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Influence of interference-fit size on bearing fatigue response of single-lap carbon fiber reinforced polymer/Ti alloy bolted joints

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ABSTRACT

Fretting accelerates damage of mechanical joint; however, the interference-fit technology which makes an oversized fastener installed into a hole has been a method for durability enhancement. An experimental investigation was conducted to determine the effect of interference-fit size on the fretting fatigue life, hole elongation, and circumferential strain of carbon fiber-reinforced polymer(CFRP)/Ti alloy bolted joints. The relationship between interference-fit sizes and fretting fatigue life with various stress levels as well as the hole elongation variation is obtained. The circumferential strains of CFRP hole are investigated during dynamic loading, and the relationship between circumferential strain evolution and interference-fit size is presented.

1. Introduction

Fretting is a contact damage process arising from surface relative motion with a small amplitude (less than 300 μm) under alternate loads, such as vibration, fatigue, electromagnetic vibration and cycling alternating loads, which most frequently occurs in bolted or mechanically fastened joints. Fretting usually causes the wear between the contact surfaces and generates changes in joints dimensions, which will lead to engagement, loosening, power loss, or increase in noise. Moreover, it can also accelerate crack initiation and propagation, greatly reducing the fatigue life [1,2]. Fretting fatigue failures are common in engineering applications, especially in aerospace, nuclear reactor, railways and automobile industry. In order to reduce the damage caused by fretting fatigue, interference fit technology is applied to connection structures [3,4]. Interference-fit technology, which makes an oversized fastener installed into a hole, is a useful method to enhance the durability of metallic and composites structures.

So far, researchers have investigated the contact interface fretting behavior of aluminum alloys, titanium, high-strength steel and composite, and a large number of studies have been carried out on fretting fatigue life prediction and fretting crack initiation from the mechanical and metallurgical perspective [4–8]. A lot of researches on fretting fatigue strength prediction have been reported based on crack nucleation parameters, fracture mechanics approaches, and damage mechanics [9–12]. Murugesan [13] predicted fretting fatigue strengths of dovetail joint and bolted joint on the basis of the generalized tangential stress range (TSR)–compressive stress range (CSR) diagram, and experimentally verified the effectiveness of TSR–CSR diagram. Hattori [14] conducted fretting fatigue strength estimation considering the fretting wear process, the results show that fretting fatigue strength decreases with the increase in the wear, and S–N curves of fretting fatigue are well coincided with the experimental results by referring to the relationship between stress intensity factor range (ΔK) and crack propagation rate (da/dN). Ding [15] presented two empirical parameters to predict the effect of surface damage on fretting fatigue. In recent years, researchers have also started to utilize finite element software to analyze fretting behavior, stress and strain of structure, crack initiation and propagation. Mirzajanzadeh [16] studied the effect of interference-fit on fretting fatigue crack initiation of pinned joints in 7075Al-alloy with FEA, the results of which demonstrate that fretting was the main reason for crack nucleation, and the crack nucleation location was precisely predicted and fatigue life enhancement was well explained. Hojjati-Talemi [17] showed an uncoupled damage evolution mode based on a thermodynamic potential function and linear-elastic fracture mechanics to model the crack initiation life and propagation life, and they also combined them together in order to calculate the total fretting fatigue life time. Lanoue [18,19] used refined mesh and sub modeling techniques to analyze rotating bending and alternated torsion, and calculated fretting fatigue strength reduction factor for the fretting zone, which could be used to optimize the shape of interference fits.

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However, due to the involvement of numerous complex factors influencing fretting fatigue phenomena such as relative slip amplitude, contact pressure, coefficient of friction, specimen geometry, specimen size, contact material, and environment [20–22], the analysis of the fretting fatigue behavior of joint proposed has still been in a limited range. For the interference fit structure components, the current researches on interference fit are limited to the pined joints or riveted joints, and there are few studies about the effect of interference fit on the fretting fatigue behavior of single-lap bolted composite joints [23–28], especially, studies about metal/composite interference joints. Both CFRP and Ti alloy have high strength-to-weight and stiffness-to-weight ratios, and the strength and stiffness of CFRP match well with the strength and stiffness of Ti alloy. In addition, it is not easy for CFRP/Ti alloy composite structure to form galvanic corrosion. Therefore, CFRP/Ti alloy joints are more and more widespreadly used in structure, such as the aft fuselage, movable wing, and inlet. In consequence, it is worth investigating the fretting behavior of CFRP/Ti alloy interference fit joints.

In this paper, an experimental study was carried out to investigate the fretting fatigue behavior of CFRP/Ti alloy single lap bolted joints with different interference fit sizes. Hole elongation evolution was presented, and surface damage was characterized. In addition, circumferential strain of holes, which can reflect the fretting fatigue process accurately, was tested and analyzed.

2. Experimental

2.1. Interference fit specimen preparation

The same carbon fiber reinforced plastic composite material and titanium alloy were selected for making tensile and fatigue specimens. CFRP was using a fabric carbon/epoxy with the thickness of 0.125 mm per ply (provided by AVIC XI'AN Aircraft Industry Company Ltd., China), and fabric areal weight 809 g/m^2. The fabricated laminate possesses a thickness of 3 mm with 24 plies, the ply orientation of which is $[0^\circ/90^\circ/\pm 45^\circ]3$ s, and has a weight fraction of 60%. Material properties of fabricated woven CFRP laminates are presented in Table 1. In order to obtain CFRP/Ti alloy specimens with interference connection, the titanium alloy HI-LOK bolts with a standard size were installed into undersized holes. The diameter of titanium alloy bolt was 6 mm, and the hole diameters of CFRP and titanium alloy plates were designed to different sizes, thus it could create several interference-fit. Fig. 1 shows the sizes of test pieces according to the ASTM D5961 [29], $W/D=6$, $E/D=3$. The desired finish dimensions of holes in CFRP and Ti alloy were achieved by drilling and reaming operations. Then, aperture of each sample was tested by using plug gauge to ensure that the sample met the requirements.

Due to the difference of material properties, CFRP and titanium alloy plates were drilled separately. Feed rate of 1.5 mm/min and spindle speed of 2000 RPM were used to drilling. Vacuum system was used to remove the chip and to provide cooling. Machined specimens were cleaned by alcohol before conducting bolt installation. Mechanical properties of Ti-alloy plate and resist shear HI-LOK bolt are shown in Table 2.

A tension and compression testing machine was used to insert the HI-LOK into the CFRP/Ti stack coupons. The bolt shank was inserted at a rate of 2 mm/min for a distance of 6 mm, and the loading and displacement data were recorded. During the interference-fit bolt installation, the pressing force is composed of two parts: hole wall deformation force, friction between bolt and hole wall. Fig. 2 shows the typical loading–displacement curve of HI-LOK installation under different interference fit, while upper plate is CFRP and lower plate is titanium alloy. As shown in Fig. 2, there was a loading decrease when bolt shank penetrated into the region between the CFRP and Ti alloy, as a dimple process was taken during the Ti alloy plate drilling.

The drive nut was screwed to clamp CFRP plate and Ti alloy plate together by torque spanner. Tightening torque of drive nut was 10 kgf cm. The drive nut would break off when tightening torque reached the value. Samples were divided into four groups, diameters of which were 6.00 mm, 5.95 mm, 5.90 mm and 5.80 mm respectively, with tolerance up to 0.003 mm. The interference-fit percent can be defined by the relation;

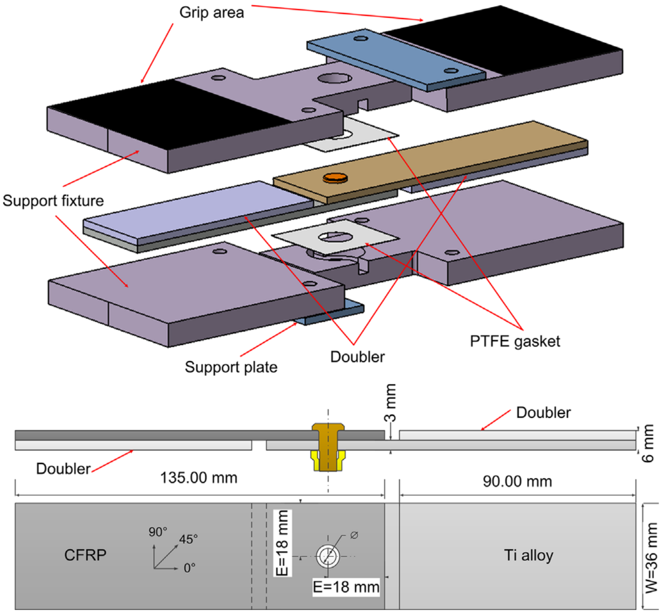

Fig. 1. Geometry and dimensions of the CFRP/Ti single-lap joint.

Table 2
Mechanical properties of Ti-alloy plate and resist shear type HI-LOK bolt.

Material	Tensile strength (MPa)	Elasticity modulus (GPa)	Ductility Δ (%)	Poisson ratio	Yield strength σ_S (MPa)	Density ρ_g/cm^{-3}
Ti–6Al–4V	896	105	10	0.34	827	4.43
Resist shear type HI-LOK bolt	931	112	10	0.29	862	4.45

Table 1
Mechanical properties of fabricated woven CFRP laminates.

Reinforcement type	Fiber weight (g/m^2)	Resin content (%)	Tensile strength (MPa)	Tensile modulus (GPa)	Ply thickness (mm)	Compressive strength (MPa)	Interlaminar shear strength (MPa)
Carbon fiber	198	40	774	80.7	0.25	750	50