of the proposed method tend to be more obvious. The proposed 2D FEM is an effective tool for designing bolted joints in large-scale composite structures.

Key words: load sharing, thick laminate, fastener flexibility, finite element, single-lap

CLC number: TB 331 Document code: A

0 Introduction

Thousands of bolts are needed to connect components together in composite aircraft structures[1]. Composite joints design is very critical since the airplane joints are often the weakest parts in aircraft structures, and it has caused 70 percent of the composite structure failures[2-3]. With the extension of composite materials from secondary load carrying structures to primary load carrying structures, the composite structures have become thicker, and the thick composite bolted joints not only have inherited the problems existed in thin composite joints, such as complicated stress concentration and low load re-distribution capability, but also have produced more severe problems, such as non-uniform stress distribution in the through-the-thickness (TTT) direction because of the increased secondary bending effect in single-lap joints[4-6]. All of these will influence the load sharing among the multiple fasteners in thick laminate joints, and the optimization of load sharing is the key to increase the joint strength.

The load sharing problem normally can be solved by using test and numerical method. When using the test method which measures the strain distribution between the fasteners, the load sharing among the multiple fasteners can be obtained. However, test method is quite expensive and time-consuming, and it is inappropriate to be used in the design phase. Using the three-dimensional (3D) finite element method (FEM) to simulate the composite mechanical joints under tensile load is resource-oriented[7]; furthermore, it cannot calculate the results of the multi-bolt joints in large-scale composite structures by using traditional computers. Thus, the two-dimensional (2D) FEM has been applied to solve the load sharing problem of composite mechanical joints by many scholars. For example, the spring-based method introduced by Tate and Rosenfeldt[8] is believed to be the earliest and simplest method. Based on the above method, Hart-Smith and other researchers[9-11] have created an empirical method, which employs the stress concentration factor and the joint efficiency to study the influences of joint geometry configuration and tightening torque on load sharing. Griffin et al.[12] have proposed a load-sharing solving method to analyze multi-fastener joints constituting a composite skin among metallic splice plates,
but the out-of-plane deformation has not been considered in their study. McCarthy et al.\cite{14} have proposed global bolted joint model (GBJM), a highly efficient 2D modeling strategy on bolted composite joints, which can consider many aspects, such as bolt-hole clearance, bolt torque, friction between laminates, secondary bending, and tertiary bending in laminate plates. But this method does not take the thickness effect into consideration. Ekh and Schon\cite{15} have brought forward a computationally effective model via structural FEM. The model is geared towards the accurate predictions of load sharing among the fasteners and accounts for bolt-hole clearances, the bolt clamp-up and the member plate friction. But it also does not consider the thickness effect. Considering the interaction of the fasteners and joint plates in detail, Rutman et al.\cite{16-17} have developed two fastener modeling methods for joining metal parts and composite parts, respectively; these two methods have already been incorporated into the Patran V2005 and V2010, respectively. However, they are just applicable to double-lap joints, and cannot deal with the single-lap joint problems.

The previous studies, applying 2D FEMs, have made great contributions in solving the load sharing problems in multi-fastener thin-laminate joints. However, the secondary bending effect will increase with the increase of joint plates’ thickness, and this will bring two problems. Firstly, the non-uniform load distribution of the fastener shank along the thickness direction cannot be ignored any more. Secondly, the load of the fastener shank will be more concentrated in the area which is close to the shearing plane (adhering surface between the joint plates). And the traditional 2D FEMs mainly focus only on thin plate structures and ignore the fastener’s non-uniform load distribution in the thickness direction induced by the second bending effect; thus, it is not accurate enough to solve the load sharing problem in thick laminate joints by using the traditional 2D FEMs. In summary, both the test method and the 3D FEM are time/cost consuming, and 2D FEM is not reliable any more. Hence, based on analyzing the flexibility of the joints and experimental verification, a more effective and accurate 2D FEM which aims to calculate the load sharing in multi-bolt single-lap thick laminate joints, will be introduced in this paper.

1 Fastener Flexibility

1.1 Force Analysis of the Fastener Under Uniform Load Distribution

A typical tensile loaded two-bolt single-lap joint is shown in Fig. 1. The left end of the joint is fixed and the right end of the joint is subjected to a tensile load \( F \) which is parallel to the faying surface of the two joint plates.

![Fig. 1 A typical two-bolt single-lap joint](image)

With regard to thin plate joints, it can be assumed that the fastener load is uniformly distributed in the TTT direction, and the loading conditions of the fastener shown in Fig. 1 can be illustrated as shown in Fig. 2(a). In Fig. 2(a), \( t_1 \) and \( t_2 \) represent the thicknesses of plate 1 and plate 2, respectively; \( l \) represents the clamping length of the fastener, which is equal to the sum of \( t_1 \) and \( t_2 \); points “a” and “b” represent the intersection points between the axis of the fastener and the two neutral planes of the joint plates, respectively; \( F_1 \) and \( F_2 \) represent the uniformly distributed bearing force of unit length on the fastener shank, which are exerted by plate 1 and plate 2, respectively; both \( F_1 t_1 \) and \( F_2 t_2 \) are equal to the tensile load \( F \).

The loading conditions shown in Fig. 2(a) is a statically indeterminate system, and it can be divided into a cantilever subjected to bearing loads and bending moment, as shown in Figs. 2(b) and 2(c), respectively. And \( M \) shown in Fig. 2(c) is the moment introduced by the contact force between the fastener head and the outer surface of plate 2.

According to Ref. [17], the rotation angles of the right end of the fastener shank produced by \( F_1 t_1 \), \( F_2 t_2 \) and \( M \) can be obtained by

\[
\theta_1 = \frac{F_1 t_1^3}{6EI}, \quad (1)
\]

\[
\theta_2 = -\frac{F_2 (l^3 - t_1^3)}{6EI}, \quad (2)
\]

![Fig. 2 Loading conditions of the fastener](image)