Evaluation of insert design on the performance of repaired composite-Ti alloy joints

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ABSTRACT

Two kinds of titanium alloy inserts, namely bushing and embedded conical nut, were designed to repair the bearing damaged zone of screwed single-lap carbon fiber/polyimide composite-TC4 alloy joints, respectively. Quasi-static tensile tests were conducted to determine the effects of such repairs in terms of joint strength and joint stiffness concepts. Based on a simplified bearing model, the deformation mechanisms of titanium inserts influencing the joint performance are further discussed. It is concluded that: 1) the load-displacement curves of screwed joints consist of five characteristic stages; 2) the screw tilt significantly increases the failure load of the screw; 3) the use of an embedded conical nut aggravates the screw tilt, while the use of a bushing reduces the effect of screw tilt by distributing the bearing deformation evenly through the thickness. This difference leads to a different repair effect in terms of joint stiffness.

1. Introduction

Because of their high specific strength and specific stiffness and outstanding design freedom, carbon fiber reinforced polymer composites (CFRP) are increasingly applied in aircraft structures, and their application objects have been transferred from non-load bearing structures to secondary structures and even primary structures. Normally, CFRP structures can only come into service after assembly with other metal structures. While considering the galvanic corrosion effect, titanium alloys are realistically the only kind of lightweight metals that can be directly attached to the CFRP materials [1]. Thus, a large amount of CFRP-titanium alloy joints can be found in aircraft structures [2–5]. Three main joining methods are widely used in CFRP-titanium alloy joints, namely mechanical fastening, bonding and hybrid joining. Compared to bonding and hybrid joining methods, mechanical fastening has advantages of high assembly efficiency, convenience of disassembly and repair, low requirements for surface treatment, etc., which makes it the most common joining method for CFRP-titanium alloy joints [6,7]. Regardless of the joining methods, some common factors that influence the joint performance of CFRP-titanium alloy joints include the joint type (but or lap [8,9], single or double lap [10], shape of joint face [11], etc.), the joint parts properties (fiber preform [10], ply stacking sequence [12,13], titanium alloy properties [1,4,5], etc.) and the service environment (temperature and humidity) [14–16]. However, for the mechanically fastened joints, the fastener hole inherently cuts off load path, reduces the effective bearing area and causes stress concentration around the hole and hereby greatly affects the joint performance. Both experimental and numerical simulation research efforts have demonstrated that factors such as the hole-related geometry of the joints (width to diameter ratio, edge distance to diameter ratio, diameter to thickness ratio, etc.) [17], process parameters of manufacturing and assembly (clearance, clamping force, friction coefficient of assembly surface, and location error of fastener hole) [13], [18–20] and fastener details (fastener material, number and arrangement [21], fastener type [22,23], washer [24], metal insert [25–27], etc.) also have a large effect on the joint performance.

Considering the fastener type, the bolt/nut combination is the most common fastener used in mechanically fastened joints on account of its high quality of out-of-plane constraints (as shown in Fig. 1(a)); and the mechanical performance of bolted joints has been widely investigated [1], [8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27]. Generally, the typical failure modes of a bolted single-shear CFRP-titanium alloy joints can be divided into two categories: in-plane failure and out-of-plane failure (as shown in Fig. 2) [6,28,29]. The in-plane failure covers net-tension, shear-out, bearing, tear-out, and cleavage of the joint plates, while the out-of-plane failure includes pull-through, tilt and bearing failure, bolt shear and bolt bending. Among all these failure
modes, bearing failure is a relatively progressive failure and is deemed as the main design principle of bolted single-shear CFRP-titanium alloy joints [6]. In order to repair the joints failed by bearing mode, it is common to re-drill the fastener holes with greater diameter and to install the fasteners with greater diameter [27]. However, this repair procedure further decreases the joint strength due to the fastener holes with greater diameter. As a consequence, in recent years, in order to repair the bearing damaged zone inside the bolted joints, there seems precious few works [25–27] dealing with an alternative repair method with bonded metal inserts (shown in Fig. 3). Nevertheless, some influencing factors are still under investigation, the mechanisms are far from being fully understood, and the repair standard has not yet been reported.

In practice, in some cases when the structure provides less inner space and a smoother surface designed for higher aerodynamic efficiency such as a joint of an engine housing shell, a screw connection is preferred over the bolt/nut combination. With regard to a typical countersunk screwed CFRP-titanium alloy joints (as shown in Fig. 1(b)), a thread is machined in the fastener hole of the titanium plate instead of using a nut, and a countersunk hole is machined in the CFRP panel. In this way, flat upper and lower surfaces of the joint can be achieved. Besides, without using the nuts, a screw connection is weight saving and facilitates assembly when only one side of the construction is accessible. Nevertheless, compared to the bolted joints, screwed joints are more sensitive to tilt and bearing failure because of the lower tilt constraints of the inner thread than nuts [29]. Due to the tilt of the screw, the effective bearing area between the screw shank and hole edge can be significantly reduced, which will in turn greatly reduce the
stiffness and strength of the joint. However, only few researchers have paid attention to the mechanical performance of screwed CFRP-titanium alloy joints, not to mention the effects of repair on the performance of screwed composite-titanium joints.

Therefore, the purpose of this paper is to experimentally investigate the mechanical performance of screwed CFRP-titanium alloy joints and the repair effects of titanium inserts for screwed joints. Two kinds of titanium inserts were designed for CFRP and titanium plates respectively. Quasi-static tensile tests for screwed CFRP-titanium alloy joints were conducted to determine the effects of repair in terms of joint strength and joint stiffness. The experimental results and repair effect are further interpreted using a simplified analytical model.

2. Experimental procedures

Due to their superior mechanical properties at high temperature and widespread application in aircraft structures, unidirectional CCF300/AC721 carbon fiber/polyimide composite and TC4 titanium alloy were selected to fabricate the lap joints investigated here. Unidirectional CCF300/AC721 carbon fiber/polyimide composite is capable of operation and application at about 300 °C as the engine housing shell materials in aircraft field, and the layup of CCF300/AC721 CFRP laminate is selected to be [45/0/0/−45/90/0/45/0/−45/90/0/45/0/−45/90/0/45/0/−45/90/0/45/0/−45/90/0/45/0/−45/90/0]s (32 layers) in this work. As a material of high modulus and strength, 30CrMnSiA alloy steel screw was used to join CFRP and TC4 plates. The mechanical properties of materials are listed in Table 1, here the mechanical properties of CCF300/AC721 CFRP laminate are experimentally determined using the coupon samples in tension, compression and in-plane shear according to ASTM standards [30–32], while those of TC4 titanium alloy and 30CrMnSiA steel are obtained from literature [33]. The dimensions of the screwed single-lap CFRP-TC4 joint are shown in Fig. 4(a). Following the suggestions of ASTM D5961/D5961M-10 [28], the width to diameter ratio and edge distance to diameter ratio were designed as 6 (here 30/5 = 6) and 3 (here 15/5 = 3) respectively. Besides, phenolic resin doubleers with thickness of 4 mm and 5 mm were bonded on grip area (shown in Fig. 4(a)) prior to mechanical testing.

Two kinds of metal inserts made of TC4 titanium alloy, namely a bushing and an embedded conical nut, were considered and fabricated to repair the bearing damage of the CFRP plate and TC4 plate respectively. Their dimensions are shown in Fig. 4(b). The countersunk hole of bushing needs to be well-fitted with the M5 countersunk head screw, and the outer diameter of bushing is large enough to prevent the plastic deformation during tightening screw. Conversely, the tapered surface of embedded conical nut should avoid the pull-out of screw due to the secondary bending moment effect and the outer diameter at the tapered end of embedded conical nut is also large enough to prevent local failure due to the bearing stress between screw and nut contact. In order to investigate the repair effects of these two kinds of inserts, screwed single-lap CFRP-TC4 joints of six fastener configurations were fabricated, namely configuration P0, P_nut, C0, C_nut, C_bushing and C_nb (as shown in Table 2). Configurations P0 and P_nut used a protruding head screw, while configurations C0, C_nut, C_bushing and C_nb used a countersunk head screw. Moreover, the embedded conical nut was used in configurations P_nut and C_nut, and the bushing was used in configuration C_bushing, whereas the embedded conical nut and bushing were combined in configuration C_nb. The bushing and the embedded conical nut were bonded to the fastener hole of the CFRP plate and the TC4 plate by using a room temperature curing epoxy resin adhesive. In order to prevent the adhesive from permeating into the contact surface, we firstly applied the adhesive evenly on the insert surface, then assembled the inserts with the corresponding plate, and finally assembled the CFRP plate and TC4 plate after curing of the adhesive. In addition, because the tightening torque of screw will significantly influence the joint strength and joint stiffness [34,35], a torque wrench was used to tighten the screw with a fixed torque of 3.6 Nm. At least 4 valid data are required for each quasi-static tensile test, implying at least 24 valid data for all fastener configurations. Quasi-static tensile tests were conducted on an INSTRON-8803-50KN servo-hydraulic machine. Quasi-static tensile load is applied to specimen to produce failure within 10 min, during which the load-global displacement data was recorded.

3. Results and discussion

3.1. Experimental results overview

Figs. 5 and 6 show the load-displacement curves and representative failed specimens for all configurations. It is shown in Fig. 5 that five stages can be distinguished in the load-displacement curves, as reported by previous literatures [18,26,27]: i) no-slip, ii) slip, iii) screw shank and hole bearing, iv) damage onset and growth, v) final failure. The load-transferring mechanisms of each stage will be discussed later. Fig. 6 shows that final failure of all specimens involved screw failure. For configurations P0, C0, P_nut and C_nut, some slight bearing damage can be observed on the edge of the hole in the CFRP plate (as shown in Fig. 6(a)–(d)). The bearing deformation around the hole appeared to be non-uniform through the thickness which might be a sign of screw tilt. Apart from this, local instable behavior in the final part of the load-displacement curves is observed, due to the brittle failure behavior of the CFRP (as shown in Fig. 5(a)–(d)). While for configurations C_bushing and C_nb, their CFRP bearing damage are severer on the surface of the specimens which corresponds to the bearing failure of 45° layer around the hole (shown in Fig. 6(e) and (f)). Above phenomena indicate that the failure modes of all configurations are screw failure combined with CFRP bearing damage. Here, because of the smooth transition between stage iii and stage iv and slight bearing damage around the hole, the damage onset was deducted to be caused by local yielding of screw shank. Besides, for configurations P_nut, C_nut and C_nb, it is clear that adhesive failure happened which led to the separation between the embedded conical nut and the taper hole (shown in Fig. 6(e), (d) and (f)).

In order to further show the joint performance change during the loading process, the joint stiffness was calculated using a moving average of the values from two adjacent data points in the load-displacement curve and were plotted in Fig. 7.

3.2. Load-displacement curves of screwed single-lap joint

As a screwed single-lap joint is a system consisting of plates and screw, its joint performance is inherently decided by its load-transferring mechanism of shear load and secondary bending moment (caused by the intrinsic eccentricity). The load-transferring mechanisms in the five characteristic stages can be explained as follows:

i) No-slip stage: Due to the clearance between the screw shank and the hole and the clamping force between plates, the shear load is transferred between the plates via static friction, while the secondary bending moment is transferred by the unequal clamping stress distributed on each side of the overlap area. In this period, this system can be seen as a rigid structure. The displacement change in this stage is mainly caused by the elastic deformation of plates. Thus, the stiffness of this stage is the highest among all
stages, which is 22 to 25 kN/mm for all configurations (as shown in Fig. 7).

ii) Slip stage: It is obvious that the friction force on the TC4 plate is one-sided (plate-plate contact), while the friction force on the CFRP plate is two-sided (plate-plate contact, plate-screw head contact, as shown in Fig. 8). Slip between the contact surfaces will occur when the shear load $F$ exceeds the maximum static friction force (equal to the product of the number of contact surfaces, the clamping force and the friction coefficient). With the same clamping force on the two contact surfaces, the slip between the TC4 plate and CFRP plate is bound to occur before the slip of the plate-screw head contact surface. Thus, this stage can be divided into two short sub stages, slip stage 1 and slip stage 2, as shown in Fig. 7(a) and (b). In slip stage 1, the TC4 plate starts to slip with respect to the CFRP plate and bearing contact arises between the screw and the threaded hole, while the screw remains static with respect to the CFRP plate. In this stage, the shear load transfer mechanism of TC4 plate is changed to dynamic friction between the plates and bearing stress around the hole, which leads to a lower joint stiffness. In slip stage 2, when the shear load transferred by the CFRP lap can overcome the two-sided static friction, the screw starts to slip with respect to the CFRP plate until the screw shank and hole come into contacts.

iii) Screw shank-hole contact stage: In this stage, the main load-transferring mechanism is by means of the bearing stresses around the hole, and the joint stiffness remains nearly constant (as shown in Fig. 7). However, it is noteworthy that, for the TC4 plate, because of the secondary bending moment transferred by the screw, the hole-edge bearing stresses become non-uniform through the thickness while the screw is tilting. In a bolted joint, the secondary bending moment can be balanced by the bearing between nut and plate surface. However, due to relatively poor tilt constraints of the inner thread, the secondary bending moment can only be balanced by the

![Fig. 4. Geometry dimension of screwed single-lap CFRP-TC4 joints and TC4 titanium inserts.](image)

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Screwed single-lap CFRP-TC4 joints.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastener configuration</td>
<td>P0</td>
</tr>
<tr>
<td>Sketch</td>
<td></td>
</tr>
<tr>
<td>Screw type</td>
<td>M5 Protruding head</td>
</tr>
<tr>
<td>Metal insert</td>
<td>Embedded conical nut</td>
</tr>
<tr>
<td>Hole</td>
<td>CFRP</td>
</tr>
<tr>
<td>Screw head</td>
<td>Straight (Φ5)</td>
</tr>
<tr>
<td>Thread</td>
<td>Taper (Φ12)</td>
</tr>
<tr>
<td>Bushing</td>
<td>Straight (Φ10)</td>
</tr>
<tr>
<td>Metal insert &amp; Bushing</td>
<td>Embedded conical nut</td>
</tr>
<tr>
<td></td>
<td>Bushing &amp; Embedded conical nut</td>
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</tbody>
</table>
local bearing between screw shank and hole, which leads to a tendency of the screw to tilt and more severe bearing stresses around the hole.

A simplified bearing model can be used to argue the screw tilt effect on the joint stiffness (joint displacement) (shown in Fig. 9), in which the screw is assumed to be rigid. Because of the screw tilt, the bearing zone around the hole edge can be approximated to the triangle in the cross-section (as shown in Fig. 9(a)). For the upper CFRP plate, the bearing zone is mainly located in the front of the hole considering the existence of the clearance between the screw shank and the hole edge. Based on the geometrical relation shown in Fig. 9(b), the relative displacement between the axes of the screw and the hole of CFRP plate can be expressed as
\[ s_1 = L_1 \tan \varphi \]  
(1)

where \( s_1 \) is the relative displacement between the axes of the screw and the hole of CFRP plate; \( L_1 \) is the side length of triangular bearing zone at the hole edge of CFRP plate; \( \varphi \) is the screw tilt angle.

For the lower TC4 plate, the clearance between screw shank and the hole edge can be neglected due to the thread connection, and thus both the front and back of the hole turn into the bearing zones (shown in Fig. 9(c)). The geometrical relation between the side length of the triangular bearing zone in the front and back of the hole can be expressed as
\[ t_2 = L_{2a} + L_{2b} \]  
(2)

Fig. 5. Load-displacement curves of all configurations.
where $t_2$ is the thickness of the TC4 plate; $L_{2,f}$ and $L_{2,b}$ are the side length of triangular bearing zones in the front and back of the hole inside TC4 plate.

Again, from the geometrical relation shown in Fig. 9(c) and Eq. (2), the relative displacement between the axes of the screw and the hole of TC4 plate can also be written as

$$s_2 = L_{2,\tan} = (t_2 - L_{2,b})\tan \varphi$$

where $s_2$ is the relative displacement between the axes of the screw and the hole in the TC4 plate.

It is well-known that the shear load and secondary bending moment are mainly transferred by bearing stress around the hole. In general, the dynamic friction is neglected, and the contact of screw shank and hole-edge can be then regarded as a short beam supported by an elastic foundation (shown in Fig. 9(d)). According to the foundation stiffness formula proposed by Barrios [36], the distributed bearing load through the thickness is

$$q(z) = kx$$

with

$$k = \frac{E}{0.8} \left(1 - \frac{D}{W}\right) \approx E$$

where $x$ is the relative displacement between screw shank and hole-edge due to the bearing deformation of the hole; $z$ is the vertical distance between the plate-plate interface and screw shank through the thickness; $k$ is the foundation stiffness of the hole-edge; $E$ is the elastic modulus of the substrate, which corresponds to the averaged in-plane longitudinal modulus of the CFRP laminate or the elastic modulus of the TC4 alloy, respectively; and $D$ and $W$ are the hole diameter and width of the plates. Considering that $D/W$ equals 1/6 in this research, the foundation stiffness $k$ can be seen to be approximately equal to $E$.

Based on the geometrical relation as shown in Fig. 9(b) and Eqs. (4) and (5), it can be shown that

$$q_1(z) = E_1 (L_1 - z)\tan \varphi, \quad (z \leq L_1)$$

where $q_1(z)$ is the distributed bearing load through the thickness around the hole of CFRP plate; $E_1$ is the averaged in-plane longitudinal modulus of the CFRP laminate.

From Eq. (6), the resultant force and the resultant bending moment on the CFRP plate are respectively

$$\begin{align*}
F_1 &= \int_0^{L_1} q_1(z)dz = \frac{1}{2}L_{2,\tan}E_1\tan \varphi \\
M_1 &= \int_0^{L_1} q_1(z)zdz = \frac{1}{2}L_{2,\tan}E_1\tan \varphi
\end{align*}$$

By means of force equilibrium, it is possible to have

$$F = F_1$$

where $F$ is the external load of the joint. By analogy aid of Eq. (7), one has

$$\begin{align*}
F_{2,b} &= \frac{1}{2}L_{2,b}E_1\tan \varphi \\
F_{2,f} &= \frac{1}{2}L_{2,f}E_1\tan \varphi \\
M_{2,b} &= \frac{1}{2}L_{2,b}^2 (t_2 - \frac{1}{2}L_{2,b}) E_1\tan \varphi \\
M_{2,f} &= \frac{1}{2}L_{2,f}^2 E_1\tan \varphi
\end{align*}$$

where, $F_{2,b}$ and $F_{2,f}$ are the resultant forces generated by the bearing stress in the back and front of the hole inside TC4 plate respectively; $M_{2,b}$ and $M_{2,f}$ are the resultant bending moments generated by the
bearing stress in the back and front of the hole inside TC4 plate respectively; $E_2$ is the elastic modulus of the TC4 alloy.

The equilibrium equation of the screw at the plate-plate interface can be shown to be

$$\begin{align*}
-M_2c - M_2f &= M_1 \\
F_2 - F_{2b} &= F_1
\end{align*}$$

(10)

Substituting Eqs. (2), (7)-(9) into Eq. (10) leads to

$$\begin{align*}
3L_{2b} - t_1 &= \left(\frac{2F}{k_{tan}}\right)^2 \frac{E_2}{E_1} \\
t_2 - 2L_{2b} &= \frac{2F}{t_2E_{tan}}
\end{align*}$$

(11)

Based on the material property data in Table 1 and the dimensions as specified in Fig. 4, eliminating $L_{2b}$ in Eq. (11) and solving Eq. (11)
shows the numerical solution for the screw tilt angle $\varphi$ (shown in Fig. 10). It is shown from Fig. 10 that the relation of $\varphi$ is almost linear, which partly reflects the linear relationship of the load–displacement curves in the stage iii because the displacement caused by the screw tilt effect is a main part of the displacement of the joints.

Finally, considering the screw tilt effect, it is possible to have the relative displacement between plates as

$$s_T = s_1 + s_2$$

(12)

where $s_T$ is the relative displacement between plates considering the screw tilt effect.

By contrast, without considering the screw tilt effect, the relative displacement between plates is attained as

$$s_0 = \frac{F}{t_1E_1} + \frac{F}{t_2E_2}$$

(13)

where $s_0$ is the relative displacement between plates without considering the screw tilt effect; $t_i$ is the thickness of the CFRP plate.

From Eq. (13), it is clear that $s_0$ is a constant. Thus, the effect of screw tilt on joint stiffness can be shown by comparing $s_T$ as shown in Fig. 10 and $s_0$, and it can be shown that the screw tilt angle has a significant negative influence on the joint stiffness.

iv) Damage onset and growth stage and v) Final failure stage: From the
aforementioned model, it is clear that, owe to a screw tilt, the largest local bearing deformation (largest bearing stress) through the thickness locates at the plate-plate interface. Both screw-CFRP bearing and screw-TC4 bearing occur at this plane and damage onset is possibly caused by compression damage of the CFRP, yielding of the TC4 and the screw. However, it is hard to observe the local failure behavior during the experiment. In reality, no obvious hole-edge deformation is observed on CFRP and TC4, and thus the damage onset is more likely initiated due to local yielding of the screw. In light of the above simplified bearing model, the bearing stresses of screw-CFRP bearing and screw-TC4 bearing at the plate-plate interface is deduced as

\[
\begin{align*}
\sigma_1 &= L_1 \tan \varphi \\
\sigma_2 &= L_2 \tan \varphi
\end{align*}
\]

where \(\sigma_1\) is the bearing stress between screw and CFRP at the plate-plate interface; \(\sigma_2\) is the bearing stress between screw and TC4 at the plate-plate interface.

Fig. 11 presents the comparison between calculated results of \(\sigma_1\) and \(\sigma_2\). From Fig. 11, it is apparent that the bearing stress between the screw and the TC4 plate is almost twice of that between the screw and the CFRP plate. This implies that the front contact between the screw and the TC4 plate is the more critical area in the plate-plate interface. Yielding of the screw will start at this area, which significantly reduces the joint stiffness. Because the toughness of 30CrMnSiA alloy steel as screw material, this damage onset is a progressive event with a slow degradation of joint stiffness (shown in Fig. 7). However, during the yielding growth period of screw, local CFRP bearing damage shows a brittle feature with an unstable damage growth, causing fluctuations in load-displacement curves. With the increased load, local yielding of screw aggravates and bearing capacity of joint declines until final failure of joints.

From Figs. 5 and 7, it can be shown that the joint stiffness in stage iii is slightly larger for configuration P0 than for configuration C0, while the joint strength (screw failure load) is significantly lower for configuration P0 than for configuration C0 and the damage onset takes place earlier. That is because the countersunk hole in configuration C0 barely shares the bearing stress as compared to the straight hole part to lead to a larger deformation in the straight hole part [22,23] (as shown in Fig. 12(a) and (b)). Meanwhile, the bearing stress is closer to the plate-plate interface for configuration C0 than for configuration P0, and thus the resultant secondary bending moment generated by the bearing stress is smaller, causing a larger screw failure load. Fig. 13 shows the fracture surface of screw in configurations P0 and C0. From Fig. 13, it can be observed that an distinct deflection from the screw axis exists on fracture surface for configuration P0, which means a sign of screw tilt, while no evident deflection appears on fracture surface for configuration C0.

3.3. Repair effect of an embedded conical nut and a bushing

In order to quantitatively evaluate the repair effect of embedded conical nut and bushing, the average values and the coefficient of variation of joint stiffness and strength for all kinds of configurations...
are the stiffness and strength respectively; \( K_0 \) and \( S_0 \) are the stiffness and strength for joints without insert repair (i.e., configurations P0 and C0) respectively.

In accordance with Eq. (15) and experimental results of joint stiffness and strength, the repair effect is evaluated (listed in Table 3).

3.3.1. Repair effect of an embedded conical nut

It can be seen from Table 3 that the use of an embedded conical nut for configurations P_nut and C_nut can regain 76.9% and 86.4% of the joint stiffnesses for configurations P0 and C0 respectively, and the stiffnesses are significantly lower for repaired joints (or configurations P_nut and C_nut) than for original joints (i.e., configurations P0 and C0). Fig. 12(c) and (d) show the hole-edge bearing conditions for configurations P_nut and C_nut. The embedded conical nut inherently adds a bearing interface between the nut and the taper hole, affecting the transfer of the shear load and secondary bending moment. For this reason, the screw tilt arises from the combined contact bearing between the nut and taper hole and between screw shank and thread hole, resulting in a larger screw tilt angle for configurations P_nut and C_nut than for configurations P0 and C0. Fig. 5(c) and (d) shows the earlier instable behaviors for configurations P_nut and C_nut than for configurations P0 and C0 (especially for configuration C_nut). This probably owes to the bearing damage of CFRP plate or the bearing failure of adhesive for configurations P_nut and C_nut. Actually, it is hard to capture the bearing damage in the CFRP plate, but the separation of embedded conical nuts from taper hole is always observed for configurations P_nut and C_nut, this implies that the earlier instable behavior is more likely attributed to the bearing failure of adhesive. From Figs. 7(b) and 8(c), it is apparent that the fluctuation on the load-stiffness curves during the stage iii is stronger, which likely means the local bearing failure of adhesive. As a result of bearing failure of adhesive, the increase in the hole clearance ascribes to larger screw tilt and bearing deformation around the hole.

From Table 3, it is interesting to notice that the use of embedded conical nut for configurations P_nut and C_nut can regain 112.5% and 98.9% of joint strengths for configurations P0 and C0 respectively, and the repair with embedded conical nut seems beneficial for configuration P0, but detrimental for configuration C0. The reason for this is that for configuration P_nut, the use of embedded conical nut aggravates the

In terms of experimental results of stiffness and strength, the repair efficiency of the inserts can be evaluated as

\[
\eta_k = \frac{K_k}{K_0} \times 100\%
\]

\[
\eta_s = \frac{S_s}{S_0} \times 100\%
\]

where \( \eta_k \) and \( \eta_s \) are the repair efficiency of the inserts in terms of the joint stiffness and strength respectively; \( K_k \) and \( S_s \) are the stiffness and strength for joints with inserts repair (or configurations P_nut, C_nut, C_bushing and C_nb) respectively; \( K_0 \) and \( S_0 \) are the stiffness and strength for joints without insert repair (i.e., configurations P0 and C0) respectively.

Table 3
Repair efficiency of embedded conical nut and bushing.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Protruding head</th>
<th>Countersunk head</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P0</td>
<td>P_nut</td>
</tr>
<tr>
<td>No. of test</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Joint stiffness (K)</td>
<td>Mean value / kN/mm</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>Coefficient of variation</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td>P value*</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>( \eta_k )</td>
<td>–</td>
</tr>
<tr>
<td>Joint strength (S)</td>
<td>Mean value/kN</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>Coefficient of variation</td>
<td>3.9%</td>
</tr>
<tr>
<td></td>
<td>P value*</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>( \eta_s )</td>
<td>–</td>
</tr>
</tbody>
</table>

*P value: The statistical significant difference level between the results of joints with inserts (configurations P_nut, C_nut, C_bushing and C_nb) and joints without insert (configurations P0 and C0).
screw tilt to make the bearing loads nearer the plate-plate interface, reducing the transferred secondary bending moment through the screw and thus increasing the yielding and final failure loads of the screw (shown in Fig. 7(b)). Conversely, for configuration C_nut, the use of embedded conical nut slightly decreases screw tilt (shown in Fig. 7(c)), indistinctively increases secondary bending moment and declines final failure load.

3.3.2. Repair effect of bushing

Table 2 shows that the hole diameter of the CFRP plate for configuration C_bushing is twice of that for configuration C0, and thus the foundation stiffness around the hole is less for configuration C_bushing than for configuration C0 on the basis of Eq. (5). Meanwhile, the bushing inherently adds a load-transfering interface between the bushing and the CFRP plate. Needless to say, the use of bushing for configuration C_bushing looks like adverse for on the joint performance. However, from Table 3, it is evident that the use of bushing for configuration C_bushing can regain 117.3% of joint stiffness and 108.0% of joint strength for configurations C0, and both stiffness and strength are greater for configurations C_bushing than for configurations C0. In fact, for configuration C_bushing, although screw tilt still exists because of the absence of nut, the use of bushing attributes to the perpendicular bearing surface of CFRP plate to the shear load, apparently reducing the bearing deformation (see Fig. 12(e)), mitigating the degradation in joint stiffness (see Fig. 7(d)) and retarding the yielding of screw. Meanwhile, since the titanium alloy has a superior plasticity as compared against the CFRP plate, local yielding of bushing at the hole-edge can relieve the stress concentration in the contact zone, slightly retarding the yielding of screw and increasing the joint strength. Also, as mentioned in previous research [25–27], the adhesive on the back of the hole for configuration C_bushing can decline the bearing stress on the front of the hole.

Again, from Table 3 and Fig. 7(f), it is distinct that the use of embedded conical nut and bushing for configuration C_nb falls in between those each one occurring on its own (i.e., configurations C_nut and C_bushing).

4. Conclusions

The repair effects with two kinds of titanium alloy inserts (bushing and embedded conical nut) are investigated experimentally for screwed single-lap carbon fiber/polyimide composite-TC4 titanium alloy joints based on joint stiffness and strength concepts. A simplified bearing model was proposed to interpret the effects of inserts on the joint performance. The following conclusions can be drawn:

1) The load-displacement curves of screwed joints consist of five characteristic stages in terms of stiffness change. However, without the use of nut, the screwed joint is more likely to fail in tilt and bearing mode. The analysis based on a simplified bearing model shows that the screw tilt has a significant influence on the stiffness of screwed joints, because it aggravates the bearing damage near the plate-plate surface.

2) For the investigated case, the use of an embedded conical nut can regain 76.9% and 86.4% of the original joint stiffness for a protruding head screw joint and a countersunk head screw joint respectively. The additional bearing plane between nut-taper hole surface leads to a larger screw tilt. Meanwhile, due to the bearing failure of adhesive, the clearance of the hole always increases to cause a larger screw tilt and a larger bearing deformation around the hole.

3) The use of embedded conical nut can regain 112.5% and 98.9% of joint strengths for a protruding head screw joint and a countersunk head screw joint respectively. The reason for this is that for a protruding head screw joint, the use of embedded conical nut aggravates the screw tilt to make the bearing loads nearer the plate-plate interface, reducing the transferred secondary bending moment through the screw and thus increasing the yielding and final failure loads of the screw. Conversely, for a countersunk head screw joint, the use of embedded conical nut slightly decreases screw tilt, indistinctively increases secondary bending moment and declines final failure load.

4) The use of a bushing can regain 117.3% of the original joint stiffness and 108.0% of the original joint strength for a countersunk head screw joint. This is mainly due to the bushing evenly distributing the bearing deformation through the thickness, which greatly reduces the effect of screw tilt, decreases the bearing deformation, relieves the stress concentration and retards the yielding of screw.

5) The combined use of an embedded conical nut and a bushing can regain 109.9% of the original joint stiffness and 104.6% of the original joint strength for a countersunk head screw joint, and the repair effect falls in between the use of each insert separately.

6) Although the screw tilt greatly reduces the joint stiffness, it significantly increases the failure load of the screw. That is because, with a larger screw tilt, the bearing zone is closer to the plate-plate surface and it in turn reduces the secondary bending moment transferred by the screw.

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Appendix A. Supplementary data

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References


