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Stress distribution modeling for interference-fit area of each individual layer around composite laminates joint

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The discussion about nonuniform stress distribution around interference-fit joint is particular significance in the design of composite laminates structures. In order to investigate the stress distribution of interference-fit area around composite laminates joint, an analytical model is developed for stress distribution based on the Lekhnitskii's complex potential theory. The normal and tangential stresses of contact are achieved by the relationship of deformation between pin and hole. The effects of ply orientation and interference percentage on stress components distributions of each individual layer around symmetrical laminates joint are discussed. In order to verify the validity of the analytical model, extensive 3D finite element models are established to simulate the stress components of laminates interference-fit joint. The results show that the analytical model is valid, and the laminate property and ply orientation have a significant effect on stress distribution trend while interference percentage mainly affects stress magnitude.

1. Introduction

High performance fiber reinforced plastics (FRP) have plenty of advantages over conventional metal materials, and are widely used in aerospace technology, automobile and many other weight sensitive structures. In the structures assembly technology, composite laminates are usually fastened to other structural components by mechanical joints such as bolts and rivets. According to statistics, composite laminates joint is the weakest part of the structures where 60%–80% of structure failure occurs at the fastening joints [1]. The interference fit technology of joint was proved that it can improve the fatigue life of metal structures observably [2,3], but also was pointed out by the McDonnell Douglas Corporation that interference-fit joining improved the fatigue life of carbon epoxy composites [4–6]. Interference fit joints require drilling holes and pressing into the metal pin, which causes nonuniform residual stress and damage to the joints. The residual stress is related to interference percentage, fiber orientation and material property directly. The appropriate stress contributes to improving the fatigue performance of structures, but oversize stress will damage the structures. However, the stress distribution around interference-fit joint is quite complex. In order to optimally design and evaluate the damage of these interference-fit joints after being jointed, it is very necessary to determine the residual stress of interference-fit area around composite laminates joints.

Extensive researches about stress distribution around joints or holes have been discussed, especially in the case of pin-loaded joint, which is also a problem about contact between hole and pin and provides reference for the interference fit case.

The determination of stress and strain distribution in notched composite plates, which is the basis of research, has been in the focus of many researchers for a long time. In the literature, many studies can be found using experimental, FEM and analytical methods. For complicated stress problem of elastic theory, Muskhelishvili [7] firstly introduced complex potential theory, deduced stress function and boundary condition, and then obtained accurate solution of stress distribution successfully. Analytical solutions for the stress distribution around different shapes of holes in anisotropic plates have been given by Lekhnitskii [8] using complex series method. Savin [9] presented a much simpler approach by conformal mapping and Cauchy integrals. There are many literature focusing on the stress distribution around cutout of finite and infinite composite plate with external loading in recent years. Ukadgaonker et al. [10,11] developed a general solution for stresses

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around triangular and arbitrary shape of holes in symmetrical laminates and unsymmetrical laminates under in-plane loading. Hufenbach et al. [12–15] published several analytical results of stress concentration for the case of elliptical, triangular, or square holes in single-layered composite plates and finite outer boundary. Wu and Mu [16] proposed an empirical calculation method for the stress concentrations for isotropic/orthotropic plates and cylinders with a circular hole, and the results agreed well with the FEM simulations which provided structure engineers a simple and efficient way to estimate the hole effect on plate structures or pressure vessels made of isotropic or orthotropic materials. Foust et al. [17] obtained the full-field individual stresses and strains throughout a finite pinned-wood joint with applying a thin birefringent coating by grey-field reflective photoelasticity test. Toubal et al. [18] experimentally investigated the tensile strain field of composite plates in the presence of stress concentration caused by geometrical cutout consisting of circular hole by Electronic Speckle Pattern Interferometer (ESPI).

Stress distribution for composite laminates with pin-load joint is investigated on the condition that the load of pin is given or supposed by experience, and they are clearance fit. De Jong [19] Zhang and Ueng [20] utilized the complex stress functions and obtained a compact analytical solution of stresses around a loaded hole with rigid pin in orthotropic plates including frictional effects. Grüber et al. [21] discussed the problem of stress concentrations in the area of pin-loaded holes. The load of pin was assumed to be a sinusoidal normal distribution of edge forces on a continuous part of the notch edge. Aluko O and Whitworth HA [22] developed an analytical method for stress components by displacement boundary method, with four trigonometry items, and friction effects were included in this research. The results showed that friction affected the stress distribution around the hole, and the maximum of stresses changed with values of frictional coefficient.

There are some research literature focusing on stress distribution for composite laminates with interference-fit joint utilizing numerical and experimental methods. Chakherlou [2] simulated cold expansion, a bigger pin squeezing through the smaller hole of plate by a 3-D FE model and calculated the residual stress distribution near the hole. Sundarraj et al. [23] achieved the 3-D stress distribution in a double-shear lap joint with interference-fit pin subjected to in-plane loads using FELJNT that is a finite element software developed for the special purpose, and the effects of clamping and flexure of the bolt are considered. Pradhan and Babu [6] created 3-D finite element models to simulate interference-fit pin-loaded joints in various composite laminates and study the effects of interference percentages for different material cases on circumferential edge stresses, stresses across the weakest section, and the out-of-plane stresses around the hole periphery. Lewis et al. [24] measured the contact stresses in a real shaft-sleeve interference-fit contact by an ultrasonic technique. The results from the experiment and FEA compared well both in the center of the fit and around the edges.

All the remarkable works contribute a lot to the analysis of the stress distribution of composite laminates. Compared with FE and experimental methods, the analytical solutions of stress distribution have many advantages in terms of reducing computation time, experimental cost and establishing theoretical basis for damage and failure. Most of the analytical solutions reported were mainly based on the fundamental works of Musskhelischwili and Lekhnitskii and integrated the mathematical methods of complex potential, conformal mapping and analytical continuation. However, these researches mainly focused on pin-loaded cases with clearance or snug fit where the pin was treated as rigid body and analytical solutions of stress distribution for composite laminates with interference-fit joint is not reported very often.

This paper is concerned with the stress distribution and magnitude of interference-fit area around composite laminates joint where the pin is made of elastic metal. An analytical method is developed for stress distribution based on Lekhnitskii's complex potential method. The normal and tangential stresses of contact are achieved by the relationship of deformations between the pin and hole. The effects of fiber orientation and interference percentage on stress distribution of individual layer around symmetrical laminates joint are discussed. In order to verify the validity of the analytical model, extensive 3-D finite element models have been established to simulate the stress components of interference-fit area around composite laminates joint. The stress components distributions of each individual layer and various interference percentages for two different composite laminates obtained from the analytical model are compared with the numerical results respectively.

2. Analytical modeling for stress distribution

2.1. Problem configuration of interference-fit joint

An infinite thin symmetrical anisotropic composite laminate with single-lap interference-fit joint, the initial diameter of pin is larger than that of hole, is considered. The geometry and configuration is shown in Fig. 1. Based on the elastic theory of anisotropic plate by Lekhnitskii [8], we can simplify the loaded laminates as a two-dimensional as a generalized plane stress problem. Multilayer CFRP (Carbon Fiber Reinforced Plastics) plate widely used in aviation is a kind of composite laminate layered by unidirectional carbon fiber reinforced lamina. The pin made of elastic metal, such as TC4, is pressed into the hole by the method of cold expansion. In the aerospace industry, relative interference percentages of diameter from 0.6% to 2% are usually used for composite laminates joints [2,25].

The relative interference percentages is defined in engineering application as

$$I = \frac{d_0 - D_0}{D_0} \times 100\% \tag{1}$$

where d_0 is the initial diameter of pin, and D_0 is the initial diameter of hole.

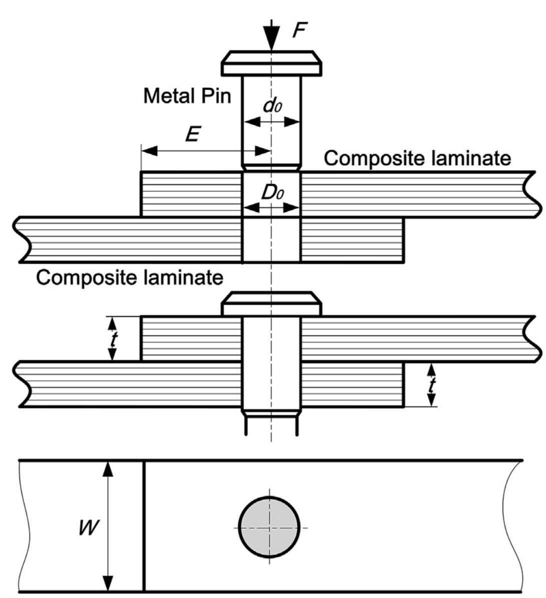

Fig. 1. Geometry and configuration for the interference-fit joint.