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Hirano, Noriyoshi
Kawasaki Heavy Industry Co.,LTD

Wang, Wen-Xue
Research Institute for Applied Mechanics, Kyushu University

Takao, Yoshihiro
Research Institute for Applied Mechanics, Kyushu University

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The Effect of Temperature on Bearing Strength of CFRP Bolted Joint with Washer Constraining

Noriyoshi HIRANO[*1], Wen-Xue WANG[*2] and Yoshihiro TAKAO[*2]

E-mail of corresponding author: *ytakao@riam.kyushu-u.ac.jp*

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Abstract

Effects of temperature on the bearing strength of a CF/Epoxy quasi-isotropic laminate bolted joint are investigated experimentally. The material system is CF/Epoxy T800H/#3631 with stacking sequence of $[0/45/-45/90]_{3S}$. In this study, a semi-circular notched specimen is chosen and loaded in compression instead of a well-known double lap joint. This method has advantages in material cost and simplicity of its damage mode. A bolted joint with the washer constraint is loaded at 25, 150 and −100 °C. Moreover, the cross section of bearing damage zone is observed with an optical microscope after polishing. The results of load-displacement response show a stable manner of damage propagation and no catastrophic load drop for all temperature cases, as compared with pinned joint without any lateral constraint. At 150 °C, the lower endurance limit of load appears than 25 and −100 °C cases. From microscopic observation, it is revealed that the initiation and increase of kinking failure of a 0 ° lamina is corresponding to the effective damage initiation of bolted joint and damage evolution, respectively.

Key words : *CF/Epoxy, Bolted joint, Bearing failure mode, Temperature environment, Lateral constraint*

1. Introduction

Carbon fiber reinforced plastic (CFRP) has high specific strength and stiffness so that it is extensively used at aerospace, sports fields etc., which demanded light weight structures. The recent aerospace community has several challenging projects such as the next super sonic transport (SST) [1] and re-useable liquid fuel tank project [2], therefore it require the advanced composite materials enduring severe environments and super sonic transport is purposed to cruise at Mach 2.2 or 2.4 and the surface is exposed to high temperatures around 180 °C at maximum, for long hours.

Many fundamental studies on temperature effects have been performed with CF/Epoxy quasi-isotropic laminate of $[0/45/-45/90]_{3S}$ cured at 180 °C under tensile load [3]. It shows that mechanisms of damage evolution and nonlinear behavior are different from each other under various environmental temperatures. Model and II interlamina fracture toughness with various fiber direction at −100, 20 and 150 °C are also investigated [4].

*1 Kawasaki Heavy Industry Co.,LTD

*2 Research Institute for Applied Mechanics, Kyushu University

A mechanical joint such as a rivet or bolt is widely used in joining practical structures due to the advantages in replacement and inspection. However, an existing hole causes the stress concentration and it leads to the decrease of load-carrying capability and the structure weight loss. Especially CFRP possesses intrinsically heterogeneous and anisotropic nature and the joint problem is more difficult to analyze than the isotropic material case.

A CFRP mechanical joint has many failure modes such as tension, shear-out and bearing, which depend on the material configuration, joint geometry, ply orientation and material properties. One of the failure modes of the mechanical joint is bearing mode that has higher strength and more stable than the other failure modes. Therefore, it should be designed to make the bearing mode occurred [5]. After microscopic observation, several researchers [6] [7] reported that the bearing mode failure of a mechanical joint of CF/Epoxy laminates at room temperature is the accumulation of matrix crack, delamination and fiber kinking. Moreover, the washer constraint to through the thickness direction restrains the catastrophic load decrease, while a pinned joint without the lateral constraint presents rapid load decrease after the maximum, which means that the lateral clamping load strongly influences the joint strength. The effects of temperatures on the mechanical are little reported. R.Y.Kim et al. [8] investigated a pin joint without lateral constraint at 127 °C experimentally and they showed that the joint strength is 40% less than the one at 20 °C.

The purpose of this experimental study is to understand the temperature effect on the bearing mode failure of a bolted joint with washer constraint and CF/Epoxy cured at 180 °C is used. Generally, epoxy matrix composite materials are expected to be used less than 150 °C [9]. Though, SST is exposed to 180 °C temperature, it is possible to use CF/Epoxy inside the body or at ever the surface of SST if less than 150 °C. Moreover, have been established CF/Epoxy is easy to study since many fundamental reference data obtained around the world.

The authors have already obtained the temperature effect on the 3-D microscopic features of damage evolution in pinned joint bearing tests at 25, 150 and –100 °C [10] [11]. In the present study, a bolted joint is investigated experimentally at 25, 150 and –100 °C, and the microscopic feature of damages is examined with an optical microscope. The results are discussed with reference to pinned joint cases.

2. Experimental Method

A semi-circular notched specimen shown in Figure 1 was adopted instead of a well-known double-lap joint. This method has an advantage in the compact size of both the specimen and thermostatic chamber, as well as it simplifies the fractographical analysis since only the bearing failure mode occurs. Compressive load was applied through a SUS pin whose diameter is 6 mm.

The bearing test jig of a bolted joint is illustrated in Figure 2. SUS blocks were placed on both surfaces of the specimen to prevent Euler buckling during compressive loading. Those accessories sandwiched the specimen by slightly clamping finger tighten steel bolts on both specimen edges and are mounted on a flat SUS plate. The collar regarded as a washer whose diameter is 18 mm applied the lateral constraint. A clamping torque 1.2 Nm was set to be and was strictly measured by torque wrench.

The material used in this study was quasi-isotropic CF/Epoxy T800H/#3631 (Toray co.) laminates with fiber volume fraction of 60%. The stacked prepregs were cured by using an autoclave at 180 °C and post-cured following the manufacturer's recommendations. The ply configuration was $[0/45/\text{-}45/90]_{3S}$, where a 0° laminate is aligned with the loading direction. The cured laminate was cut into rectangular plate of 100 mm width and76 mm height. A hole with diameter of 6 mm was machined by using diamond-coated tools and the plate was cut into two specimens of the size of 36 mm height. The thickness is about 3 mm. The finished hole surface of all specimens was inspected with an optical microscope and damaged ones were omitted.

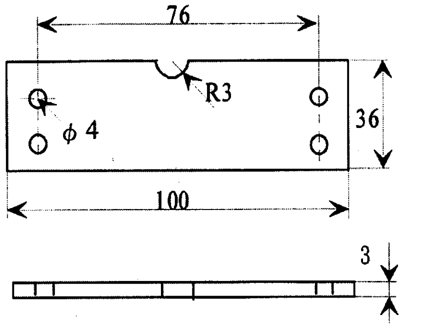


Figure 1 The half circular notched specimen

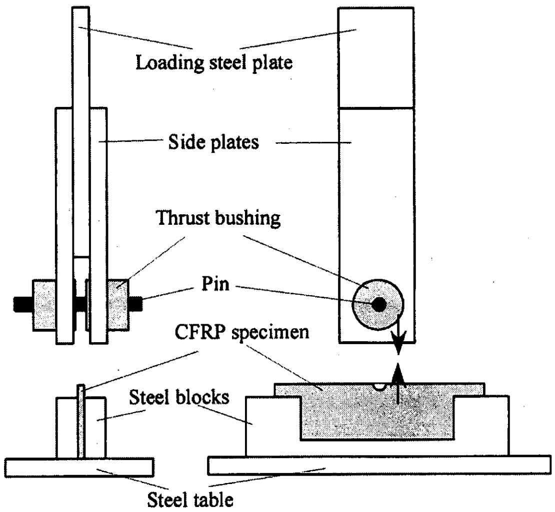


Figure 2 Schematic figure of bolt joint bearing test

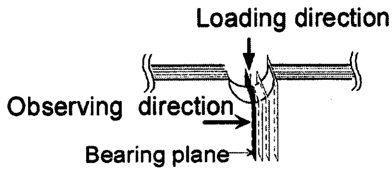


Figure 3 Observing cross-sections

An MTS 810.21 servo-hydraulic testing with a thermostatic chamber was used. An electric heater and liquid nitrogen were used to control environmental temperatures of 150 °C and –100 °C, respectively. Before loading, the specimen set to the jig was kept for one hour in the prescribed temperature condition. After that, the lateral clamping was applied. The crosshead speed was controlled to be 1.5 mm/min. The data were acquired from the load cell and displacement detector attached to the testing machine.

After being loaded to the prescribed conditions, the specimen was detached from the testing machine and sectioned along the centerline with a diamond saw to make a sample for microscopic observation. The surface of the sample placed in epoxy resin was polished and the bearing failure region was investigated with an optical microscope as shown in Figure 3.

3. Test Results

The load-displacement curves are shown in Figures 4-6. The pinned joint data is referred from [10].

For pinned joint cases, indicated in open triangle, the curves present the gradual increase at first stage, almost linear increase at the second stage and nonlinear behavior at the third stage. At the peak, a sharp drop does not appear and load-displacement curve decreases gradually. After that, the load decreases rapidly with a large sound reaches to about a half of the ultimate load and keeps constant. However, for bolted joint cases, lateral support restrains deformation along through the thickness direction and the higher load is sustained without decreasing the load-carrying capability.

At 25 °C, shown in Figure 4, the L-D response shows nonlinear behavior around 15 kN with a sound and a knee point is appeared. After that, the load increases linearly up to 18-20kN and decreases about 4-5kN from the maximum point gradually. At 150 °C L-D curve on the small load level shows the similar manner to the result of 25 °C and the knee point appears obviously around 12 kN. After that the load increases gradually and slightly decreases at 15 kN without a sound as contrasted with the 25 °C case. The load level at 150 °C is lower than 25 °C in general. Figure 6 shows the L-D response at −100 °C. The load increases linearly until knee point appears. After that the load leads to the maximum value of 25kN and decreases with a large sound. The load level at −100 °C is higher than those at 25 and 150 °C. The knee point appears at 20 kN and a second linear deformation slope is observed to the higher load level. The same is true for a pinned joint.

The strength at various environmental temperatures is shown in Figure 7 and listed in Table 1. Bearing strength was defined as the load divided by the product of pin-diameter and thickness. The data of the strength for a pinned joint were obtained by the maximum values on the L-D curve. For bolted joint, the load at the knee point was used. It indicates that the strength decreases with the temperature increasing. The difference of strength between a pinned joint and bolted joint also decreases with the temperature increasing. This result shows that the temperature influences the effect of through the thickness constraint on the strength.

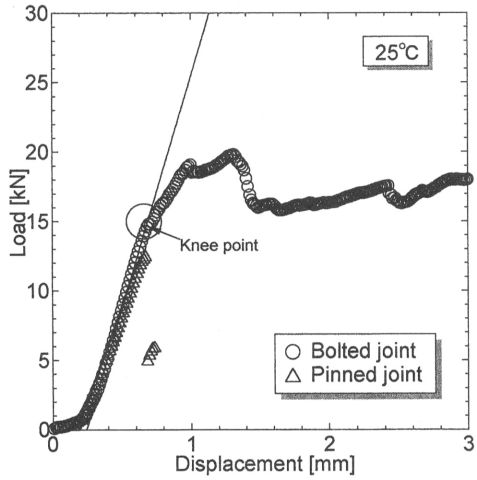


Figure 4 Load-displacement curves at 25 °C

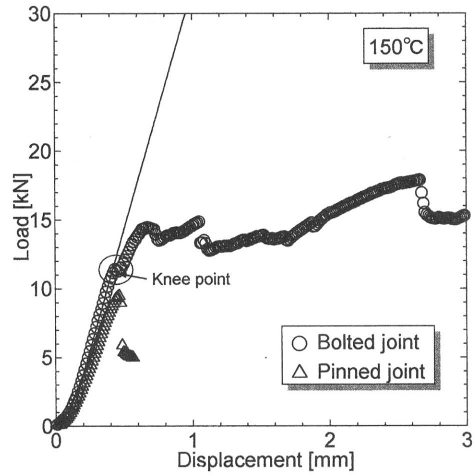


Figure 5 Load-displacement curves at 150 °C

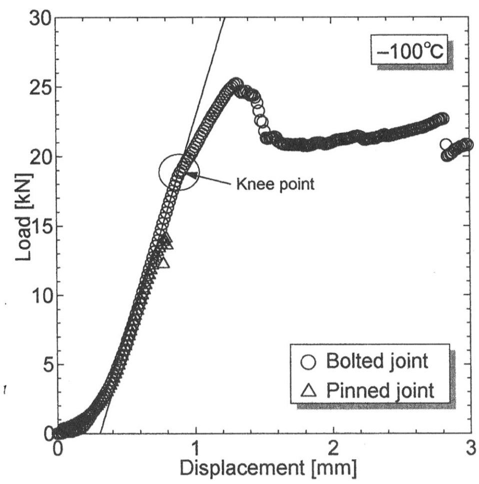


Figure 6 Load-displacement curves at −100 °C

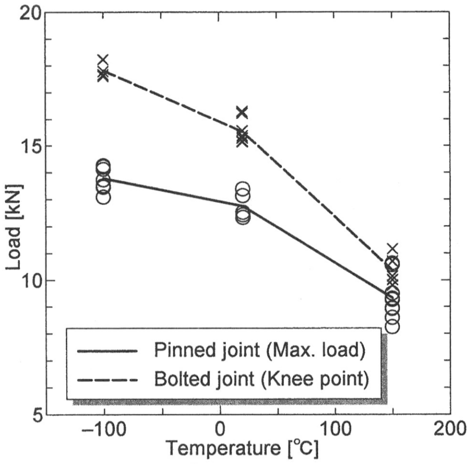
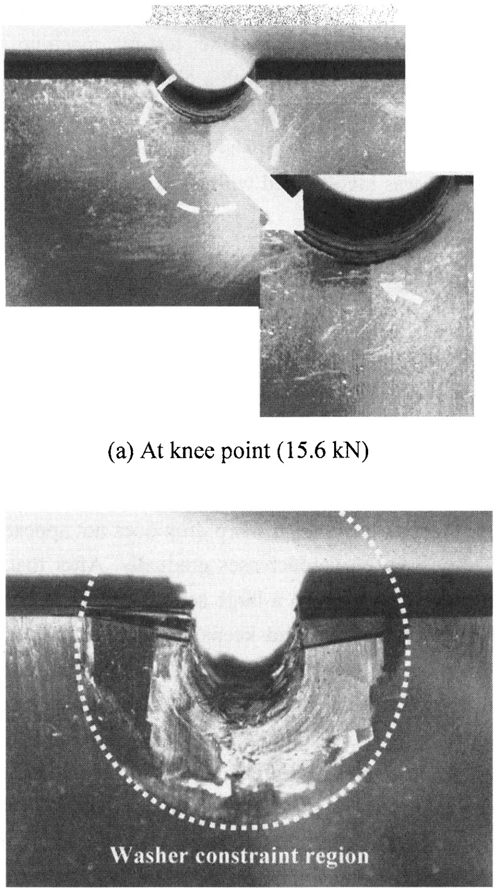


Figure 7 Strength at various temperatures

Table 1 Test results of mechanical joint bearing test

	Pinned joint (max. load)		Bolted joint (knee point)	
	[kN]	[MPa]	[kN]	[MPa]
-100 °C	13.79	684.9	17.82	989.6
25 °C	12.75	641.6	15.53	862.6
150 °C	9.33	467.8	10.36	575.8

The specimen surface after loaded at 25 °C is shown in Figure 8. Around the knee point, the 0° lamina surface presents a splitting being similar to a pinned joint case at 95% or near the maximum load [11]. As a pin moves up to 4.5 mm, damage occurs in the washer constraint region and the specimen swells to through the thickness direction within the constrained area.



(a) At knee point (15.6 kN)

(b) At stroke of 4.5 mm

Figure 8 Surface morphology of damaged specimen

4. Microscopic Observation and Discussion

The damage of bearing failure mode was investigated with an optical microscope. Sectional fractograph of the damaged specimen was examined and its result was compared with pinned joint cases. Photographs of the pinned joint were obtained by loading to the vicinity of the maximum load. This idea was accomplished with the MTS TestStar II™ application. That is, the testing machine was programmed to be unloaded after the 40N decrease from the previous load (ultimate load in this case) and this load point is called "40N-drop" point here. In this section, characteristic features at each temperature are described. The typical results are shown in Figures 9 to 11. A magnification of 50 was used in this examination.

25 °C (compared with pinned joint)

Microphotographs of the bearing failure of a bolted joint at 25 °C are shown in Figure 9 together with a pinned joint case. At the knee point, fiber-kinking failure is observed in 0° layers and delamination between 45° and –45° appears distinctly, shown in (b). This result is very similar to the fractograph of a pinned joint bearing at 40N-drop point illustrated in (a), except for a large delamination between 0° and 45° next to the surface of the specimen. It indicates that the washer restrains deformation along through the thickness direction and that the delamination by peeling or opening operation could not be expected as in a pined joint case, where without washer constraint, the specimen loses load-carrying capability and the load rapidly decreases. Beyond the knee point, delamination, matrix shear cracks and fiber kinking evolve with a pin moving to the end shortening direction. The fractgraph at the first maximum point is shown in (c). The 0° surface layer fails in the washer region and

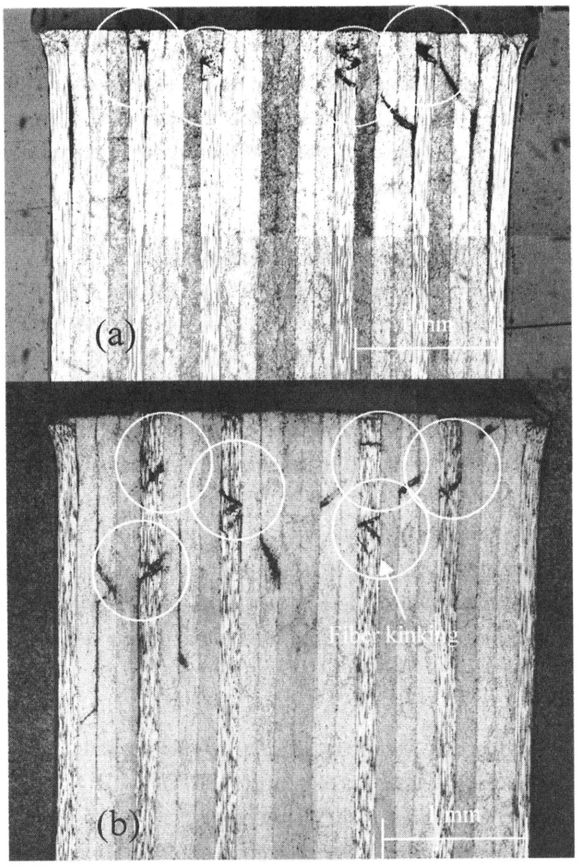
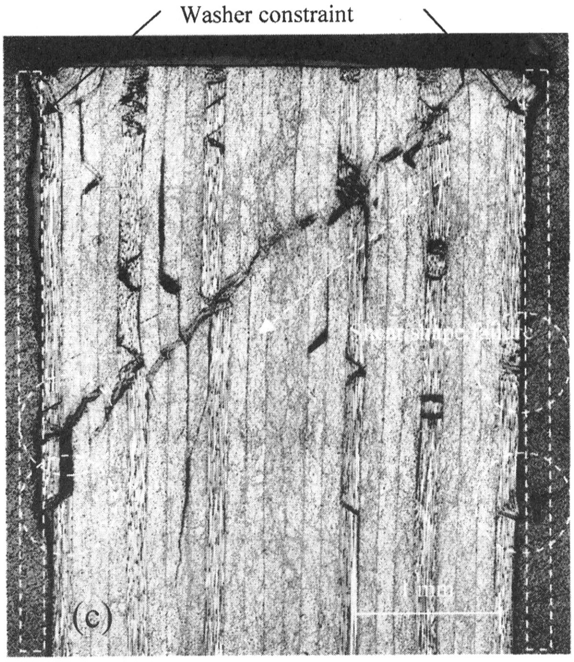


Figure 9 Microphotographs of the bearing failure of a mechanical joint at 25 °C
(a) Pinned joint, at 40N-drop point[11],
(b) Bolted joint, at the knee point (15.6 kN), (c) Bolted joint, at the first maximum point



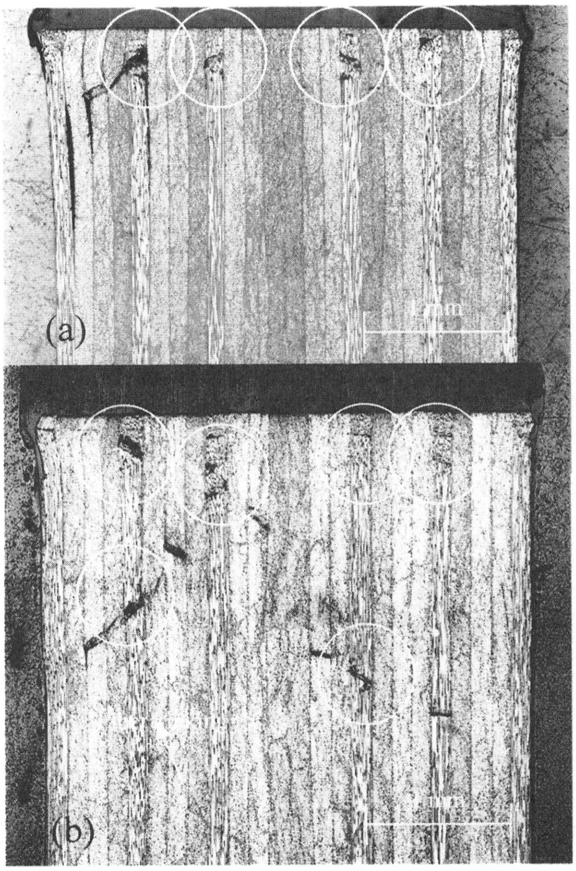
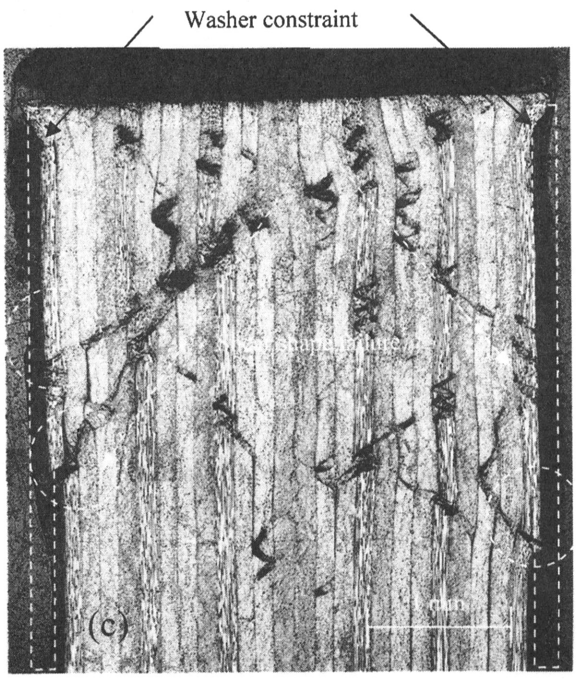


Figure 10 Microphotograph of the bearing failure of a mechanical joint at 150 °C
(a) Pinned joint, at 40N-drop point[11],
(b) Bolted joint, at the knee point (12.54 kN),
(c) Bolted joint, at the first maximum point



leads to the load decreasing. External delamination, out-of-plane shear cracks and internal delaminations are also observed on the bearing plane. The shear crack is formed as the accumulation of microscopic damages, that is, 0° fiber kinking and 45°, -45° and 90° matrix crack. It seems that the fiber kinking failure links to the matrix shear cracks of the next lamina and the damage evolves toward the 45° inclined direction and is connected to the delamination, and furthermore it reaches to surface 0° layers.

150 °C (compared with pinned joint)

Microphotographs of the bearing failure at 150 °C are shown in Figure 10. At the knee point, fiber kinking is observed as similar to the result of 25 °C. At the first maximum load point, damages evolve more as well as 25 °C case. However, at 150 °C, both large kink-band width and large fiber inclination angle appear, which is observed in a pinned joint bearing test at the final failure stage. Delamination and shear cracks are observed on the bearing plane, but shear cracks do not appear clearly compared to the
25 °C case. Large deformation due to permanent buckling or yielding is seen near the loaded upper plane. It seems that this is due to the reduction of the matrix or interface stiffness at a high temperature.

-100 °C (compared with pinned joint)

Microphotographs of the bearing failure at –100°C are shown in Figure 11. At the knee point, fiber kinking is observed being similar to the results of 25 °C and 150 °C. Contrasted with other temperatures, a narrow kink band is observed and deformation along through the thickness direction is small. At the first maximum load point, damages evolve more as well as 25 °C and 150 °C cases. However, both the damage intensity and region at –100 °C are larger than the 25 °C case. It seems that bearing failure at –100 °C is brittle and its scale is rather large. The shear shape failure inclined less than 45° from the loading direction is observed

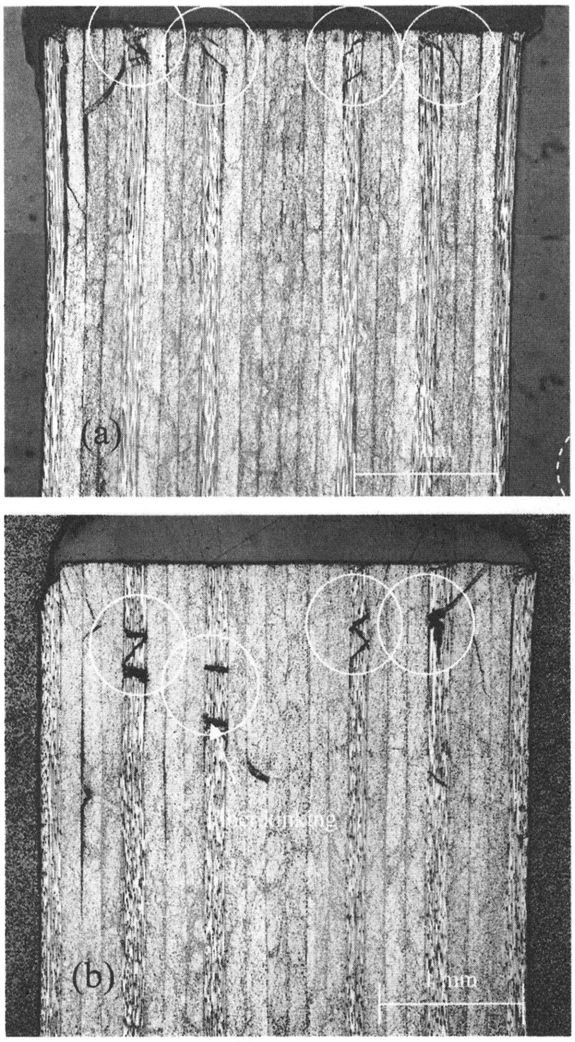
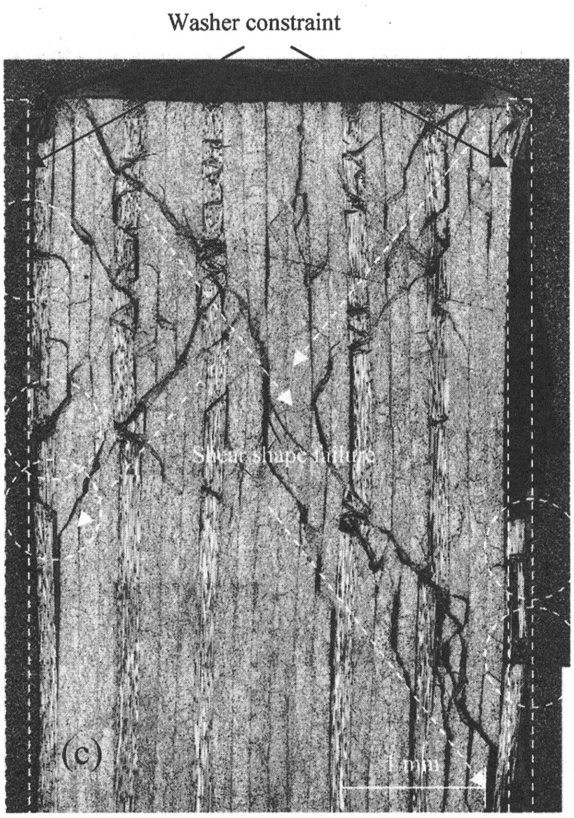


Figure 11 Microphotographs of the bearing failure of a mechanical joint at -100 °C
(a) Pinned joint, at 40N-drop point[11],
(b) Bolted joint, at the knee point (21.91 kN)
and (c) Bolted joint, at the first maximum point



and its arrival point to surface layers is far from the pin-contact upper surface.

As mentioned above, difference of the load between knee point (of a bolted joint) and the maximum load (of a pinned joint) decrease with temperature increasing. This is not revealed from this microscopic observation. However, it seems that the fiber kinking of the 0 ° lamina shows the different manners in each temperature and it might lead to prescribed results

5. Conclusions

The bearing test of a bolted joint was conducted at 25 °C, 150 °C and −100 °C. Microscopic damage of bearing mode was examined with an optical microscope and its characteristic features were studied. The information mentioned below is obtained.

1) The load level of the bolted bearing joint at 150 °C was lower than 25 °C and −100 °C cases.
2) The high bearing strength was achieved at −100 °C.
3) The difference of strength between pinned joint and bolted joint decreases with temperature increasing.
4) Delamination and shear cracks were observed at the bearing failure region and shear cracks were inclined about 45° from the loading direction at various temperatures.
5) Shear cracks was not appeared clearly at 150 °C compared to the 25 °C.
6) The feature of bearing damage at −100 °C was brittle manner and the one at 150 °C was plastic deformation.

References

1) Shimokawa, T., Y. Hamaguchi, T. Sanda, H. Mizuno and Y. Toi, "Effect of Isothermal Aging on Ultimate Strength on High-Temperature Composite Materials for SST Structures", J. of Composite Materials, 33,1999, pp1104-1117
2) Ishikawa, T., Y. Morino et al., J. of the Japan Soc. For Composite Materials, 24, 1998, pp169-175 (in Japanese)
3) Kim, H.S., Y. Takao et al., "Microscopic Damage of Quasi-Isotropic Carbon/Epoxy Laminates at Various Temperatures", J. Soc. Mat. Sci. Japan, 47, 1998, pp599-605 (in Japanese)
4) Kim, H.S., Y.Takao et al., "Effect of Temperature and Fiber Orientation on the Mode I Interlaminar Fracture Toughness of Carbon/Epoxy Composites", Proceedings of the 12-th ICCM, Paris, 154 in CD ROM, 1999
5) "Joining Fibre-Reinforced Plastics" Elsevier Applied Science Publishers LTD, editted by F.L. Matthews, 1987
6) Wang, H.S., C.L. Hung and F.K. Chang, "Bearing Failure of Bolted Composite Joints. Part I: Experimental Characterization", J. of Composite Materials, 30, 1996, pp1284-1313
7) Camanho, P.P., S. Bowron and F.L. Matthews, "Failure Mechanisms in Bolted CFRP", J. Reinforced Plastics and Composites, 17,1998, pp205-233
8) Kim, R.Y., and J.M. Whitney, "Effect of Temperature and Moisture on Pin Bearing Strength of Composite Laminates", J. of Composite Materials, 10 April 1976, pp149-155
9) "Composite Materials in Aircraft Structures", Longman Scientific & Technical, editted by D.H. Middleton, 1990
10) Hirano, N., S. Matsunaga et al., "Three-Dimensional Investigation of the Bearing Failure Mode of Quasi-Isotropic CF/Epoxy Laminates under Various Environmental Temperatures", Proceedings of the 13-th ICCM, Beijing, 1451 in CD-ROM (2001)
11) Hirano, N., W.X.Wang and Y. Takao, "Three-dimensional Damage Analysis of a Pin-Loaded CFRP Quasi-Isotropic Laminate under Various Temperatures", Proc. of the 3rd Japan-Korea Joint Symposium on Composite Materials, 2002, pp43-44