FEATURES OF NEAR-INFRARED RING HEATER AND SERVO-PRESS IN CF/PEEK RIVET FASTENING

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ABSTRACT

This study aims to develop a high-reliable and efficient fastening process using carbon fibre reinforced thermoplastic rivets. The material is a round rod manufactured from unidirectional carbon fibre reinforced poly-ether-ether-ketone (CF/PEEK) prepreg sheet using a laboratory-developed thermoplastic pultrusion machine. The feature of the proposed process is to thermoform the head and fasten the rivets using a compact servo-press unit and a near-infrared (NIR) ring heater. The heating behavior of round rod tip heated by NIR ring heater, and deformation states of the round rod tip at various displacements were investigated, thus the thermoforming condition of servo-press unit was optimized, and CF/PEEK laminates were fastened by CF/PEEK rivet and aluminium alloy (A5056-H32) rivet. The difference of rivet material in the fastening strengths were investigated by tensile shear strength test and pull through strength test and the head tensile test was also carried out for both rivets. In addition, the effects of the head height of CF/PEEK rivet on the single-lap tensile and the head tensile strengths were investigated. It was found that by changing the rivet head height, the orientation of the carbon fibers in the thermoforming of the rivet head is significantly different, which greatly affects their strengths. It was shown that from the surface observation and the distribution measurement of strains generated around the hole in the single-lap tensile specimen of CF/PEEK laminates that the tensile shear strength of the CF/PEEK rivet showed sufficient high compared to aluminium alloy rivet. This is because the structure where the rivet head and body are united with continuous fibers and also CF/PEEK pin with shank deformation caused less damage to CF/PEEK laminates than the aluminium alloy pin. These experimental results prove that the rivet fastening process using CF/PEEK rod developed was a highly available for multimaterials joining.

1 INTRODUCTION

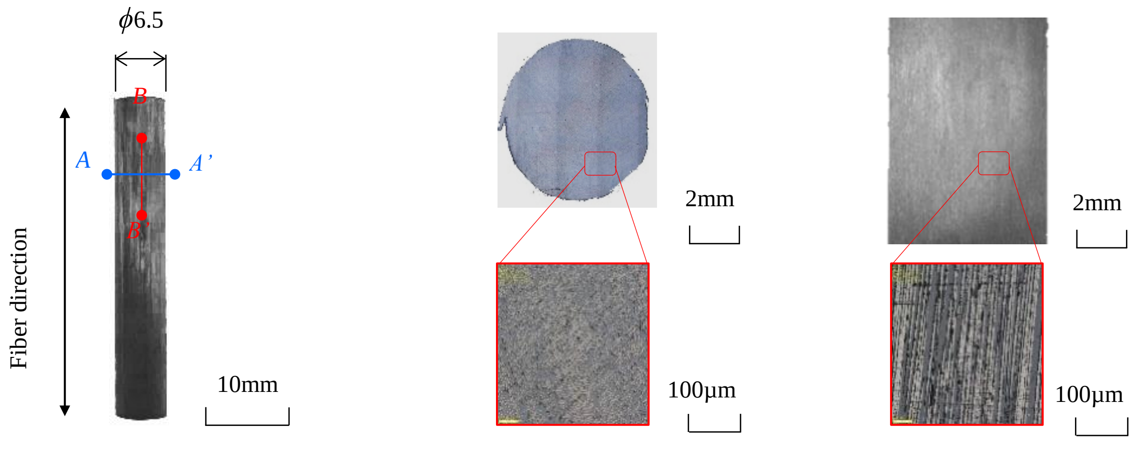
Multimaterials are composed of metals and polymer composites and recently has been attracting attention as one of the candidates for weight reduction methods with high cost-performance. In order to manufacture large structures with complex shape, these materials must be assembled by some joining method, but the joining strength of such dissimilar materials is much lower than the polymer composites themselves. Therefore, they are often joined by some mechanical fastening in addition to adhesive bonding by thermosetting resin. While mechanical fastening such as bolts and rivets is a traditional joining method, it is superior in that it is easy to disassemble when replacing parts and has high reliability and durability [1]. However, there are problems such as increased weight, galvanic corrosion, and reduced strength in addition to the increased in fastening work costs [2]. On the other hand, advanced thermoplastic composites focus on some properties that are superior to thermosetting composites. In particular, it has the advantage that secondary processing by reheating is possible in the same way as metal plastic processing. However, thermoplastics are not suitable for adhesive bonding, because they do not involve chemical reactions. Therefore, several fusion joining methods such as electric resistance welding, induction welding and ultrasonic welding have been proposed recently for advanced thermoplastic composites. However, none of the composites have sufficient joining strength, and delamination occurs when cyclic loads or impact loads are applied, the reliability and durability are reduced. Therefore, it is desirable to use mechanical joints such as thermoformable CFRTP rivets for joining multi-materials including CFRP and CFRTP. Unidirectional carbon fibre reinforced thermoplastic rivets have excellent galvanic corrosion resistance and high mechanical strength [3]. However, if bolts or rivets are used, the continuous fibers of the laminates must be cut and pierced. Mechanical joints also have a significant drawback of damage due to stress concentration around the hole. This study aims to develop a fastening process for CF/PEEK rivets using a newly developed ultra-compact servo-press, evaluate the fastening ability of CF/PEEK rivets, and damage behavior around the hole due to mechanical fastening was investigated through a single-lap tensile test.

2 EXPERIMENTAL MATERIALS AND METHODS

2.1 CF/PEEK round rod

CF/PEEK rivet was thermoformed using CF/PEEK round rod. The rod (ϕ6.5mm) was produced from a CF/PEEK prepreg sheet (Cetex® TC1200, fibre volume content: V_f =59%, Toray Advanced Composites) using the laboratory-scale heat pultrusion machine developed originally. A pultruded round rod (ϕ6.5mm) was machined to a uniform size by cylindrical grinding to an outer diameter of ϕ6mm and used in the experiment.

Figure 1 shows the appearance and cross and axial-sectional images of CF/PEEK round rod manufactured by thermal pultrusion process. In the appearance image, it is shown that the longitudinal streak-like grooves of the carbon fibre on the rod surface. From the cross-sectional and axial-sectional images, it can be seen that the carbon fibers and PEEK polymer are evenly distributed within the rod, there are almost no voids or fiber bundles in the cross-section, and the thermal pultrusion moulding is possible under extremely high-density pressure.



(a) Appearance (b) Cross-section *A-A'* (c) Axial-section *B-B'*

Figure 1: Cross and axial-sectional images of CF/PEEK round rod.

2.2 Thermoforming and fastening process

The thermoforming process of CF/PEEK rivets is shown in Figure 2(a). (i) Insert the CF/PEEK round rod into the hole of the lower die and rapidly heat the upper end-part of the rod with a near-infrared ring heater (Heraeus, Omega heater, OMG250/23-G1) above the melting temperature of polymer. (ii) The outer punch of the upper die attached to the servo-press unit is brought into contact with the top of the lower die while appropriately controlling the pressing load and moving distance of the upper die. Then, the air space for the head part is generated in the outer punch. (iii) CF/PEEK rivet heads are thermoformed by moving the inner punch downwards and cooled while maintaining the specified load. After the upper die moves upward, the rivet is de-molded from the lower die.

The fastening process of CF/PEEK rivet is shown in Figure 2(b). A CF/PEEK rivet is inserted into the hole drilled in the plate to be joined, and the upper end-part of the rod is rapidly heated above the melting temperature of polymer with near infrared ring heater. The following processes are similar to the thermoforming of rivet heads.

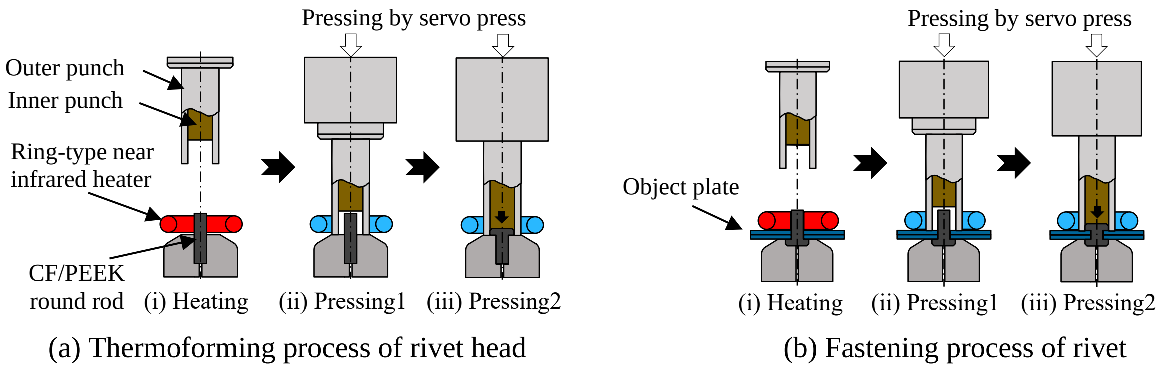


Figure 2: Thermoforming and fastening process of CF/PEEK rivet.

2.3 Evaluation of CFRTP rivets by mechanical test

The mechanical properties of CF/PEEK rivets were evaluated by several strength tests as shown in Figure 3. In the single lap tensile test shown in Figure 3(a), the stainless-steel plate was fastened by CFRTP and aluminium alloy rivets. Also, in the pull-through strength test (NASM 1312-8) shown in Figure 3(b), a 38mm square stainless-steel plate fastened with CFRTP and Aluminium alloy rivets was used. Head tensile test of CFRTP and aluminium alloy rivets were also performed using a special device as shown in Figure 3(c). The crosshead speed for the tests was 1mm/min for (a), 0.5mm/min for (b) and 1mm/min for (c).

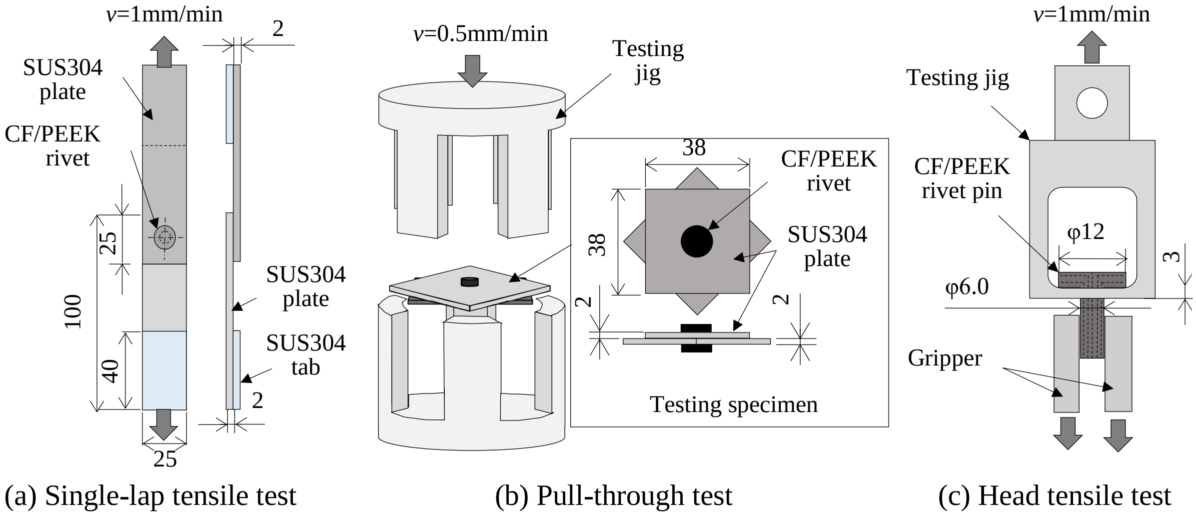


Figure 3: Testing methods for evaluation of rivet head.

2.4 Damage assessment around holes of specimen by pin

In this study, the damage around the hole of CF/PEEK laminate joints using aluminium alloy and CF/PEEK pins was observed. Damage to the hole by the pin was confirmed by a single-lap shear test. A schematic of a single lap joint of CF/PEEK laminate with a pin penetrating through the hole is shown in Figure 4. The laminate was manufactured from CF/PEEK prepreg sheet (Cetex® TC1200, Fiber volume content : V_f=59%, Toray Advanced Composites) using a hot-press forming process. The laminate stacking sequence for the single lap joining configuration was [0/90/0/90/0/90/0]s. The thickness of laminate is 1.90mm. Specimens are made with reference to the KS B ISO 14273 standard. The tab was of the same material and thickness as the specimen. All specimens and pin holes were cut using high pressure water jet cutting. Aluminum alloy A5056-H32 (MS20470B, Hanson rivet) and CF/PEEK were used for joint pin. The crosshead speed of the test was 1mm/min.

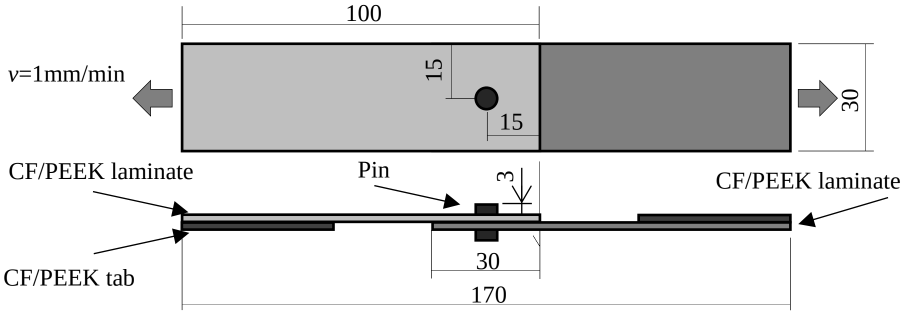
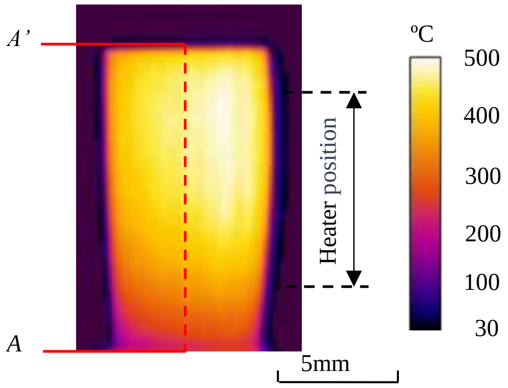


Figure 4: Schematic diagram of the test method.

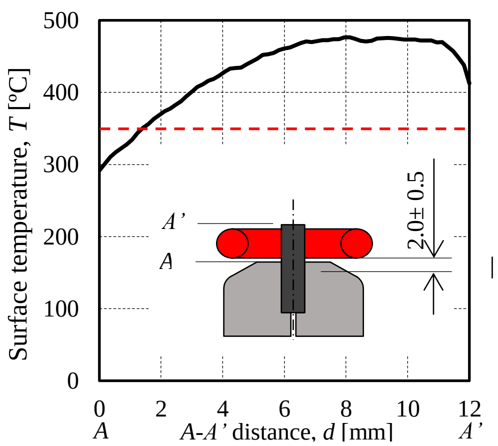
3 RESULTS AND DISCUSSIONS

3.1 Heating behavior on near-infrared ring heater

The thermal image and the longitudinal temperature distribution of CF/PEEK round rod heated with a near-infrared ring heating are shown in Figure 5(a) and 5(b). The heating time was set to 30 seconds. From the thermal image shown in Figure 5(a), it was found that the temperature in heater position of the round rod reached sufficiently above the melting temperature of PEEK polymer at the heating time of 30 seconds. From A-A' longitudinal temperature distribution plot shown in Figure 5(b), it was found that the 92% of rivet surface was heated above the melting temperature of PEEK polymer (343°C) in at the heating time of 30 seconds. The temperature was low at top edge of round rod. This is probably due to cool by room air. And, the temperature near the bottom of the round rod was lower than that at the heater position This is probably due to absorb the heat to the lower die.



(a) Thermal image



(b) Surface temperature distribution of rod

Figure 5: Temperature profiles of CF/PEEK round rod heated by near-infrared ring heater.

3.2 Deformation behavior and control methods of head thermoforming

A compact and high-precise servo-press unit was used for the thermoforming process of rivet head. As shown in Figure 6, the displacement (z) of the upper mold descends from z=0mm to z=-22.45mm under constant speed control, and then changes to constant load control to hold maximum press load. Figure 6 also shows the change of the detected load (P) and displacement (z) of the upper mold with respect to the processing time.

In this graph of Figure 6, at position (i), the folder and punch are located at the upper portion away from the round rod when it is heated. At position (ii), the inner punch and rod tip have descended to 2.67 mm from the contact position, and buckling has progressed with the forming. At position (iii) Interlayers start to form inside the head. Then, at position (iv) carbon fibers spread outwards in the radial direction near the lower part of the opposite side to the buckling side, and the head is formed with interlayers inside. When it is pressurized to the set load, at position (v), the height of the head decreases and is held under pressure until below the glass transition temperature of the resin, resulting in an extremely high-density rivet head being formed. The head forming process was interrupted in the middle, and the rivet in the process of forming was taken out at each displacement to observe the deformation states from the appearance. The fastening condition of CF/PEEK rivets were a heating time of 30 seconds, a surface heating temperature of 400-420°C, a maximum press load of 4.9kN, and a press speed of 50mm/s. Figure 7 shows the appearance images of the CF/PEEK rivet head at each position marked in Figure 6.

Head forming of CF/PEEK rivets is thus very complex, and fibers deformation during head forming is not always constant because the fibers orientation of the rod is not constant and the temperature distribution during heating is not uniform. Therefore, it is likely that stable, high-quality head forming can be achieved by monitoring the load and displacement during head forming using a servo-press unit and precisely controlling the displacement and load.

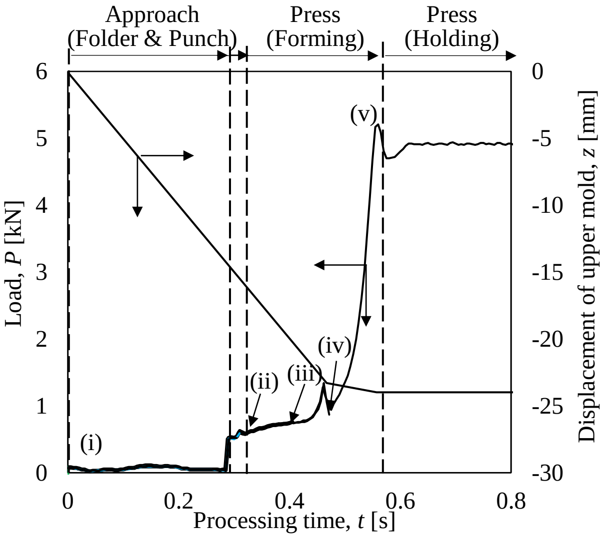
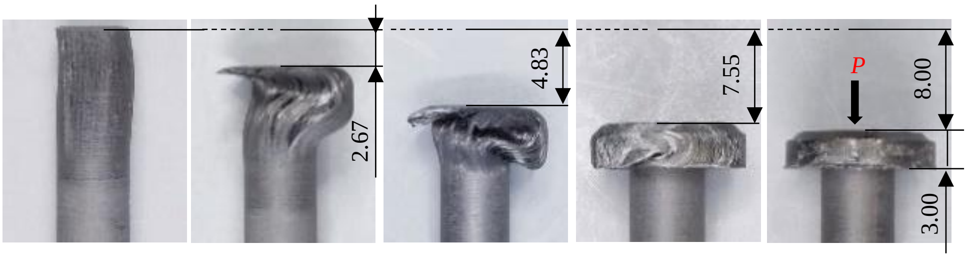


Figure 6: Servo-press control and change of load detected in rivet head thermoforming.



(i) After heating (ii) +2.67mm (iii) +4.83mm (iv) +7.55mm (v) +8.00mm

Figure 7: Deformation states of the round rod tip interrupted at various displacements.

3.3 Appearance of CF/PEEK rivet and fasten specimen

Figure 8 shows the appearance images of CF/PEEK round rod, rivet and stainless-steel plate fastening test specimen using CF/PEEK rivet. These appearance images confirm that the rivet head during the forming and fastening process is free of forming defects, obvious defects, and burrs. An axial cross-sectional image of the CF/PEEK rivet is shown in Figure 8(d). At the bottom of the head, it can be seen that carbon fibers are oriented so that they spread radially outwards. At the boundary between the head and the shank, the shank remains unformed in the head portion. This is thought to be due to insufficient heating near the lower mold head of the CF/PEEK round rod. In the area indicated by the solid line in the axial cross-sectional image, the carbon fibers are bend and oriented from the shank to the bottom of the head.

(a) Round rod (b) Rivet (c) Fastened specimen

(d) Axial cross-section of rivet

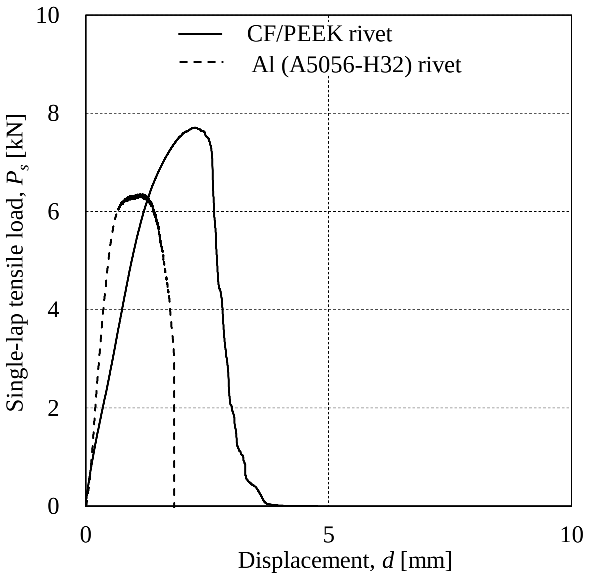
Figure 8: Appearance of CF/PEEK rod, rivet pin, fastened specimen and axial cross-section of rivet.

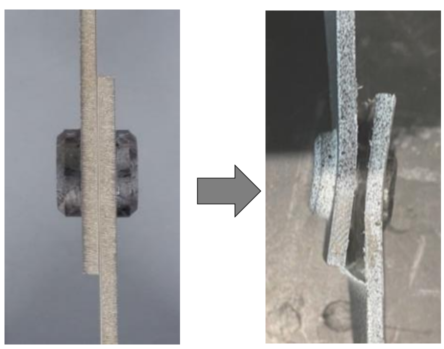
3.4 Mechanical properties of CF/PEEK rivet

3.4.1 Single-lap tensile test

Figure 9(a) and 9(b) show the load-displacement curves of the single-lap shear strength test of stainless-steel plates fastened with CF/PEEK and aluminium alloy rivets, and the appearances before and after the test. CF/PEEK rivet has a lower elastic modulus in the lateral direction than aluminium alloy rivets, the amount of displacement is approximately double and the amount of deformation is large, but the maximum load is approximately 23% larger, and the joining strength is high.

As shown in the appearance image in Figure 9(b), a large out-of-plane bending deformation occurred in the stainless-steel plate after the test. Some of the fibres in the shank of CF/PEEK rivet were broken, but the CF/PEEK rivet has high deformation resistance and can be expected to joint with excellent impact resistance. This was because the unidirectional carbon fibres were vertically arranged between the two plates, and the rigid carbon fibres greatly resisted the shear deformation of the two plates.



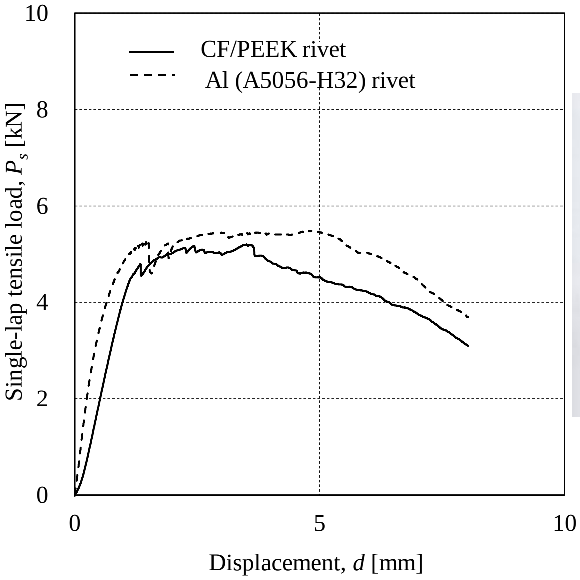


(a) Load-displacement curves (b) Specimen appearance before and after test

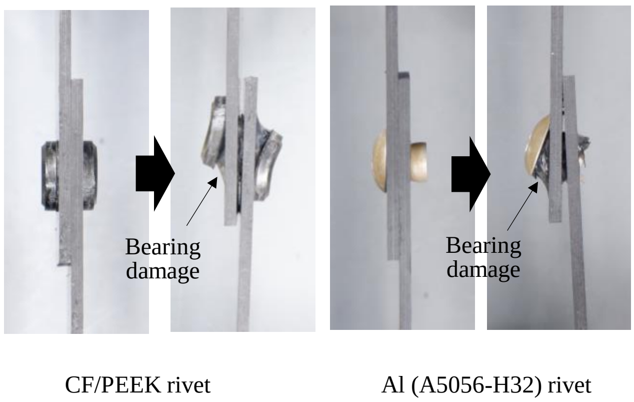
Figure 9: Single-lap tensile test of stainless-steel plates specimen.

Figure 10(a) and 10(b) show the load-displacement curves of the single-lap shear strength test of CF/PEEK laminate fastened with CF/PEEK and aluminium alloy rivets, and the appearances before and after the test. Similar to the single-lap tensile test results of the stainless-steel specimen in Figure 9, CF/PEEK rivets have a lower lateral elastic modulus, resulting in approximately 1.5 times larger displacement within elastic deformation. However, once the yield point is exceeded, damage to the CF/PEEK laminate progress on both rivets, the effects of which is reflected in the load changes.

As shown in Figure 10(b), both test specimens showed significant damage due to out-of-plane bending deformation and in-plane pressure in the laminates after the test. CF/PEEK rivets reduce damage to laminate due to shank deformation compared to aluminium alloy rivets. In the load-displacement curve of CF/PEEK rivets, the decrease in load from d=3.6mm is larger than that of aluminium alloy rivets, and this is due to the deformation of the rivet shank. After the test, the aluminium alloy rivet specimen showed severe damage due to pressure bearing.



(a) Load-displacement curves

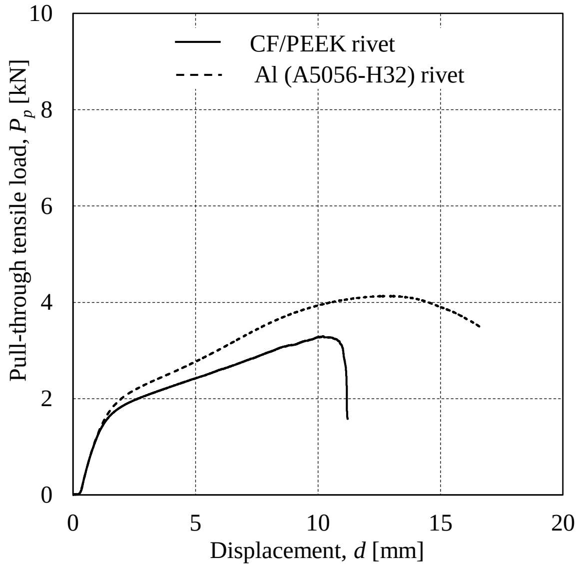


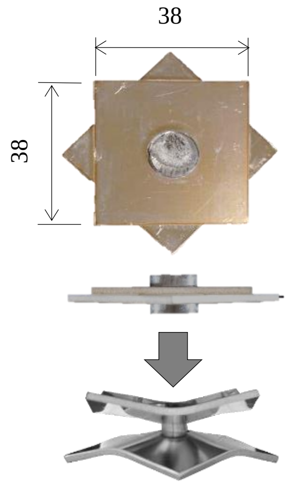
(b) Specimen appearance before and after test

Figure 10: Single-lap tensile test of CF/PEEK laminates.

3.4.2 Pull-through strength test

Figure 11(a) and 11(b) show the load-displacement curves of the pull-through strength test of a 38mm square stainless-steel specimen using CF/PEEK and aluminium alloy rivets, and the appearances before and after the test. As shown in Figure 11(b), the stainless-steel plate of the pull-through strength test specimen bent greatly after the test, and the centre of the upper edge of CF/PEEK rivet head became dented in the mortar bowl shape. This is probably because the carbon fibres near the centre of the rivet shank were pulled in by the tensile load and exhibited high resistance. Similarly, a stainless-steel plate with aluminium rivet also suffered a large amount of bending. The aluminium rivet showed plastic deformation such that the shank elongated in the axial direction. The large bending of the stainless-steel plate makes it difficult to accurately assess rivet head distortion and damage. Therefore, it is necessary to evaluate the performance of the rivet heads on one side only.





(a) Load-displacement curves (b) Specimen appearance before and after the test

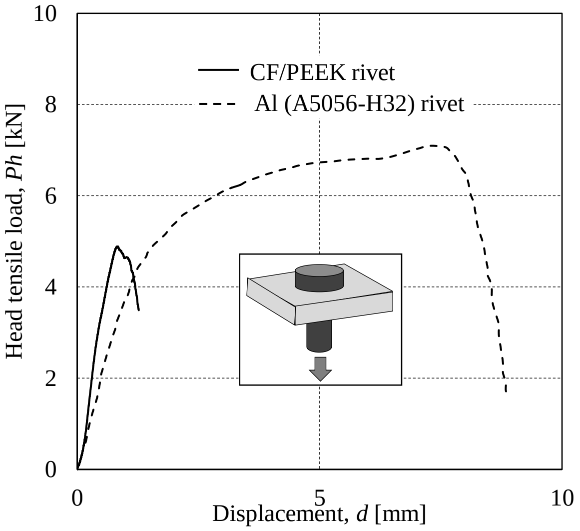
Figure 11: Load-displacement curves in Pull-through test.

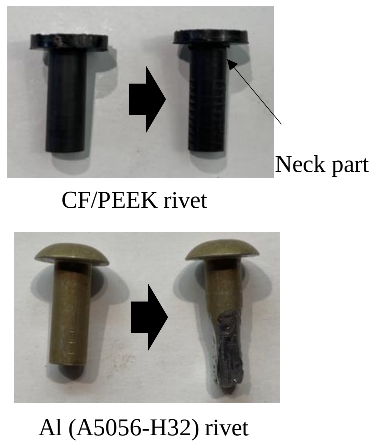
3.4.3 Head tensile test

Figure 12(a) and 12(b) show the load-displacement curves of the head tensile test of CF/PEEK and aluminium alloy rivet, and the appearances before and after the test. The head tensile test is performed by gripping the shank of the rivet inserted into the circular hole of the jig with a chuck. Unlike the pull-through strength test specimen shown in Figure 11, the head tensile test fixture did not deform after testing. The tensile load-displacement curve, excluding the effects of the test fixture shows the tensile strength and displacement due to the deformation and damage of the rivet head.

As shown in Figure 12(b), the aluminium rivets exhibited high tensile loads and displacements due to large localized deformations in the gripping area, whereas the CF/PEEK rivets showed no deformation in the shank, the damage occurred as the shank is pulled out from inside the head.

Figure 13 shows a cross-sectional image of a CF/PEEK rivet after a head tensile test. In this head tensile test, the load appears to be transverse to the fibers inside the rivet head, resulting in significant delamination at low tensile loads at the interface.





(a) Load-displacement curves (b) Specimen appearance before and after the test

Figure 12: Load-displacement curves in head tensile test of CF/PEEK and aluminium alloy rivets.

Figure 13: Cross-sectional image of CF/PEEK rivet after head tensile test.

3.5 Effects of head height of CF/PEEK rivet

In order to investigate the effect of head height on mechanical properties, CF/PEEK rivets with head heights varying from H_h=1mm to H_h=5mm were prepared, and a single-lap tensile test and a head tensile test were performed by the same method. Cross-sectional images of CF/PEEK rivet heads at various heights are shown in Figure14. When the head height of H_h=2mm, the carbon fibres are oriented horizontally around the head. On the other hand, if the head height is H_h=3mm, H_h=4mm and H_h=5mm, there will be an un-melted portion inside the head. This is probably because the insufficient heating at the bottom of the round rod disappeared when the steel mold was fixed, and the carbon fibres were buckled and oriented from the shank to the bottom of the head.

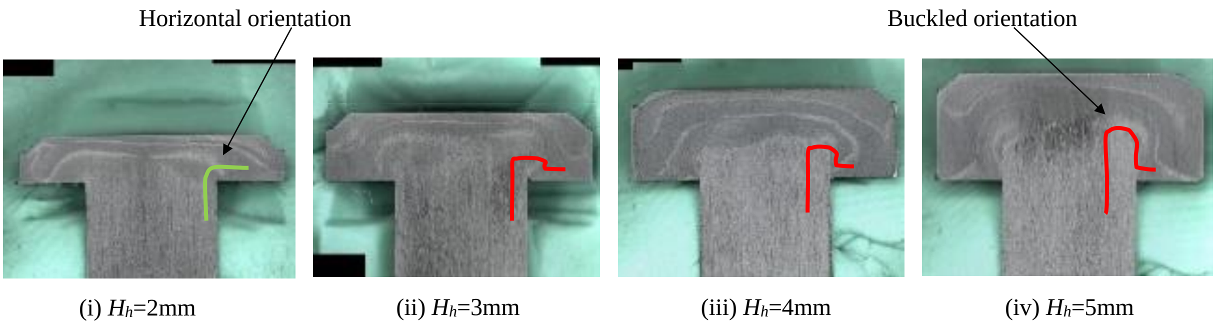
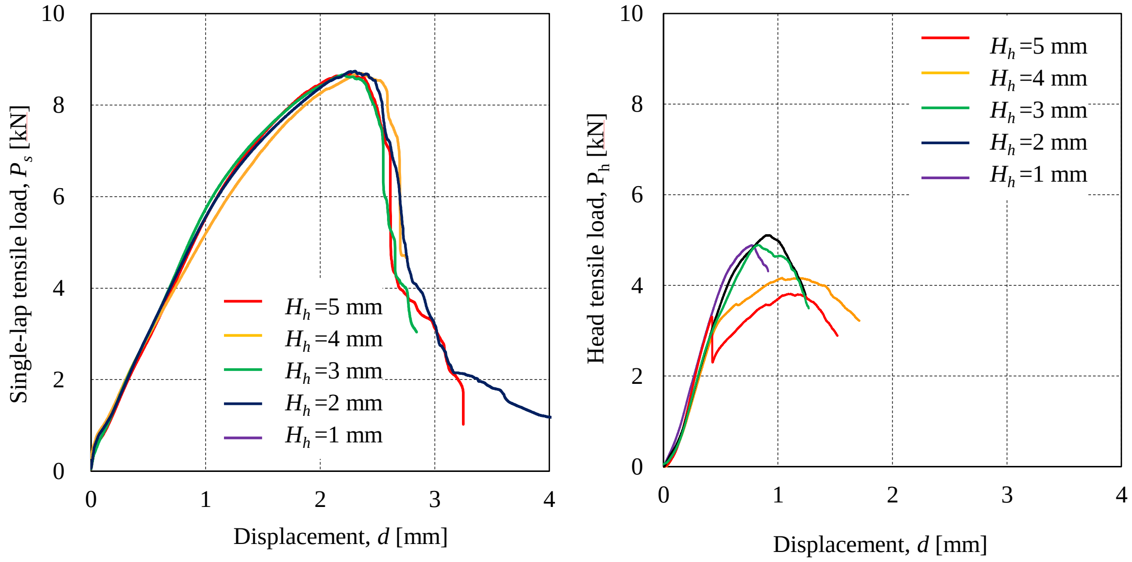


Figure 14: Cross-sectional images of CF/PEEK rivet head with various heights.

Figure 15(a) and (b) show the tensile load-displacement curves of single-lap tensile test and head tensile test of UD-CF/PPEK rivet with head heights varied from H_h=1mm to H_h=5mm. Figure 16 shows the maximum single-lap tensile load and the maximum head tensile load obtained from the test. As shown in Figure 15(a) and Figure 16, no significant difference was observed in single-lap tensile behavior and the maximum single lap tensile load were observed by changing of head height. This is because the single lap joining is dominated by the lateral shear strength in the shank of CF/PEEK rivet and is not significant by the rivet head part.

As shown in Figure 15(b), the head tensile behavior changed when the rivet head height was H_h=4mm or more. Rivets with a head height of H_h=3mm or less became nonlinear with displacement near d=0.4mm, but there was no significant change and the maximum head tensile load was rapidly reached. A rivet with a head height of H_h=4mm also displaced around d=0.4mm and became nonlinear, but then reached the maximum head tensile load. A rivet with a head height of H_h=5mm showed a sudden drop in load at a displacement near d=0.4mm, and then slowly reached the maximum head tensile load. This is likely due to the insufficient heating in higher rivet head height of H_h=5mm. The effect of buckling orientation is confirmed in the cross-sectional image of the higher height specimens shown in Figure 14. It should also be noted that the arrangement of fibers in the head differs depending on the head height. As shown in Figure 16, at the maximum head tensile load, there is a significant linear decreasing trend from head height of H_h=2mm to H_h=5mm.



(a) Single-lap tensile test (b) head tensile test

Figure 15: Load-displacement curves in the tests of various CF/PEEK rivet head height.

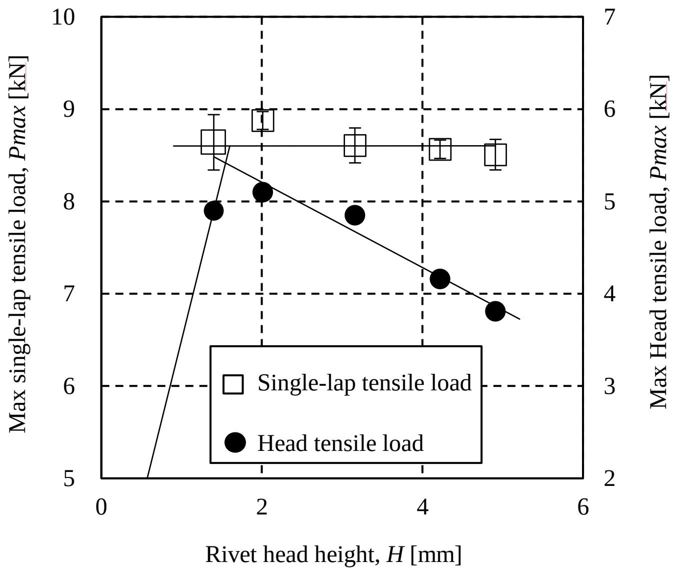
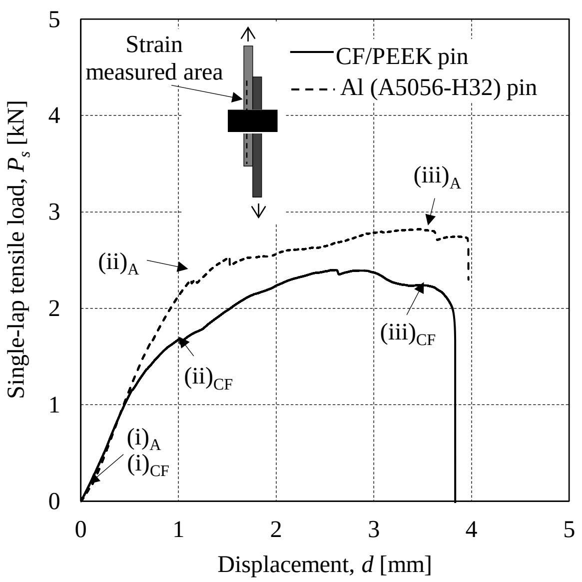


Figure 16: Max tensile load in single lap tensile and head tensile tests of various rivet head height.

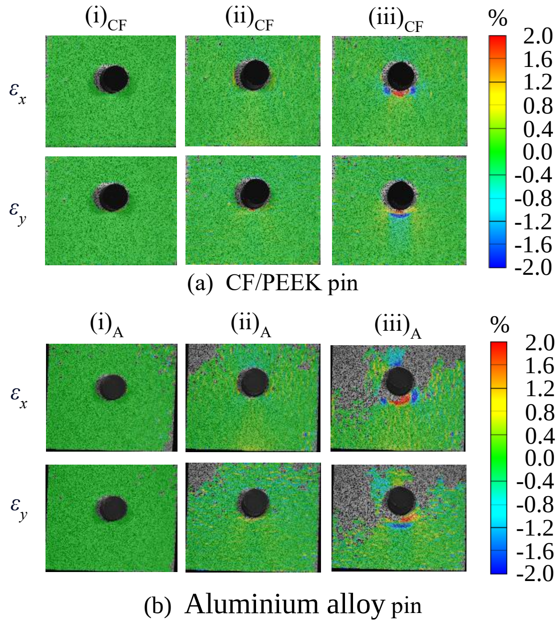
3.6 Damages around the hole of CF/PEEK laminates

In order to investigate the damage of CF/PEEK laminate joints caused by CF/PEEK and aluminium alloy fasteners in detail, strain distribution measurements were performed by digital image correlation (DIC) method and appearance observation was carried out mainly around the joint hole of the laminates in the single-lap tensile test of CF/PEEK laminate specimen joined by inserting the CF/PEEK or aluminium alloy pin. The strain generated on the surface of CF/PEEK laminate specimen was measured by a three-dimensional strain distribution measurement device (Aramis^{TM}, GOM) using a DIC method.

The load-displacement curve obtained from the tensile test using the specimen configuration shown in Figure 4 is presented in Figure 17(a). As shown in Figure 17(a), there is a difference between in load increase after the yield point between CF/PEEK pins and aluminium alloy pins. The transverse (ε_x) and longitudinal (ε_y) strain distributions around the hole of a single-lap joint using CF/PEEK and Al pins during tensile tests are shown in Figure 17(b). Data cannot be acquired near the left and right poles of the pin due to the blind spots of the camera. The surface strain distribution shows two strain fields ε_x in the transverse direction and ε_y in the longitudinal direction. The strain distribution shows the distribution of (i) pre-test, (ii) yield point, and (iii) ultimate failure within the load-displacement curve, respectively. Comparing the distributions, it can be seen that the laminates using the aluminium alloy pin at the yield point (ii), tensile strain starts to appear on the upper side of the pin and a compressive strain of approximately 1% begins to appear on the upper side of the pin around the hole, respectively. Finally, in (iii) the strain distribution at final failure, the CF/PEEK pins also exhibit tensile and compressive strains similar to the aluminium alloy pins, but the aluminium alloy pins have a wider range and are more pronounced. With aluminium alloy pin, the strain distribution measurement range narrows as the displacement increases. This is because the tilt of the pin causes more out-of-plane bending, which defocuses the camera. On the other hand, in CF/PEEK pins, shaft deformation progresses and out-of-plane bending is suppressed. Pin tilt indicates that the load-bearing surface has changed from the primary bearing surface to the secondary bearing surface. The inclination of the aluminium alloy pin, which is larger than that of the CF/PEEK pin, can be confirmed at (iii) the final failure.



(a) Load-displacement curves



(b) Strain distribution around the hole

Figure 17: Relationship between single-lap tensile load using pin and strain distribution around the hole.

Figure 18 shows the appearance images of the CF/PEEK laminate after testing, which was observed to assess the degree of damage. On the S1 side of laminate 1, both the CF/PEEK pin and the aluminium alloy pin show compression due to bearing damage on the underside of the pin during the early stages of testing. The lower side of the hole on the S2 side of Laminate 1 and the upper side of hole on the S3 side of Laminate 2 were damaged due to the change in bearing surface from the primary bearing surface to the secondary bearing surface, which was occurred by the inclination of the pin. From the images of S2 and S3 surfaces, it was found that the lamination using aluminium alloy pins caused more damage. Moreover, in S4 of laminate 2, the tilt change without deformation of the aluminium alloy pin caused significant damage to the laminate.

From the above experimental results, it was found that CF/PEEK, which deforms the shank in the shear test, causes less damage around the fastening hole than aluminium alloy pins.

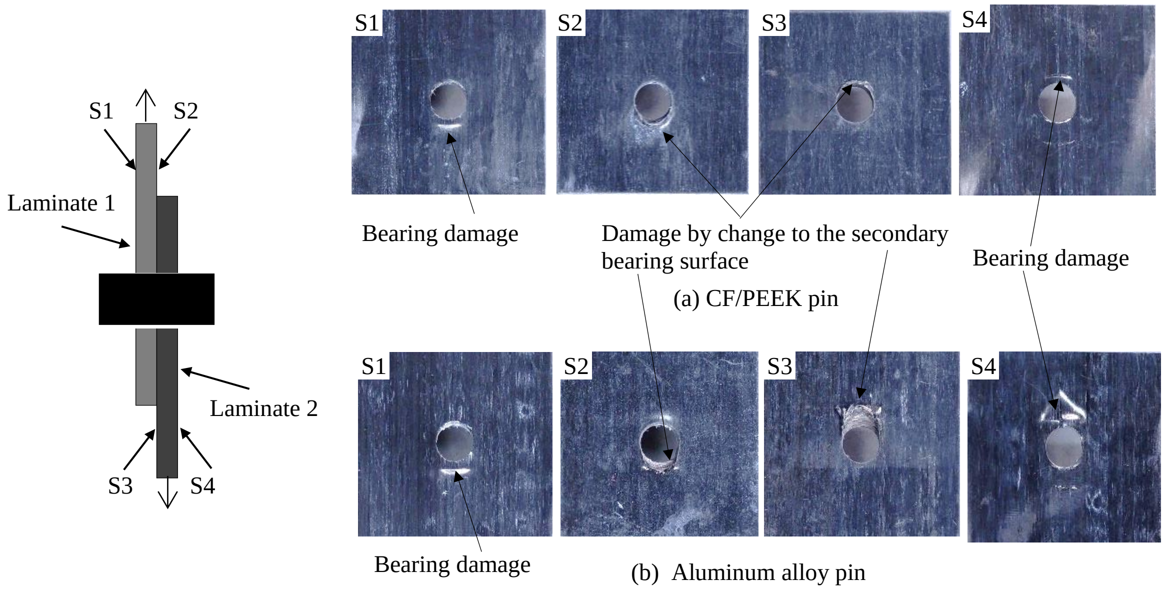


Figure 18: Failure states of single-lap joints during loading.

4 CONCLUSIONS

The aim of this study is to investigate the joint strength of CF/PEEK rivets through tensile shear strength test, pull-through strength test and cross-sectional observation. Furthermore, the fracture caused by CF/PEEK rivets and aluminium alloy rivets, and the strain around the holes in CF/PEEK laminates were experimentally evaluated and compared. The strain distribution was measured by a three-dimensional strain distribution measuring device based on digital image correlation method. The conclusion is as follows.

(1) In the single-lap tensile test, CF/PEEK rivet have a lower elastic modulus in the lateral direction than aluminium alloy rivet, so the amount of displacement is about twice as large, and the maximum load is about 23% higher, the high joint strength was achieved. This is because the unidirectional carbon fibres are vertically arranged between the two plates, and the rigid carbon fibres greatly resisted the shear deformation of the two plates. Furthermore, in the pull-through test, the head and shank of the CF/PEEK rivet are integrated with continuous carbon fibre showing high strength. In addition, the shank has no deformation in the vertical direction due to the unidirectionally oriented carbon fibres.

(2) CF/PEEK rivets reduce damage to laminates due to the shank deformation compared to aluminium alloy rivet. It can be observed that the damage due to bearing pressure is significant in the laminates tested with aluminium alloy rivets after testing. On the other hand, in CF/PEEK pins, shaft deformation progresses and out-of-plane bending is suppressed.

(3) The tilt of the pin in the shear test indicates that the bearing surface has changed from the primary bearing surface to the secondary bearing surface. At this time, CF/PEEK pin with shank deformation caused less damage to CF/PEEK laminate than the aluminium alloy pin. Furthermore, it was found that the deformation of the shank reduces the out-of-plane deflection of the specimen.

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