Effect of interference-fit percentage and preload on the mechanical behaviour of single-shear lap composite joint

Peng Zou\textsuperscript{1*}, Hui Cheng\textsuperscript{2}

\textsuperscript{1}AVIC aircraft strength research institute, Xi’an 710072, China
\textsuperscript{2}School of Mechanical Engineering, Northwestern Polytechnical University, Xi’an 710072, China
zoupeng_0625@126.com

Abstract. The mechanical behaviour of composite interference-fit structure is affected by both interference-fit percentage and bolt preload. These two factors combine and interact with each other, leading to a complex joint behaviour. In this paper, the effect of interference-fit percentage and bolt preload on load and damage of single-lap bolted joint is studied from both experiment and finite-element model (FEM). Firstly, an interference-fit preload applying experiment was made. Preloads on both nut and bolt head were measured for different percentages and torques, and the torque coefficient was calibrated. A scanning electron microscope (SEM) analysis on the experimental joint was also conducted to research damages around the hole. Then, the relationship between torque and multi-layer preloads and a composite preload FEM based on progressive damage mechanism were built. The multi-layer preloads were obtained and compared with the experimental measured ones, which verified the reliability of the FEM. In addition, the damage mechanism of different percentages and torques were also analysed and discussed with the simulation results.

1. Introduction

Composites are widely used in aviation, aerospace fields due to their high ratio of strength to weight and stiffness to weight. Limited to forming technology, they are commonly connected with other components through bonding, riveting, bolting and other forms. Among these, bolted joint is widely accepted for its high load bearing capacity. However, the traditional clearance-fit is prone to cause stress concentration around hole, accelerate structural cumulative damage and reduce joint strength. According to researches\cite{1,2}, the joint strength is affected not only by material property, joint parameters, fastener type and loading condition, but also by bolt preloads and fit condition between the fastener shank and hole.

As a high-efficient way, the interference fit is widely used in metallic structures for its advantages in reducing stress amplitude and putting off fatigue crack initiation \cite{3}. For composites, recent studies \cite{4}~\cite{6} have indicated that appropriate interference percentage reduces stress concentration around the hole, thus improves the joint strength and fatigue performance. However, due to the poor ductility and low interlaminar strength \cite{4}\cite{7}, excessive percentage will not only cause premature damage around the hole but also increase damage zone, and then decrease the loading capacity. Kim et al.\cite{8} performed experiments and finite-element researches on the interference-fit pin installation process, they analyzed the effects of different interference sizes on strain and damage around the hole, and partial damage modes are discussed with the experiments. Meanwhile, Zou et al. analyzed the influence of interference-fit percentage on stress and damage mechanism \cite{5} and mode 1 delamination...
mechanism during CFRP interference-fit pin installation process [9]. Most researchers put their focus on the effects of interference percentages on static-loading strength and fatigue performance. Zou et al. [6] predicted the bearing strength and failure modes of interference-fit double shear-lap pin-loaded composite during both installation and loading process. Kiral [10] researched the effects of clearance-fit and interference-fit on the failure mode, failure load and bearing strength of the pin-loaded joints. On interference-fit bolted joint, Wei et al. [11] studied the effects of interference sizes on fatigue life by experiments, the results indicated that a certain amount of interference-fit can improve the fatigue life efficiently than the clearance-fit. In their study, the bolt preload is considered as a constant. From the above researches, it can be concluded that the interference-fit structure is widely researched upon installing and loading process for pin-loaded and bolt-loaded condition, but the preload effect gets limited attention or is just taken as a constant.

A preload is an advance force produced by the tightening torque on the nut or bolt head in the fastener assembling process. The clamping effect will make the structure in an axial-compressive state and enhance the friction between jointing structures, which improves load transmitting and bearing ability. But it also should be noted that, the composite properties in thickness direction are dominated by matrix performance [12]. Excessive preload will produce matrix cracks around the hole leading to a premature failure. Rosales-Iriarte et al. [13] have studied the effect of preload and hole clearance on the composites plates subjected to bearing versus bypass loading. They found that due to the existence of preload, the mechanism of bolted load is different from that of the pinned joints. On the combined effects of interference fit and preload, Liu et al. [2] made a deep study of their effects on contact pressure around the fastener hole and loading capacity. But as a result of tight contact between the hole and bolt, the preload’s change in the axial-transmitting process will cause a non-uniform axial preload distribute and hole damage, which is not considered in their study.

From all the above analyses, it can be seen that there are many intensive studies on composite interference-fit installing and loading process, and the effects of preloads on clearance-fit structure are also deeply investigated. However, researches on the combined effects of interference fit and preload are insufficient. In this study, the preload applying experiment and progressive damage based FEM of composite interference-fit single-lap structure were conducted and analyzed to clarify the preload axial-transmitting process and damage mechanism due to pin-hole interaction.

2. Experimental procedure

2.1. Specimen preparation

As shown in Figure 1, composites made of high strength CFRP unidirectional prepreg tape T700/BA9916 with 16-layer \([0/\pm 45/90]_{2s}\) laminates are used here. The total thickness of each specimen is 4mm with every laminar 0.25mm. The bolt is made from Ti-6Al-4V, and the nut and washer are made from 45# steel. Material properties are shown in Table 1 and Table 2. Detailed dimensions are depicted in Figure 1, where w/D=6, e/D=3 and b/D=19.5.
Table 1 Mechanical properties of T700/BA9916.

| Property | $E_1$ (GPa) | $E_2$ (GPa) | $E_3$ (GPa) | $G_{12}$ (GPa) | $G_{13}$ (GPa) | $G_{23}$ (GPa) | $V_{12}$ | $V_{13}$ | $V_{23}$ |
|----------|-------------|-------------|-------------|----------------|----------------|----------------|---------|---------|---------|
| Value    | 114         | 8.61        | 8.61        | 4.16           | 4.16           | 3              | 0.3     | 0.3     | 0.45    |

Table 2 Mechanical properties of bolt joint.

| Material         | Elastic modulus (GPa) | Poisson ratio | Tensile strength (MPa) | Yield strength (MPa) |
|-----------------|----------------------|---------------|------------------------|----------------------|
| Ti-6Al-4V       | 112                  | 0.29          | 931                    | 862                  |
| 45# Steel       | 210                  | 0.3           | 625                    | 381                  |

The interference percentage 0.0%, 0.4%, 0.8% and 1.2% is analysed here, which is defined as follows,

$$I = \frac{(d - D)}{D} \times 100\%$$  \hspace{1cm} (1)

where $d$ and $D$ are separately the diameters of the bolt and composite hole. The diameter of the Ti Alloy bolt in the experiment is 6mm and the post-cutting specimens are processed with precise drilling to be qualified specimens of different percentages.

2.2. Mechanical test procedure

The bolt installation experiment was performed on a MTS Criterion 60 serious C64.305 static hydraulic testing machine. Two Kistler SlimLine Sensors 9133B washer-type force sensors are used here to record the preloads. Firstly, a washer and a force sensor were put onto the bolt shank in sequence. Secondly, the pin was pressed into the composite hole with 2mm/min until the pin head came into contact with the washer and a value emerged on the monitor. Then, the specimen was fixed on the fixture and the other two force sensor and washer were put onto the shank. A professional torque wrench was used to apply torque on the bolt nut with every 1 Nm increment. Force sensors recorded and translated both two signals to the HBM G2Ni signal recorder via Kistler 5073 charge-amplifier, as shown in Figure 2. After the experiment, specimens are cut and cleared and damage around the hole is observed with SEM.

2.3. Relation between torque and preload

In order to simulate the preloading process in FEM, a connection relating experimental torque and preload used in FEM should firstly be constructed. The relationship between torque and preload on bolt nut is related with thread pitch, bolt dimension and friction between bolt and nut[1], which can be expressed as follows
where, $T$ is the bolt torque, $k$ is a coefficient calibrated by experiment, $d$ is the bolt diameter and $F_{nut}$ is the preload on the nut.

Since there is a tight contact between hole and bolt shank, the friction on the contact surface results in preload reduction on the bolt head as shown in Figure 3. The decrement is related with interference percentage, interface contact and preload on the nut. When the preload on the nut is big enough to overcome interface static friction and transfers to the bolt head, the relation can be expressed as follows,

$$
\begin{align}
F_{int} &= F_{nut} - f_{i1} \\
F_{bolt} &= F_{int} - f_{i2}
\end{align}
$$

According to classical friction law, the interface friction $f_{ii}$ is related with friction coefficient $u_i$, and contact pressure $N_i$,

$$
f_{ii} = u_i N_i \tag{4}
$$

where $i=1,2$, and the contact pressure $N_i$ can be calculated as follows,[9]

$$
N_i = \frac{t_r \Delta \pi}{R \beta} \left(2 \alpha - 2 \nu_{12} + \delta + \alpha \delta \right) \tag{5}
$$

where $\alpha = \sqrt{E_1/E_2}$, $\beta = (1-\nu_{12}\nu_{21})/E_2 + \alpha/G_{12}$, $\delta = \sqrt{2(E_1/E_2 - \nu_{12}) + E_1/G_{12}}$, $\Delta = r - R$, $E_1, E_2$ are the longitudinal and transverse modulus, and $G_{12}$ is the shear modulus of the composite. $\nu_{12}$ and $\nu_{21}$ are Poisson’s ratios.

So the preload reduction $F_\Delta$ between the nut and the bolt head can be expressed,

$$
F_\Delta = F_{nut} - F_{bolt} = f_{i1} + f_{i2} \tag{6}
$$

3. Finite element simulation

3.1. Finite element model

The interference-fit preload simulation model is shown in Figure 4, which is based on Abaqus 6.11. The model is composed of five parts: two CFRP plates, bolt, nut and washer. The bolt is built with 1988 C3D8R elements and 476 C3D6 elements. The nut and washer are separately established with 2124 and 560 C3D8R elements. One element in the thickness direction for per ply method is used to model the composite, and there are total 69120 C3D8R elements with every layer 4320 ones. To
balance calculating precision and time consumption, meshes around the hole are refined. 12 elements are equally distributed along the radial direction with each element about 0.253mm long, and 96 elements distributed along the circumferential direction with each one about 0.194mm. Thus, the aspect ratio of the refined elements surrounding the hole is about 1.3, which satisfies the convergence requirement. There are totally 5 contact pairs in the model, which are located between bolt shank and composite hole, bolt head and plate outer surface, washer and plate outer surface, washer and nut, and the two composite plates. The contact property is set to be finite sliding formulation, with hard contact in the normal direction and penalty behaviour in the tangential direction. Referring to references [2][8], the coefficients are set to be 0.1, 0.4, 0.1 and 0.2 for shank/hole, plate/plate, washer/plate and washer/nut interfaces, separately. The specific interference percentage is achieved by the ‘interference fit’ option in Abaqus interaction module. While the preload is applied on a cross-section surface specified cutting through the bolt shank near the nut by ‘bolt load’ in Abaqus[15], which can automatically adjust shank length to get desired contact forces.

Figure 4 Finite element model of interference-fit preload simulation.

3.2. Damage model and implementation

The composite interference-fit structure shows a typical three dimensional stress status, thus the failure modes include: fiber tensile/compression failure, matrix tensile/compression failure in transverse direction and thickness direction and fiber-matrix shear out failure. Under loading, these defects accumulate gradually leading to progressive degradation and properties degrade in local district [16]. Thus, the key point for damage prediction is to choose appropriate failure criteria and property degradation rules. Hashin criteria are widely adopted in researches for its consideration of every damage modes separately. But experimental study shows that, when shear stress is large, the predictions with Hashin fiber failure criteria do not agree well with experimental results. To solve this problem, the fiber failure criteria is replaced by the maximum stress criteria. Meanwhile, the nonlinear shear stress-strain relationship is also considered [5][6]. The final modified 3D Hashin criteria is shown in Table 3.

| Failure mode | criteria                  |
|--------------|--------------------------|
| Fiber failure| $\varepsilon^2 = \left( \frac{\sigma_1}{X_f} \right)^2$ $(\sigma_1 \geq 0)$ |
|              | $\varepsilon^2_{fc} = \left( \frac{\sigma_1}{X_{fc}} \right)^2$ $(\sigma_1 \leq 0)$ |
IOP Conf. Series: Materials Science and Engineering 531 (2019) 012074 doi:10.1088/1757-899X/531/1/012074

Modeling in Mechanics and Materials

0.0024.

0.168, which is also the torque coefficient in this experiment, and the fitting standard deviation is obvious linear trend. The linear fitting result is also shown in can be s

can be s

can be s

\[ k = \frac{T}{F_{nut}d} \] (7)

The torque coefficient is calibrated from the nut preload. Torque distribution varying with preload (dealt with multiplying bolt diameter) for all three interference percentages is shown in Figure 5. As can be seen, the product of preload and bolt diameter rises with the increasing torque, which shows an obvious linear trend. The linear fitting result is also shown in Figure 5. The gradient of the line is 0.168, which is also the torque coefficient in this experiment, and the fitting standard deviation is 0.0024.
4.2. Effect on multi-layer preloads

Referring to the calibrated coefficient, the preloads are 3968.25N, 7936.51N and 11904.76N corresponding to 4Nm, 8Nm and 12Nm respectively. After applying the preloads in FEM, the loads on the bolt head are obtained. The preloads differences are then calculated for all three methods.

As shown in Figure 6, the experimental preload difference shows obvious three stages for all three interference percentages. The first stage is load-increasing stage, which mainly happens below 2Nm. In this stage the preload on the nut increases, but cannot supply enough load to overcome friction and transfer to the bolt head, which leads to a negligible load variation. As preload is big enough, the load difference become stable, which is the second stage named load-stabilizing stage. With torque increasing forward, the difference goes down, which is the third load-decreasing stage. In this stage, there is a complex interaction between bolt shank and composite hole. Apart from radial pressure on the bolt shank induced by axial compression due to Poisson’s Effect, matrix damage also happens around the hole affecting the contact interface. The combined interaction between the bolt and composite finally results in a load-decreasing trend.

The finite element result and the experimental one agree well for the case of 4Nm and 8Nm, while there is a little deviation for 12Nm. Although there is also some preload decline in FEM, it is not as obvious as that of the experimental result. The main reason lies in that with preload increasing, apart from hole damage happens, the interface contact property also changes, which cannot be considered in the FEM. The theoretical result also has a similar trend with the experimental one of the second stage with interference percentage increasing, but the values are larger than the experimental ones. Taking deformation and interaction variation between the composite and bolt can improve the accuracy.
4.3. Effect on damage around the hole

The damage mode and range are illustrated in Figure 7 for 0.8% interference and 8Nm torque. To clearly understand the damage mechanism, both FVs and SDVs are shown in the figure. It appears several main damage modes: matrix compression failure in both transverse (FV2/SDV2) and thickness (FV7/SDV7) directions and fiber-matrix shear out failure (FV5/SDV5). The weak matrix strength and fiber-matrix interface are responsible for the damages. The compression imposed by the torque also leads to the most severe matrix compression damage. In addition, for the matrix tensile failure (SDV6) in the thickness direction, it can be found that the potential damage location lies in the vicinity of the bolt head outer edge. This is because the preload forces the bolt head to compress the plate, the matrix suffers a tensile load on the contact edge. Further loading may finally lead to damage.

The matrix compression damage in the thickness direction of 0.8% percentage for different torques is shown in Figure 8. There is no damage for 0Nm and 4Nm. A slight compression trace mainly occurs at the bolt head-composite contact region for 0Nm. This is mainly because the interference fit makes composite hole expand along axial direction and contact with the bolt head. With torque increasing, the contact between bolt head and composite plate becomes more obvious. When the torque gets to be 8Nm, matrix damage occurs. A large range of matrix damage covering all the region under the head can be seen for 12Nm, and the damage also propagates along the axial direction.

Figure 7 Damage around the hole (FV1/SDV1 and FV2/SDV2: matrix tensile and compression failure in transverse direction; FV3/SDV3 and FV4/SDV4: fiber tensile and compression failure; FV5/SDV5: fiber-matrix shear-out failure; FV6/SDV6 and FV7/SDV7: matrix tensile and compression failure in thickness direction).

Figure 8 Matrix compression damage around the hole for different torques.

Figure 9 illustrates matrix compression damage in the thickness direction of 8Nm with different percentages. It is found in the figure that although the matrix compression failure in thickness
direction is mainly caused by excessive torque, the damage for 0.0% and 1.2% has an obvious difference from the other two ones. The main reason is as stated above that the effect of interaction between the bolt shank and hole on load transfer. For 0.0% interference, the weak friction can hardly discourage preload from transferring to the bolt head and there is a sufficient contact between the bolt head and plate. Damage propagates along axial and radial direction. While for 1.2% interference, the preload transfer is stopped by the strong bolt-hole interaction, there is not enough preload on the head to compress the plate, thus the damage just distributes around the hole.

![Figure 9 Matrix compression damage around the hole for different interference percentages.](image)

4.4. SEM analyses on damage

The experimental specimens are cut, polished and cleaned to observe damages on the cross section under a SEM after experiment. Figure 10 shows damage in region 1 and region 2 for different torques (4Nm, 8Nm and 12Nm). In region 1, it can be seen that with torque increasing, the squeezing depth of bolt head applied on composite plate increases. Especially for 12Nm, the obvious squeezing phenomenon can be observed. Meanwhile, it can also be discovered from the partial enlarged detail that the matrix height on the contact surface decreases with increasing the torque, which shows a process of matrix being squeezed, squashed and compacted. The phenomenon results from the matrix compression damage as shown in Figure 8. In region 2, damage range enlarges with increasing torque, and various damage emerges in this region lead to the loss of stability of plate surface.

![Figure 10 Effect of torque on damage around the hole.](image)

The effect of interference-fit percentage on damage around the hole for the same torque is depicted in Figure 11. For region 3, with the interference-fit percentage increasing, the fiber damage mode changes from buckling to fracture. The reason is that the composite in this region firstly bears the axial friction and radial pressure from the bolt shank, then bears the pressure from bolt head when the bolt head contacts with the plate. The composite here shows a complex deformation as a result of Poisson’s Effect. When the percentage increases steadily, the squeezing effect that the fiber bears gets serious, leading to fiber bending. Once reaching to the strength limit, fiber breaks off. Part of the fibers break away and move along with the bolt shank. Delamination and a large scale of matrix fracture are also
found in 1.2% percentage. In region 4, the main damage is fiber buckling, the fiber has not broken off. Compared with the hole entrance corner, on one hand, the interference-fit percentage is more closer to the preset one, on the other hand, there is no constraint at the bottom, fibers can bend downward. Thus, no large scale of fiber fracture happens.

![Figure 11 Effect of interference-fit percentage on damage around the hole.](image)

5. Conclusions
The effect of interference-fit percentage and preload on single-shear lap composite joint is researched in this paper. Based on progressive damage theory, the multi-layer preloads and damage mechanism are compared and analysed. Main conclusions are as follows,

1) On multi-layer preloads, for the same torque, the preload difference shows a trend of increase with the increasing interference percentage. For the same percentage, the preload difference first increases, then keeps stable and last drops down with the increasing torque.

2) On damage, two main damage modes happen: matrix compression failure and fiber-matrix shear out failure. For the same percentage, the damage around the hole spread along radial and axial directions from the hole vicinity with increasing torque. While for the same torque, compared with neat fit, a certain amount of interference can slow load transfer and reduce damage.

References
[1]. Khashaba UA, Sallam, H.E.M., Al-Shorbagy, A.E., Seif, M.A.: Effect of washer size and tightening torque on the performance of bolted joints in composite structures. Compos Struct 73(3), 310-317 (2006). doi:DOI 10.1016/j.compstruct.2005.02.004
[2]. Liu LQ, Zhang, J.Q., Chen, K.K., Wang, H.: Combined and interactive effects of interference fit and preloads on composite joints. Chinese J Aeronaut 27(3), 716-729 (2014).
[3]. Jiang JF, Bi YB, Dong HY, Ke YL, Fan XT, Du KP. Influence of interference fit size on hole deformation and residual stress in hi-lock bolt insertion. P I Mech Eng C-J Mec. 2014; 228(18):3296-305.
[4]. Cao ZQ, Cardew-Hall M. Interference-fit riveting technique in fiber composite laminates. Aerosp Sci Technol. 2006; 10(4):327-30.
[5]. Zou P, Li Y, Zhang K, Cheng H, Li J. Influence of interference-fit percentage on stress and damage mechanism in hi-lock pin installation process of CFRP. J Compos Mater. 0(0):0021998316689601.
[6]. Zou P, Zhang K, Li Y, Liu P, Xie H. Bearing strength and failure analysis on the interference-fit double shear-lap pin-loaded composite. Int J of Damage Mech. 2016:1056789516671774.
[7]. Cestino E, Romeo G, Piana P, Danzi F. Numerical/experimental evaluation of buckling behaviour and residual tensile strength of composite aerospace structures after low velocity impact, Aerosp Sci Technol, 2016;54:1-9.

[8]. Kim SY, He B, Shim CS, Kim D. An experimental and numerical study on the interference-fit pin installation process for cross-ply glass fiber reinforced plastics (GFRP). Compos Part B-Eng. 2013; 54: 153-62.

[9]. Zou P, Li Y, Zhang K, Liu P, Zhong H. Mode I delamination mechanism analysis on CFRP interference-fit during the installation process. Mater Design. 2017; 116: 268-77.

[10]. Kiral BG. Effect of the clearance and interference-fit on failure of the pin-loaded composites. Mater Design. 2010; 31(1):85-93.

[11]. Wei JC, Jiao GQ, Jia PR, Huang T. The effect of interference fit size on the fatigue life of bolted joints in composite laminates. Compos Part B-Eng. 2013; 53: 62-8.

[12]. Zhao L, Zhi J, Zhang J, Liu Z, Hu N. XFEM simulation of delamination in composite laminates. Compos Part A-Appl S. 2016; 80: 61–71.

[13]. Rosales-Iriarte F, Fellows NA, Durodola JF. Experimental evaluation of the effect of clamping force and hole clearance on carbon composites subjected to bearing versus bypass loading. Compos Struct. 2011; 93(3):1096-102.

[14]. Olmedo A, Santiuste C. On the prediction of bolted single-lap composite joints. Compos Struct. 2012; 94(6):2110-7.

[15]. ABAQUS user’s manual 6.11, Providence, RI: Dassault Systems. (2011).

[16]. Chen J-F, Morozov EV, Shankar K. Simulating progressive failure of composite laminates including in-ply and delamination damage effects. Composites Part A: Applied Science and Manufacturing. 2014;61:185-200.

[17]. Duan Y. The preloading behavior and strength of bolted CFRP laminate joints with interference-fit. 2016. Northwestern Polytechnical University. (In Chinese)