Effect of interference fit size on tensile strength and fatigue life of CFRP/Ti alloy bolt joints

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Received 15 May 2015; accepted 16 August 2016

An experimental investigation is conducted to determine the effect of interference-fit size on tensile strength and fatigue of CFRP (carbon fiber-reinforced plastic)/Ti alloy bolted joining structure. The tensile test and fatigue experiments of interference-fit specimens are performed. The joints with four interferences-fit sizes (0%, 0.8%, 1.7% and 3.4%) are tested. The loading-displacement curves and fatigue life data of CFRP/Ti alloy bolted joints with various interference-fit sizes are obtained, and the relationship between interference-fit sizes and fatigue life are presented. The results show that the fatigue life of CFRP/Ti alloy bolted joint are associated with the size of interference fit and the dynamic stress levels, and the appropriate interference fit can improve fatigue life of CFRP/Ti alloy bolted joints compared with non-interference fit. Excessive interference fit can decrease the initial stiffness, ultimate bearing strength and fatigue life. In this paper, the joints with 1.7% interference fit have the best bearing and fatigue performances. Besides, fatigue empirical formula and fatigue damage of mechanism have been presented.

Keywords: Interference fit, Fatigue, Mechanics testing, CFRP

Mechanical joints are commonly used for thin and thick members of aircraft structures and components as metallic bolts, rivets and pins. These mechanical joints require holes in composite laminates and metal structures, and these fastener holes can become the origin of fatigue cracking\textsuperscript{1-3}. One main solution to improve the structure strength is the process of interference fit which has been used in both military and civil aircrafts. Because interference fit can retard crack initiation and reduce crack growth rates\textsuperscript{4,6}. Compressive residual stress induced by interference-fit can reduce the effective hoop stress at the periphery of the fastener hole and result in significant gain in fatigue\textsuperscript{7}. Interference-fit technique has also been adapted to the composites, and some studies show the positive results\textsuperscript{8-10} Due to high strength-to-weight, CFRP has been successfully integrated into aircraft structures such as wings and fuselages\textsuperscript{11}. Due to the involvement of numerous complex factors influencing fatigue phenomena, such as size of interference fit, contact pressure, coefficient of friction, specimen geometry, specimen size, contact material, and environment\textsuperscript{12}, the analysis on the fatigue behavior of joint proposed is still in a limited range. The researches on effect of interference-fit size on fatigue life are relatively rare, especially for the interference-fit structure of the metal/composite. Researchers have investigated the fatigue behavior of metal/metal and composite/composite, and these studies have been carried out on fatigue life prediction, crack initiation based on finite element analysis and mechanical test. For prediction of fatigue life and crack initiation, researchers mainly use the finite element software to investigate the contribution of stress distribution state during uploading and unloading by considering reverse yielding and elastic-plastic\textsuperscript{13-18}. For example, Chakherlou et al\textsuperscript{19} investigated the stress distribution and effect of interference fit on fatigue life of Al-alloy mechanical joints by using a series of experiments and FEA, and the results reveal that damage crack raise from entrance of the hole. There are also some experimental studies to investigate the effect of interference-fit size on fatigue life\textsuperscript{20-22}. For example, Wei et al\textsuperscript{21} have investigated the effect of interference fit size on the fatigue life of bolted joints in composite laminates.

The mechanical joint of CFRP/Ti alloy has been used for advanced engineering structures in many fields ranging from aerospace to automotive, civil and

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mechanical engineering in order to optimize existing designs and create more effective products. On the other hand, extensive studies show that fatigue and related phenomena are the most frequent causes of structural failures in engineering structures. It is necessary to characterize CFRP/Ti stacked structure quasi-static and fatigue behavior in order to develop theories that can assist the design process. Therefore, in this paper, an experimental study is carried out to investigate the static and fatigue behavior of CFRP/Ti alloy bolted joints with different interference fit sizes.

**Experimental Procedure**

**Materials and specimen preparation**

The same carbon fiber reinforced plastic composite material and titanium alloy were selected. The CFRP materials were an epoxy matrix composite with carbon fiber (T300B-3000) reinforcement (provided by Guangwei Composite Ltd., China). The laminates were 60% (volume content) carbon fiber with quasi isotropic layer ([0°/90°/±45°]). Mechanical properties of the materials used at room temperature in the study were shown in Table 1. Due to the Ti-6Al-4V alloy widely using in aerospace, the Ti alloy plate and Hi-Lok bolt which made by Ti-6Al-4V alloy were picked, and the mechanical properties of Ti alloy plate and resisting shear type Hi-Lok bolt are given in Table 2.

In order to obtain CFRP/Ti alloy interference connection specimens, 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 various interference-fit sizes. Figure 1 is the size of the test piece according to the ASTM D5961, W/D=6, E/D=3. The upper is CFRP plate, and lower is Ti alloy plate. The undersized hole in CFRP and Ti alloy was made by drilling and reaming operations to get desired finish dimensions. Then, plug gauge was used to test aperture of each sample to ensure that the hole diameter meets the requirements. Samples were divided into four groups according to various interference-fit sizes (0%, 0.8%, 1.7%, and 3.4%), and each group had more than 3 samples. The interference-fit percent can be defined by the relation:

\[ I = \left( \frac{D - d}{d} \right) \times 100\% \quad \ldots (1) \]

Where D is the diameter of the bolt and d is the specimen hole diameter.

Quasi-static tests were conducted in universal testing machine (INSTRON 5567) and fatigue tests were performed using INSTRON 8802 dynamic test machine. Quasi-static tests were conducted under room condition with 2 mm/min ramp speed, and quasi-static tensile tests had been chosen based on ASTM D 5961 (Standard test method for bearing response of polymer matrix composite laminates).

For fatigue tests, the loading cycle applied to all specimens was a constant amplitude sinusoidal cycles with a stress ratio of \( R = 0.1 \) at the frequency of 6 Hz. Fatigue tests were conducted according to the ASTM D 6873 (Standard practice for bearing fatigue response of polymer matrix composite materials) at a room temperature of 20°C. Specimens with different interference fit sizes (0%, 0.8%, 1.7%, and 3.4%) were tested to determine the effect of interference fit on fatigue life for CFRP/Ti alloy joints. In order to reduce buckling of the joints, lateral supports had been used in the test. The test set-up is given in Fig. 2. Test was not generally terminated until enough bolt-hole elongation was produced, in this paper, the

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<th>Table 1 – Mechanical properties of CFRP</th>
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<th>Table 2 – Mechanical properties of Ti-alloy plate and resisting shear type Hi-Lok bolt</th>
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<td>Material</td>
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<td>Tensile strength (MPa)</td>
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<td>Poisson ratio</td>
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<td>Yield strength ( \sigma_S ) (MPa)</td>
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Fig. 1 – Geometrical configuration of CFRP/Ti alloy bolted joint specimen
test was suspended and that specimen was considered a run-out when 10% deformation of hole diameter was achieved. For each specimen group, the effect of the interference fit on the joint performance in both static and fatigue loads have also been given in the Table 3.

**Results and Discussion**

**Quasi-static tensile test**

Tensile tests were taken for the specimens with the sizes of $I = 0\%, 0.8\%, 1.7\%$ and $3.4\%$. The tensile failure mode is CFRP fracture, because CFRP does not have tensile resistance as strong as titanium alloy. The quasi-static ultimate tensile strength is the value of tensile stress, at the maximum load capability of a tensile specimen, using the following relation to calculate:

$$\sigma_{ut} = \frac{F_{ut}}{Dh} \quad \ldots (2)$$

Where $D$ is the nominal bolt diameter, $h$ is the nominal thickness of the sheets of bolted joints.

Figure 3 shows the typical loading-displacement curves with various interference fit during tensile test. The definition of tensile failure is defined as the maximum load achieved during the test. As shown in Fig. 3, the difference of interference fit sizes eventually lead to different ultimate tensile strength of CFRP/Ti alloy joints. Interference fit of $I=1.7\%$ has the largest ultimate strength. Due to hole surface suffered severe damage during bolt installation, the specimens of interference-fit $3.4\%$ have minimum ultimate strength. Also larger size of interference fit leads to delamination and fiber-matrix fracture of CFRP, which reduces the tensile strength of interference fit bolt joint greatly (ultimate bearing strength of $I=3.4\%$ is 66% of $I=1.7\%$, and 74% of $I=0.8\%$). Therefore, an appropriate interference-fit size can improve the ultimate tensile strength of CFRP/Ti alloy joints, and excessive interference-fit size can decrease the ultimate tensile strength.

![Fig. 3 – Typical loading-displacement curves with various interference-fit sizes](image-url)
The linear elastic region and the nonlinearity region can be observed in load-displacement curve in Fig. 3. The two stages are damage initiation and damage propagation. Damage initiation is interference fit within 100 µm. During the linear elastic region, stiffness of joint in interference-fit area has been calculated, and the relationship between initial stiffness and interference-fit size has been shown in Fig. 4. When net fit or interference-fit are small, the value of stiffness is small, which means the interface is not close fit in connection area. When interference-fit size is excessive, severe damage in connection area would make the stiffness decrease, so \( I = 3.4\% \) has the smallest initial stiffness.

**Interference fit effect on fatigue life**

Four interference-fit sizes were considered in the tests: 0%, 0.8%, 1.7%, and 3.4% respectively. Due to the fact that ultimate strength of the specimen varies with the interference fit, the same ratio of nominal maximum bearing strength (average value of maximum bearing strength are 574, 612, 667 and 502 MPa respectively) is taken in fatigue tests for getting better comparison of fatigue results. Tests contained five levels of tensile strength amplitude, 30% \( U_{\text{max}} \), 40% \( U_{\text{max}} \), 50% \( U_{\text{max}} \), 67% \( U_{\text{max}} \), and 75% \( U_{\text{max}} \) \( (U_{\text{max}} \) is the maximum bearing strength). Fatigue lives of CFRP/Ti alloy joints with five stress levels were obtained.

The fatigue life is directly influenced by the size of interference fit. Figure 5 shows that fatigue life has a trend of climbing up at first and then decreasing with the increase of the interference fit size. S-N curves of CFRP/Ti alloy joints have a great change with the various interference-fit sizes, and the fatigue cycles have a small difference with 75% \( U_{\text{max}} \), while the fatigue life difference value has increased with the bearing level decrease. Also the joints with 1.7%...
interference fit have the best bearing and fatigue performance. Furthermore, the lower the stress level, the longer the fatigue life of the CFRP/Ti alloy joint. The interference fit of CFRP/Ti alloy structure can improve the fatigue life, and the important factors in designing CFRP/Ti alloy bolted joint not only include the static ultimate bearing strength and the size of interference fit, but also the stress level which the bolted joints generally is applied. Figures 5(b)–(d) show that specimens with 1.7% interference-fit size have the best fatigue life.

There are some reasons that why interference fit can improve the fatigue life of CFRP/Ti alloy bolted joint. Due to interference fit with an oversized fastener installed into a hole, matrix and fibers around the hole of CFRP suffered compression and friction force, and formed cracking and fracture at the hole surface. These damage types lead to stress release which is benefit to relief stress concentration and retard the crack propagation effectively. Residual stress has been redistribution with the interference connection on the side of the hole, and comparing with non-interference joints, stress concentration reduces at the dangerous area. An appropriate interference-fit size makes a close fit, and contact area is larger than net fit. Thus, it makes more uniform stress distribution, and contact stress is smaller than non-interference fit. In addition, joint will form a clearance fit with alternating load, but due to interference fit fasteners are taken, the formation of clearance fit is delayed. The bolt-hole has a close fit with interference-fit, which could reduce the impact damage. Therefore, interference fit can improve the fatigue life of CFRP/Ti alloy joint.

**Fatigue life prediction model**

The cycle numbers (horizontal coordinate in Fig. 5(a)) can be expressed as a logarithmical form, then the $S$-$N$ curve can be changed into the classic form. As shown in Fig. 6, the $S$-$N$ curves of CFRP/Ti alloy single-lap bolted joint are approximately linear with different slopes. Therefore, the $S$-$N$ curves with various interference-fit sizes can be linear fitted by using software Origin, and the empirical formula of fitting curve is calculated using the follow relation:

$$S = A \cdot B \lg(N)$$

Where $A$ and $B$ are constants which depend on material properties, and can be obtained by experimental data, $N$ is fatigue life and $S$ is the stress level.

So, the formulas can be presented as follows when $I$ are 0%, 0.8%, 1.7%, and 3.4%:

$$S = 1678.539 - 257.475 \lg(N) \quad I = 0\% \quad \ldots \ (4)$$

$$S = 1689.521 - 250.0661 \lg(N) \quad I = 0.8\% \quad \ldots \ (5)$$

$$S = 1657.716 - 237.0091 \lg(N) \quad I = 1.7\% \quad \ldots \ (6)$$

$$S = 1776.74 - 285.3461 \lg(N) \quad I = 3.4\% \quad \ldots \ (7)$$

The interference fit technique will lead the stress redistribution around the connecting hole, and the parameters of $A$ and $B$ can be associated with sizes of interference fit in Fig. 7. Thus, the fitting curves of $A$ and $B$ can be expressed as follows:

$$A = 1687.65 - 41.539I + 19.68I^2 \quad \ldots \ (8)$$

$$B = 260.05 - 28.93I + 10.63I^2 \quad \ldots \ (9)$$

Then, the parameters of $A$ and $B$ were quadratic fit, and the fitting curves of $A$ and $B$ were shown in Fig. 7. When the parameters of $A$ and $B$ have been taken up by Eqs (8) and (9), the fatigue life model in Eq.(10) can be derived as follows:
\[ S = 1687.65 - 41.539f + 19.68f^2 \]
\[-(260.05 - 28.93f + 10.63f^2) \] … (10)

**Fatigue damage mechanism**

As shown in Figs 8~10, CFRP, and Ti alloy have different kinds of damage style during joint loading. Compression fracture is the main damage type of CFRP in Fig. 8. Due to the fracture of CFRP and plastic deformation of Ti alloy during the fatigue loading, as well as the migration of wear debris in the hole wall, the hole elongation increases gradually, and interference fit changes to clearance fit finally. Clearance fit leads to impact damage and accelerates crack propagation, which makes the joint premature failure eventually. The brittle cracking of fiber-matrix is the main source of failure for composites and may initiate other modes of failure. In this paper, delamination has also been observed. Delamination is the most commonly encountered failure modes in composite laminates and may become a major source of concern in the performance and safety of composites by reducing the ductility, stiffness and strength of the composite specimen and even causes sudden brittle fracture mechanisms. Delamination can be extended from high stress concentrations that originates from loading conditions, especially sudden concentrated loadings such as impact. Furthermore, due to friction between bolt shank and CFRP hole wall, it forms axial component force which also leads to delamination. Figure 9 shows the typical fatigue fracture morphology of titanium alloy, and the fatigue fracture locates at the middle of Ti alloy layer. Because of fretting wear on the interface between bolt and Ti alloy, micro-crack initiates on the fretting interface. The micro-cracks propagate, convergence, and fracture eventually. Figure 9(a) shows fatigue cracks were observed on the surface of titanium alloy. Figure 9(b) shows multi-cracks propagation at initial crack section during fatigue loading. Figure 10 shows the fretting wear behavior on the hole wall of Ti alloy layer, fretting scar can be observed on the surface of Ti alloy hole wall. As shown in Fig. 10, the whole surface of Ti alloy hole wall can be divided into three parts: CFRP debris area, fretting wear area and Ti alloy debris area. CFRP debris area is made of carbon fiber and matrix particles, which migrate into Ti alloy layer during the process of interference bolt installation and fatigue loading. The CFRP debris adheres to the titanium surface, and they can reduce interface wear and protect the surface as a buffer layer. Therefore, CFRP debris area is the minimal damage in Ti alloy layer. Fretting wear area is observed between CFRP debris area and Ti alloy debris area. Due to axial displacement components, fretting wear forms between Ti alloy and bolt shank. The damage is severe at fretting wear area, lots of grooves generate on the surface of Ti alloy, and micro-cracks are easy to form in these areas. Furthermore, the fatigue crack initiates in this area. Ti alloy cracking and particles spalling are the main...
damage types at Ti alloy debris area. Due to the special structure of Hi-Lok bolt, an unconstrained region exists along the thickness direction at this area, which makes titanium easy to deform and Ti alloy debris spalling during dynamic load. The plastic deformation and debris spalling can reduce contact stress and surface wear.

It’s worth noting that the priority damage area of structure has relationship with size of interference-fit. CFRP is prior failure when $I$ is small ($I=0$ and 0.8%) or oversize ($I=3.4$%), and titanium fretting wear and bolt fatigue damage are the main failure type when $I=1.7$%. When the size of interference-fit is small, the bolted joint is easy to form impact damage, and delamination can be generated during interference bolt installation when $I$ is large enough. Therefore, CFRP damage is the main damage type when size of interference fit are small or excessive large. For the appropriate interference-fit, fiber buckling and stress softening can play a protective role from our earlier research. In addition, fretting wear of Ti alloy hole wall can accelerate the cracks initiation and propagation which can reduce the fatigue life of Ti alloy. Therefore, the position of damaged area can be adjusted by the size of interference fit, which can be used in the optimization of CFRP/Ti alloy interference structure.

Conclusions
This paper investigates the effect of interference fit on the fatigue behavior of CFRP/Ti alloy bolted joints. The following conclusions can be drawn from this study:

(i) Bearing strength varies with the different interference-fit size, and interference fit also affects the stiffness of CFRP/Ti alloy mechanical joint. The bearing strength and stiffness of bolted joint increase at first and then decrease with the increase of interference-fit size. An appropriate interference fit size makes positive effect on tensile strength of CFRP/Ti alloy bolt joints. In this paper, interference fit 1.7% has the best tensile strength and initial stiffness.

(ii) Compared with net fit, proper interference fit can increase the fatigue life. The interference fit size has a significant effect on fatigue life of CFRP/Ti alloy bolt joints, and excessive size of interference fit can decrease the fatigue life. Furthermore, the fatigue life of the best and the worst interference-fit size has a difference of 2-5 times as seen from the S-N curves. In this paper, the joints with 1.7% interference fit have the best fatigue performance. In addition, the fatigue empirical formula of CFRP/Ti alloy interference fit joint has been presented.

(iii) Several types of fatigue damage mechanism exist in bolted joint. Fiber-matrix facture and delamination are the main failure types of CFRP, and interface fretting wear and fatigue fracture can be observed in titanium.

(iv) The damage areas of CFRP/Ti bolted joints has relationship with interference-fit size. CFRP is priority failure when interference-fit size are small or excessive large ($I=0$, 0.8%, and 3.4%), and titanium alloy fatigue fracture and interface fretting wear are the main failure types when $I$ is 1.7%.

Acknowledgements
The work reported herein is sponsored by National Natural Science Foundation of China (Grand No: 51275410 and 51305349) and Aviation Science Foundation of China (2014ZE53056).

Reference