A Study on Failure behavior of CFRP Bolted Joints with Cone Washers by Using AE Monitoring

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Abstract

Bolted joints are one of the common assembling methods for carbon fiber reinforced plastic (CFRP) members. During bolt tightening of CFRP members, cracks or plastic deformation likely occur around bolt holes when employing high fastening forces. To prevent these kinds of damages, the fastening force is controlled in low level. When an external joint load is applied to CFRP bolted joints, most of the external load is transmitted via a bolt. As a result, CFRP failure around bolt holes occurs by stress concentration, and the strength of a CFRP joint is reduced.

To address this problem, we have tried to gain friction force between CFRP members by increasing a friction coefficient and a bolt-fastening force. To increase a friction coefficient, we have inserted a thin sheet having a high friction coefficient between CFRP members. On the other hand, to increase a bolt-fastening force without cause damages, cone washer which was proposed in previous paper was utilized.

In this study, the joint strength and the failure behaviour of conventional and proposed joint were examined by finite element method analyses with degradation rules. The results show that the joint strength of the proposed joint was higher than that of conventional joint and the failure behaviour was different from that of the conventional joint. To investigate the joint strength and the failure behaviour of the actual proposed joint, the single-lap joint tensile tests with AE monitoring were conducted. The failure strengths of CFRP bolted joints with high-friction sheets and cone washers were higher than those of conventional CFRP bolted joints. Cumulative AE energy shows that the failure initiation load of the proposed joint was higher than that of the conventional joint, and the failure behaviour of the proposed joint was different from that of the conventional joint just like the finite element method analyses.

Introduction

In modern aircraft, carbon fiber reinforced plastic (CFRP) members are widely used for weight reduction. One of the major assembling methods for the CFRP members is the bolted joint. For example, it is used for manufacturing main wings, stabilizers, fuselages and so on.

In general, increase in bolt-fastening forces lead increase in joint strength compared to the pin joint [1, 2]. However, to prevent damages of the CFRP around bolt holes during bolt fastening, bolt-fastening forces are controlled to be low [3]. Because of the low bolt-fastening forces, friction forces at the interface between CFRP members are low and bearing forces acting on the sides of bolt holes become large [4]. This causes stress concentrations around bolt holes when external loads are applied to the joints. For this reason, CFRP and bolt failure tend to occur around bolt holes. Hence, the strengths of conventional CFRP bolted joints are 20-50% of the CFRP laminate strength [3]. The typical macroscopic failure modes of composite bolted joints are following six types: bearing failure, tension failure, share-out failure, cleavage failure, bolt
pulling through laminate and bolt failure. These are shown in Fig. 1. In general, CFRP bolted joints are designed as critical in bearing failure [3] to prevent catastrophic failure of the members.

To address these problems and increase the strengths of CFRP bolted joints with minimum weight gain, high friction forces at the interfaces between CFRP members are required. We have proposed two approaches for increasing friction forces. The first approach is increasing the friction coefficient of CFRP contact surfaces and the other is increasing bolt-fastening forces without damaging the CFRP. In this study, to verify effectiveness of the proposed joint, we investigated joint strength and failure behaviour of the proposed joint by three-dimensional FEM analyses with degradation rules and joint tensile tests with AE monitoring.

**Configurations of joint specimens**

In this study, the joint specimens were single-lap type with two bolts. The CFRP specimens had a stacking sequence of 16-layer quasi-isotropic [(45/0/-45/90)]\textsubscript{S}. The thickness of the CFRP plate was 3.6 mm. The geometry of CFRP specimens was based on ASTM D5961 [5] and shown in Fig. 2.

Since titanium alloy fastener is commonly used for CFRP members of aircraft to prevent galvanic corrosion [3] and to reduce the weight, we used titanium alloy (Ti-6Al-4V) bolts for the joints. The bolt diameter was 6.0 mm. As the first proposed method, we used a high-friction sheet to increase the friction coefficient of CFRP contact surface. The sheet was made of two sandpapers (#240), which were bonded with two-component epoxy adhesive (Huntsman advanced materials, Araldite rapid), and it was inserted between CFRP members. Sandpaper has a high friction coefficient that does not depend on the normal stress on the contact area, unlike the coefficient of high-friction sheets currently available for joints, such as rubber sheets [6] and adhesive tapes [7]. The measured friction coefficient of between untreated CFRP plates was 0.36, and that of between CFRP plates inserted high-friction sheet was 0.68 [8].

![Fig. 1 Typical macroscopic failure modes of composite bolted joints.](image)

![Fig. 2 Configuration of the specimen based on ASTM D5961 (unit : mm).](image)
As the second proposed method, we used the cone washer as shown in Figs. 3(a) and (b). The configuration of this washer was determined to maximize allowable bolt-fastening forces without CFRP damage by using finite element method analyses [8].

**FEM analyses**

To investigate the joint strength and failure behaviour, three-dimensional (3-D) finite element method (FEM) analyses were conducted. The finite element code which we used was ANSYS 11.0. Figure 4(a) and 4(b) show the whole of the model and the finite element mesh of the area around bolt holes respectively. In the model, CFRP was represented by SOLID46 eight-node layered elements with three displacement degree per node. The bolts were represented by SOLID45 six-node elements and the washers were represented by SOLID 92 four-node elements. The frictions between CFRPs, CFRPs and washers, CFRPs and bolts and washers and bolts were considered by using CONTA173, 174 and TARGE170 elements, which are generally used for surface-surface contact problems. The one grip area of the CFRP was fixed and forced displacements were applied on the other grip area as external loads. The material properties and failure stress of the CFRP used for the analyses are from Ref. [9]. Hashin failure criteria [9] were used to judge CFRP failure. The failure criteria can distinguish four failure modes of matrix crack, fiber failure, fiber-matrix share-out and delamination. Additionally, maximum stress failure criteria were used for the bolts and washers.

![Fig. 3 Configurations of the proposed cone washer: (a) photograph; (b) geometry (unit: mm).](image)

![Fig. 4 Finite element model of the analyses: (a) whole of the model; (b) finite element mesh of the area around bolt hole in the CFRP.](image)

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Material properties</th>
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<tbody>
<tr>
<td>Matrix crack</td>
<td>( E_x = 0, \nu_{xy} = 0 )</td>
</tr>
<tr>
<td>Fiber failure</td>
<td>( E_x = E_y = E_z = G_{xy} = G_{yz} = G_{xz} = 0 )</td>
</tr>
<tr>
<td>Fiber-matrix share-out</td>
<td>( v_{xy} = v_{yz} = v_{xz} = 0 )</td>
</tr>
<tr>
<td>Delamination</td>
<td>( G_{xy} = 0, v_{xy} = 0 )</td>
</tr>
<tr>
<td></td>
<td>( G_{yz} = G_{xz} = 0, v_{yz} = v_{xz} = 0 )</td>
</tr>
</tbody>
</table>

x : Fiber direction, y : Transverse direction, z : Thickness direction
In these analyses, to investigate the progression of failure behaviour, the material properties of the CFRP were changed by the degradation rules when the failure occurs in the CFRP as reported in Refs. [9, 10, 11]. Table 1 shows the degradation rules [9] used for the analyses.

The results of the analyses are presented in Table 2 and Figs. 5(a) and (b). Table 2 presents the joint strengths when using the conventional plain washers and proposed high-friction sheet and cone washers. The results show that use of the proposed high-friction sheet and cone washer increases the CFRP bolted joint strength. Figure 5(a) shows the failure progression of the CFRP with conventional plain washers when a 13.7 kN joint load and 1.0 kN bolt-fastening forces (representing finger-tightened bolts) were applied. In the figure, the blue areas represent the elements occurring matrix crack, the green areas represent the elements occurring matrix crack and delamination. The red areas represent the elements occurring matrix crack, delamination and fiber failure. The result shows the large area near the bolt hole was damaged. And the damages were concentrated in one side of the two bolt holes because of the bending deformation of the single-lap joint. In the initial failure stage, delamination occurred followed by matrix failure. In the progressive failure stage, fiber failure occurred as shown in Fig. 5(a). Figure 5(b) shows the failure progression of the CFRP with the proposed high-friction sheet and cone washers when a 17.4 kN joint load and 5.5 kN bolt-fastening forces were applied. In the figure, coloured areas represent the elements occurring failure just as Fig. 5(a). Since the increase of the friction forces and the decrease of the bearing forces, the damaged area (b) was small compared to that of conventional joint (a) even the larger joint load was applied. Although the process of the failure progression was same as that of the conventional joint, the failures exist around both bolt holes unlike in the case of the conventional joint because of the effect of the displacement restraint by the cone washers, and the effect can reduce the failure concentration as shown in Fig. 5(a). By these analyses, it was clarified that the proposed joint can increase the failure initiation load and restrains the failure progression unlike the conventional joint.

**Joint tests with AE monitoring**

To examine the proposed joining method of inserting the high-friction sheet and using cone washers, single-lap joint tests were conducted for a conventional CFRP bolted joint and the proposed joint. These were conducted according to ASTM D5961 [5]. The testing machine was Autograph AG-I 100kN (SHIMADZU Corporation) and the tensile speed was 1.0 mm/min. During the tests, AE monitoring was conducted using PCI-DSP4 system (Physical Acoustics Corporation) and two small AE sensors (Type: PICO, Physical Acoustics Corporation). The sensors were attached to the CFRP specimen.

<table>
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<tr>
<th>Joint type</th>
<th>Joint failure load [kN]</th>
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<tbody>
<tr>
<td>Conventional</td>
<td>7.7</td>
</tr>
<tr>
<td>Proposed</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 2 Joint strengths determined from the FEM analyses

Fig. 5 Failure prediction for the CFRP in the progressive failure stage: (a) conventional joint; (b) proposed joint.
Outputs of the AE sensors were amplified 40 dB by preamplifiers (NF Electronic instruments, Type: 9913) and filtered by band-pass filters of 100k to 700kHz.

The CFRP specimens were made of PYROFIL380 prepreg (Mitsubishi Rayon Corporation) and had a stacking sequence of 16-layer quasi-isotropic [(45/0/-45/90)_s]. The bolts were made of titanium alloy (Ti-6Al-4V) and had diameters of 6.0 mm. Two strain gages (Kyowa Electronic Instruments, KFG-0.2-120-C1-11L1M2R) were attached on the CFRP specimen. The geometrical configuration of the sensors is shown in Fig. 6. Strain gages (Kyowa Electronic Instruments, KFG-1.5-120-C20-11) were inserted for all bolts to measure the axial strain. The cone washers were made of aluminium alloy (A2017) and had the configurations shown in Fig. 3(b).

![Fig. 6 Geometrical configuration of the sensors (unit : mm).](image)

![Fig. 7 Specimens of the joint tests: (a) conventional joint; (b) proposed joint.](image)

![Fig. 8 Relationships between joint load, crosshead displacement and bolt axial strain: (a) for the conventional joint; (b) for the proposed joint.](image)
For the conventional CFRP bolted joints, normal plane washers with a diameter of 14 mm and thickness of 1.6 mm were used and bolts were tightened by hand. For the proposed CFRP bolted joints, cone washers with a diameter of 35 mm and thickness of 10 mm were used and the fastening force was 5.5 kN. Figure 7 shows the specimen of the conventional CFRP bolted joint (a) and proposed CFRP bolted joint (b) respectively.

The relationships among joint load, crosshead displacement and bolt axial strain for both joint types are shown in Figs. 8(a) and (b). The joint load increased with crosshead displacement in a relatively linear manner in the first period (<1.0 mm crosshead displacement for the conventional joint, and <3.0 mm crosshead displacement for the proposed joint, except during the very initial stage). The onsets of non-linear behaviour were determined by drawing a line parallel to the linear portion of the load–crosshead displacement curve corresponding the beginning of the bolt axial strain increasing but offset by 0.2% strain and investigating the crossing-point of the two curves as shown in Figs. 8(a) and (b). We took the loads at the crossing-points as the joint failure loads $P_{0.2\%}$.

The macroscopic failure modes of the conventional joint were bearing failure and bolt failure. On the other hand, that of the proposed joint was bearing failure only because of the decrease in stress concentration around bolt holes due to the change in the manner of external force transmission; that is, the bearing forces were reduced and the friction forces were increased.

The AE monitoring results are shown in Figs. 9(a) and (b).

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**Fig. 9** Relationships between joint load, crosshead displacement and cumulative AE energy: (a) for the conventional joint; (b) for the proposed joint.

**Fig. 10** Waveforms of the AE signals: (a) with the short rise time (<55 µsec), (b) with the long rise time (>55 µsec).
The figures show the relationships among the joint load, crosshead displacement and cumulative AE energy for both joint types. We extracted AE signals above 60dB peak amplitude and obtained cumulative AE energy. Figure 9(b) shows that AE signals with low energies were dominant in the initial period (<4.0 mm crosshead displacement) of the proposed joint test. The rise times of those AE signals were shorter than 55 μsec as shown in Fig. 10(a). On the other hand, the rise times of the many AE signals monitored in later period of the proposed joint test and all period of the conventional joint test are longer than 55 μsec as shown in Fig. 10(b). Therefore, it is conceivable that the AE signals with short rise time (<55 μsec) were related to the friction between CFRPs or CFRP and high-friction sheet. In other words, the AE signals with longer rise time (>55 μsec) were related to the failure of the joints. Figures 11(a) and 11(b) show the relationships among the joint load, crosshead displacement and cumulative AE energy without short rise time (<55 μsec) signals for both joint types. In the figures, the behaviour of the cumulative AE energy can be divided into three stages. In the first stage shown by yellow areas in the figures, the cumulative AE energies begin increasing and may relate to the tiny failure occurrence around bolt holes. In the second stage shown by red areas in the figures, the cumulative AE energies rapidly increase at first. Then, those were nearly-constant. The second stages may relate to the beginning of the small bearing failure. In the third stage shown by purple areas in the figures, the cumulative AE energies rapidly increase, and the stages may relate to the progression of bearing failure. Therefore, we took the loads when the first failure stages (yellow areas in Figs. 11(a) and (b)) started as the initial failure loads $P_i$. In the same way, we took the loads when the second failure stages (red areas in Figs. 11(a) and (b)) started as the bearing failure loads $P_b$.

The results of the tests are presented in Table 3. All failure loads for the proposed joint were about 50% greater than those for the conventional joint. The difference of the failure loads was caused by the friction force in the proposed joint and the effect of the displacement restraint by the cone washers as presented by FEM analyses. Especially, the difference of the bearing load $P_b$ presented that the bearing strength of the proposed joint was higher than that of the conventional joint. These results verify the effectiveness of the proposed joint.

![Fig. 11 Relationships between joint load, crosshead displacement and cumulative AE energy without short rise time (<55 μsec) signals: (a) for the conventional joint; (b) for the proposed joint.](image)

<table>
<thead>
<tr>
<th>Failure load type</th>
<th>Conventional joint</th>
<th>Proposed joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{0.2%}$</td>
<td>12.3 [kN]</td>
<td>18.5 [kN]</td>
</tr>
<tr>
<td>$P_i$</td>
<td>10.0 [kN]</td>
<td>15.2 [kN]</td>
</tr>
<tr>
<td>$P_b$</td>
<td>13.6 [kN]</td>
<td>20.3 [kN]</td>
</tr>
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</table>
Conclusions

In this study, 3-D FEM analyses showed the proposed joint has a better failure load and different failure behaviour compared with those of the conventional joint. Joint tensile tests with AE monitoring for the both joints were conducted according to ASTM D5961. The results of AE monitoring showed that the failure loads of the proposed joint were greater than that of the conventional joint. From these results, the effectiveness of the proposed joint was verified.

References