Composites Part B 100 (2016) 176–185

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Analytical modeling for stress distribution around interference fit holes on pinned composite plates under tensile load

Tao Wu, Kaifu Zhang*, Hui Cheng, Ping Liu, Danlong Song, Yuan Li

The Ministry of Education Key Lab of Contemporary Design and Integrated Manufacturing Technology, Northwestern Polytechnical University, West YouYi Road 127#, Xi'an, Shaanxi, 710072, China

A R T I C L E I N F O

Article history:
Received 20 February 2016
Received in revised form
23 May 2016
Accepted 3 June 2016
Available online 6 June 2016

Keywords:
Laminates
Residual/internal stress
Analytical modelling
Joints/joining
Interference fit

A B S T R A C T

Interference fit can bring benefits such as fatigue life enhancement to mechanical joints. In this paper, an analytical method is proposed to calculate stress around interference fit holes on composite pinned plates under tensile load. Displacement and load conditions along the edge of hole are analyzed. Load transfer affected by interference deformation is solved by spring-mass model. Stress functions considering interference stress and tensile load are developed to calculate stress components. Experiment results in reference and 3D finite element models are used to verify the accuracy of the proposed method, and good agreement is observed. The effects of ply property, ply stack and load level on stress distribution are discussed. Ply property and ply stack show obvious effects on stress distribution, and the effects are more apparent on hoop stress than on radial stress. Stress increase introduced by tensile load depends on contact state of the pin and hole, and it is apparently decreased when the pin and hole are not separated.

1. Introduction

Composite materials have been widely used in aircraft industry due to their high mechanical properties and low weights [1]. On these applications, mechanical joints, such as pinned and bolted joints, are required for their simplicity and easiness to disassemble [2–4]. However, mechanical joints require drilling holes, which causes stress concentration and does harmful to mechanical properties [5]. Interference fit is thought to be able to improve the joints' mechanical performance by introducing residual compressive stress, and has drawn the attention of researches in the past years [6].

The schematic diagram of interference fit joints is shown in Fig. 1. An oversized pin is installed into a hole, and plates deform due to the squeeze of the pin. Final radius of the holes is $R2(r<R2<R1)$. Especially, if the pin is viewed as rigid, $R2$ will equal to $R1$. Interference value (I), which decides the pre-deformation and residual stress around holes before loading, affects the mechanical behavior of joints and is commonly limited in the range no larger than 3% [6].

$$I = \frac{R-r}{r} \times 100\%$$

Stress in the vicinity of joints, where damage always happens, is an important factor for design and safe evaluation. Due to the anisotropic property, stress around composite interference fit joints is affected by several factors such as material direction, I and applied load, which is more complex than in metal cases and should be analyzed.

Stress around interference fit joints on isotropic structures has been studied by experimental, analytical and numerical methods. Regalbut et al. [7] conducted experimental and analytical analyses on interference fit structures of isotropic material under uniaxial tension, and good agreement were observed between these two methods. Antoni et al. [8] proposed analytical models for bush fitting and pin-loading conditions in isotropic material structures. Calculation of the stress distribution around lugs was done. Vallieres et al. [9] studied the fatigue behavior of aluminum interference-fit structures with short edge margins. Experimental and finite element analyses were implemented. Kumar et al. [10] developed a finite element contact stress algorithm to study interference fit pins with radial through cracks. The effects of crack length and edge distance on the contact, stress intensity and stress distributions were showed.

Due to the differences between composites and isotropic

* Corresponding author.
E-mail address: zhangkf@nwpu.edu.cn (K. Zhang).

http://dx.doi.org/10.1016/j.compositesb.2016.06.011

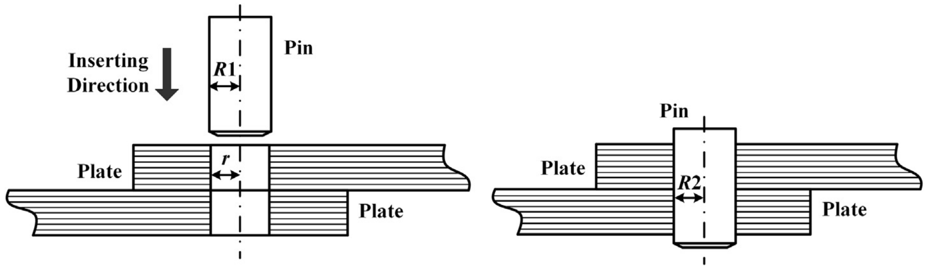

Fig. 1. Schematic diagram of interference fit pinned plates.

materials, the mechanic effects of interference fit, including residual stress and fatigue life improvement, on composite structures have been analyzed. Wei et al. [11] studied the effects of interference fit size on fatigue life of double lap-type single bolted composite joints. Experiment results showed that the interference fit could improve fatigue life. Kapti et al. [12] investigated the effects of interference-fit on bearing strength and failure mode in composite plates with experimental and numerical methods. Stress and strain distributions of GFRP interference fit pin structures were analyzed by Kim et al. [6]. 3D simulation and experiments were conducted. Di Scalea et al. [13] studied the elastic behavior of composite plates loaded in tension through pins. Both of clearance and interference fits were examined. Finite element method (FEM) with nonlinear contact was employed and results verified that interference can improve the fatigue life of joints. Song et al. [14] developed an analytical method for stress distribution of interference-fit area around composite laminates joints. The method was based on Lekhnitskii complex potential theory. The effects of ply orientation and interference percentage have been discussed.

Stress distribution around composite mechanical joints subjected to tensile load has always been a focus of researchers. Ramamurthy [15] employed FEM with inverse technique in stress distribution analysis of clearance fit pins subjected to bearing load. Nonlinear effects of load parameter and load type on maximum bearing stress on the hole boundary was observed. Kelly and Stefan [2] investigated the effects of bolt-hole clearance on stress field near the hole by 3D nonlinear FEM. Results showed that clearance had significant effects on both stress magnitude and distribution. McCarthy et al. [16] developed 3D progressive damage finite element models for multi-bolt composite joints. Stress, damage and load re-distribution after bearing failure could be obtained by this work. Bearing stress of countersunk composite joints was analyzed by Chishti et al. [17]. Finite element model was built in Abaqus/Explicit with continuum shells employed to model in-plane ply failure. The stress and strain distribution in the sandwich pin-contact structures under compressive bearing load was investigated by Di Bella et al. [18] using finite element method. Bearing stress was also obtained by experiments. Combined with failure criterion, stress analysis by FEM could be further used in strength prediction as it was shown by Atas and Soutis [19]. Finite element models including cohesive zone elements were developed and the effects of joint geometries and laminate lay-ups were discussed. In the research of Kishore et al. [20], failure in composite joints was analyzed using 3D finite element models. Von-Mises stress was employed in progressive damage analysis, and the propagation of damage was predicted. Zhou et al. [21] developed a fatigue model to predict multiaxial fatigue life of composite bolted joints. FEM was employed to obtain stress state of the joints under constant amplitude cycle loading. Qin et al. [22] used 3D FEM to analyze the stress and deformation of double-lap bolted joints with perfect or clearance fit. The effects of fastener types, protruding head or countersink, are discussed.

Analytical methods were also employed in stress distribution analysis of pin-loaded composite structures, and the Lekhnitskii complex potential theory has been proved quite useful. De Jong [23] developed an analytical model to investigate the stress distribution around a pin-loaded hole in an elastically orthotropic or isotropic plate. Kratochvil et al. [24] analyzed the stress distribution of composite bolted joints. The Lekhnitskii complex potential method was employed, and underlying boundary conditions were used to determine the coefficients in stress functions. Naidu et al. [25] successfully applied the Lekhnitskii theory in finite composite plates with smooth rigid pins. All of interference, perfect or clearance fit cases were discussed. By directly assuming the radial stress in the form of Fourier series, they presented the stress functions, in which the unknown constants were solved by a successive integration technique. Lie et al. [26] developed a method to analyze the stress and strength of joints with multiple fasteners. Fastener force was calculated by boundary element equations, and stress distribution was then obtained based on it. Echavarria et al. [27] developed a compact analytical solution for stress analysis around pin-loaded hole in orthotropic plates. The method could minimize the computational effort with acceptable accuracy. As a milestone, Zhang et al. [28] creatively developed a compact method for stress distribution calculation of perfect fit pin-loaded joints. Stress functions were expressed in the form of trigonometric series with two terms, and unknown coefficients were determined by displacement expression. This method directly connected the stress expression and displacement condition, and has been used in researches [29–32] due to its impressive convenience and accuracy. Aluko [29] built a more detailed model on the basis of Zhang' method. Stress expression with four terms was proposed and the effects of friction were analyzed. In another paper [30], characteristic curve theory was employed and the failure strength of pin loaded composite joints could be obtained. Olmedo et al. [31] proposed an analytical model to analyze the strength of pinned composite plates. Zhang's method has been used in stress calculation in this model.

Researches have been done on interference stress and pin-loaded stress using both analytical and numerical methods. The effects of material property, geometry sizes and load have been discussed. However, for composite interference fit joints under load, the load and displacement conditions are changed by combined effects of load and interference deformation, and methods for stress analysis considering these condition differences are still needed for these joints.

In this paper, an analytical method is proposed to calculate the stress distribution around composite pin-loaded holes with interference fit. Displacement condition of the holes was analyzed, and corresponding expressions consisting of pin-loaded term based on Zhang' method and interference fit term is developed. Load transfer regulation is analyzed by modified spring model, based on which