DEVELOPMENT AND MECHANICAL PROPERTIES OF OPEN-HOLED CFRP WITH NON-CUT FIBERS

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Abstract
In this paper, the open-holed CFRP structure with non-cut fibers was proposed in order to reduce the stress concentration of fibers around open-hole. The mechanical properties of the unidirectional (UD) and plain-woven (PW) CFRP laminates under tensile loading were first investigated. Then, the effect of the open-hole CFRP structure with non-cut fibers on the increase of OHT strength was cleared. Furthermore, the stress concentration around open-hole was evaluated by the FE analyses in the case of basic UD CFRP with open-holes. It was clarified that the stress concentration in the case of UD CFRP with non-cut fibers was quantitatively less than that for conventional OHT. Finally, the bearing strength of double-lap pin joint between the plain-woven CFRP and metal plates was investigated. The result showed that the bearing strength with non-cut fibers was higher than that of conventional joint system. It is expected that the open-holed CFRP structure with non-cut fibers is applied for the practical joint system.

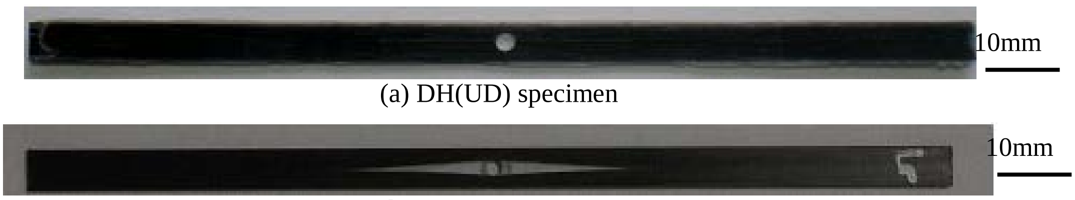
1 Introduction
Advanced composite materials, such as CFRP, are often applied to primary load-bearing structures in various industries because of their good specific stiffness and strength. There are two major methods for joining CFRP with metals: mechanical fastening and adhesive bonding. Mechanical fastening system using bolts or rivets is simple, so that it is possible to obtain high joining strength; thereby it is widely used in joining CFRP structure. The disadvantages of mechanical joints are an increase in weight of the whole structure and low sealing performance. Especially in the case of the FRP structures, a drilling process to fabricate bolt holes breaks reinforcing fibers, and causes (i) peeling of the higher plies at the entry of the hole, (ii) fiber wrenching and resin degradation on the wall of the hole, and (iii) delamination of the lower plies in the laminate [1]. Since these damages can initiate micro cracks, mechanical fastening in FRP structures severely decreases the mechanical properties.
It is known that CFRP with open-hole structures cause stress concentration around the pin-loaded holes. These stress concentrations induce a complicated damage process that concurrently includes splits, transverse cracks, and delamination under tensile loading [2]. It has been shown by a number of researchers [2-5] that CFRP laminate notched strength decreases with increasing notch size. One possible explanation for this was proposed by Whitney and Nuismer [6] for open hole laminates, who showed that even though the stress

concentration factor, K_t, is over 3 for holes of all sizes in quasi-isotropic open-hole tension (OHT) specimens, the stress drops off more steeply moving away from the hole, for smaller holes. It was reasoned that this increased the probability of having a large flaw in the highly stressed region around a large hole, resulting in a lower average strength for a laminate with a large hole.
In this paper, the open-holed CFRP structure with non-cut fibers was proposed in order to reduce the stress concentration of fibers near open-hole. In this method, fiber continuity is maintained in a specimen, which yields a local increase in fiber volume fraction around open-hole. The mechanical properties of the unidirectional and plain-woven CFRP laminates under tensile loading were first investigated. Next, the stress concentration of fibers near open-hole was evaluated by the finite element analysis in the case of unidirectional CFRP with open-holes. The bearing strength of double-lap pin joint between the plain-woven CFRP and metal plates was finally investigated.

2 Experimental

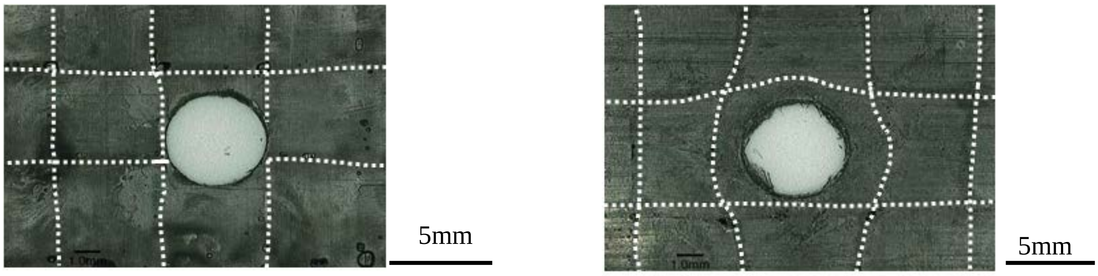
2.1 Materials

Unidirectional (UD) and plain-woven (PW) CFRP laminates were prepared in this study.
Carbon fibers TRH50 supplied from Mitsubishi Rayon Co., LTD. were used as reinforcement for UD CFRP laminates. One tow of the carbon fibers consists of 12,000 monofilaments, and the diameter of fiber is 6.7μm. Araldite® AY103/HY956 supplied by Huntsman Japan Co. Ltd. was used as matrix. The matrix consists of two components. The contents ratio of mixture was 100:18. The fiber volume fraction was 18%. The gage length, width *W* and thickness of the UD CFRP specimens are 30 mm, 5 mm and 0.5 mm, respectively. The open holes were adopted by two methods; one is the conventional drilling method, the other is the pin inserting method in the dry fiber tows before the curing process at the center of specimens. The specimens developed by the drilling for tensile tests present a discontinuous fiber structure around the open hole, and those by the pin inserting method are a continuous (non-cut) fiber structure. These specimens are abbreviated to DH(UD) and CH(UD), respectively. The diameters of holes *D* were 1, 1.5, 2 and 2.5mm. The tapered GFRP tabs were bonded at the end of specimens. The overviews of these specimens were shown in fig.1.



(a) DH(UD) specimen
(b) CH(UD) specimen
Figure 1. Tensile specimen of UD CFRP laminates

The PW CFRP prepreg (supplied from Mitsubishi Rayon Co., Ltd) consists of TR50S carbon fibers and epoxy resin. One tow of the carbon fibers consists of 12,000 monofilaments. The stacking sequence of the PW CFRP laminates was $[0/90]_2$. The gage length, width *W* and thickness *t* of the specimens for tensile tests are 150, 25 and 0.5 mm, respectively. The fiber volume fraction was 57%. The open holes were also adopted by two methods as mentioned previously. These specimens developed by the drill and pin inserting methods also present discontinuous and continuous (non-cut) fiber structures around hole; these are abbreviated to DH(PW) and CH(PW), respectively. The diameters of holes *D* were 2 and 4 mm. The tapered GFRP tabs were bonded at the end of specimens. The overviews around the hole of these specimens were shown in fig.2.



(a) DH(PW) (b) CH(PW)

Figure 2. The vicinity of the hole for the plain-woven CFRP laminates

The PW CFRP prepreg was also used for double-lap pin joint specimens. The stacking sequence of the plain woven CFRP laminates was $[0/90]_2$. The gage length, width *W* and thickness *t* of the specimens for bearing tests are 175, 25 and 0.85 mm, respectively. The open holes were also adopted by two methods as mentioned previously. The diameters of holes *D* were 4, 5 and 8 mm. The end distances of speceimen were 20, 25 and 40mm, respectively.

2.2 Testing methods

The tensile tests were carried out at 1.5mm/min cross-head speed by using an Instron-type testing machine (IS-5000, Shimadzu Co., Ltd). The configuration of the double-lap pin joint test was shown in fig.3. This testing was carried out such that no restraint of out-of-plane was working for specimen. The diameters of pins made from carbon steel (JIS S45C) were changed to 4, 5 and 8 mm based on the diameter of open holes. The strain was measured by strain gauge, which was pasted enough far from the hole at the specimens.

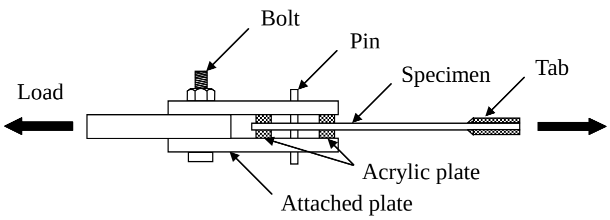


Figure 3. Configuration of double-lap pin joint test

3 Tensile properties

3.1 Tensile strength with open hole

Fig. 4 shows the tensile test results for unidirectional CFRP specimens with open-hole. These tensile strengths were normalized by the strength of regular unidirectional CFRP (RL) without open hole. The normalized OHT strengths obtained from the drilling method of Russo [4] and Pipes [5] were also shown in this figure in order to present the validity of the driling method for DH(UD) specimens in the present study. It was found that the tensile strengths of DH(UD) decreased in the range of 40-67% from that of RL, while those of CH(UD) decreased in the range of only 12-24%. The fracture aspects of DH(UD) and CH(UD) after final failure were shown in fig.5, respectively. It was clear from these observations that the crack propagation occurred near open-hole in the case of DH(UD), while, the crack propagation occurred far from open-hole in the case of CH(UD). It is presumed that the defference of position for crack occurrences is attributable to the stress concentration of fibers near open-holes.

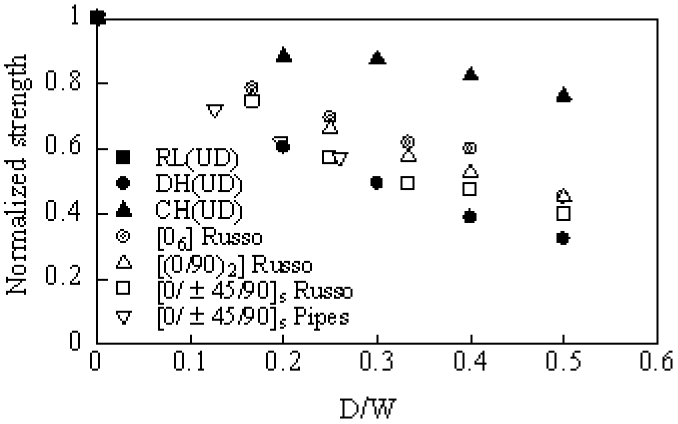


Figure 4. Relation between normalized tensile strength and circular hole diameter ratio

(a) DH(UD) 10mm

(b) CH(UD) 10mm

Figure 5. Fracture aspect for tensile unidirectional specimens

Fig. 6 shows the tensile test results for plain-woven CFRP specimens with open-hole. These tensile strengths were normalized by the strength of regular plain-woven CFRP (RL) without open hole. The normalized tensile strengths obtained from Belmonte [7] were also shown in this figure. It was found that the tensile strengths of DH(PW) decreased in the range of 24-39% from that of RL, while those of CH(PW) decreased in the range of only 17-30%. The fracture aspects of DH(PW) and CH(PW) after final failure were shown in fig.7, respectively. It was clear from these observations that the crack propagation occurred near open-hole in the case of DH(PW), while, the crack propagation occurred far from open-hole in the case of CH(PW). Additionally, the fiber bundle-like failure was also generated for the case of CH(PW) because of low stress concentration around the open-hole.

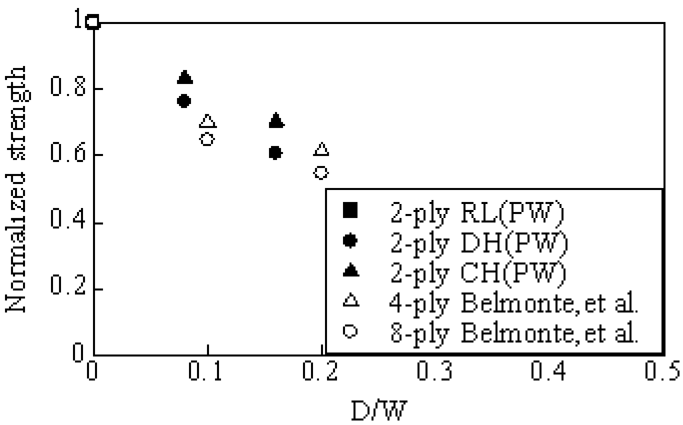
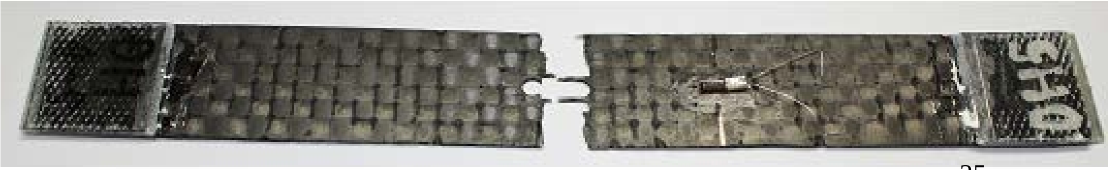
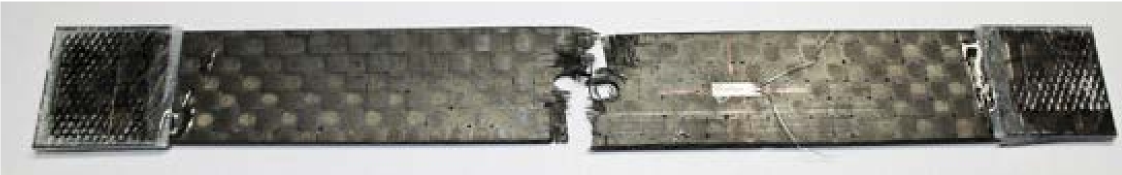


Figure 6. Relation between normalized tensile strength and circular hole diameter ratio



(a) DH(PW) 25mm



(b) CH(PW) 25mm

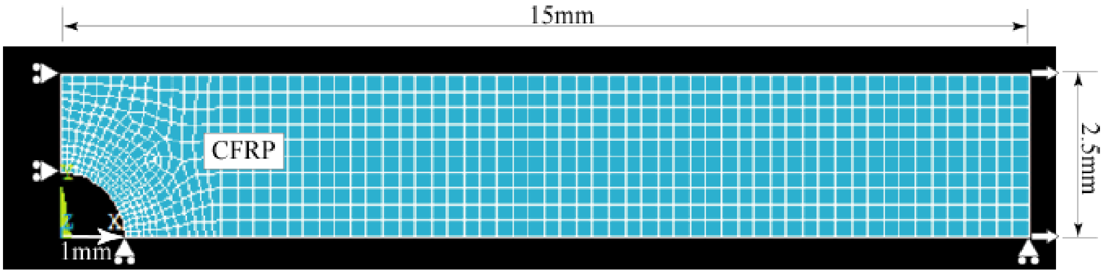
Figure 7. Fracture aspect for tensile plain-woven specimens

3.2 Stress analysis

The finite element analyses for DH(UD) and CH(UD) CFRP laminates were elastically conducted in order to estimate the stress concentration around the open-hole. The one quarter region of specimen was modeled including the open-hole. DH(UD) laminates consisted of the orthotropic CFRP regions and CH(UD) consisted of the orthotropic and resin regions. The material properties of elements were shown in table 1. The finite element meshes were shown in figs. 8(a) and 8(b). In the case of CH(UD) model, the fiber orientation angle and fiber volume fraction vary based on the distance from hole. In this model, therefore, the fiber orientation angle in each element was changed from 4 degree to 0 degree in proportion with the distance from the hole along the transverse direction. The fiber volume fraction in each element was also changed from 30% to 18% in proportion with the distance from the hole along the longitudinal direction. The stress distributions for σ_{xx} were shown in fig. 9. It is found that the stress concentration near the hole for CH(UD) is less than that for DH(UD), and the stress increase region in CH(UD) broadened more largely. The relation between stress concentration factor near the open hole and *D/W* was shown in fig.10. The stress concentration factor predicted by Whitney and Nuismer [6] was also added in this figure. It was clarified that the stress concentration in the case of CH(UD) was drastically less than that of conventional DH(UD) because of fiber continuity around a hole.

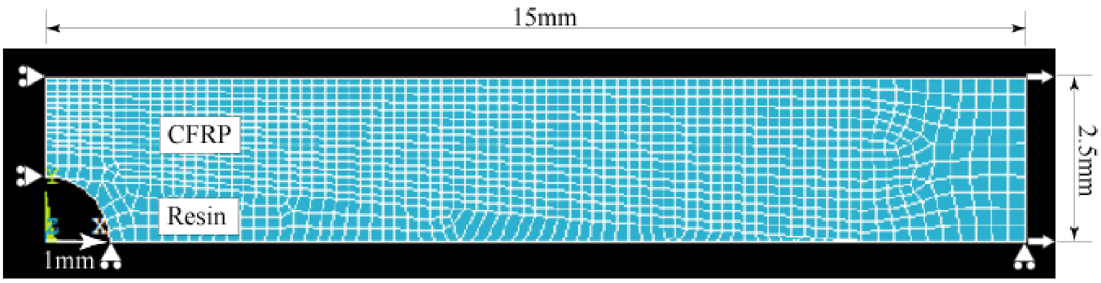
Table 1 Material properties for finite element analyses

CFRP (V_f=0.3)					Resin	
E_X [GPa]	E_Y [GPa]	G_{XY} [GPa]	ν_{XY}	ν_{YX}	E_m[GPa]	ν_m
44.2	4.25	2.97	0.37	0.035	3.5	0.39



Number of nodes: 1250, Number of elements: 1146

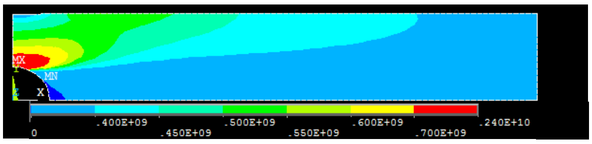
(a) DH(UD) model



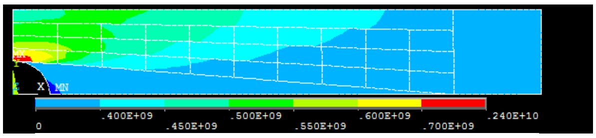
Number of nodes: 1464, Number of elements: 1375

(b) CH(UD) model

Figure 8. FEM model



(a) DH(UD)



(b) CH(UD)

Figure 9. Stress distribution σ_{xx} for UD-CFRP

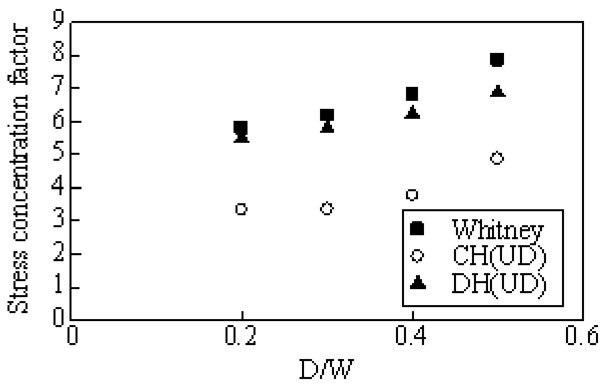
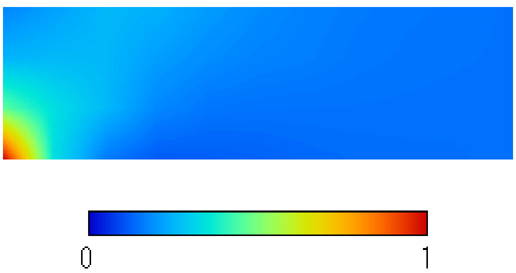
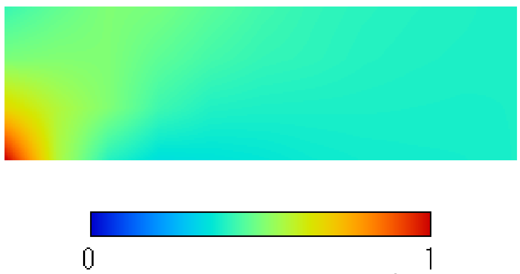


Figure 10. Relation between stress concentration factor and D/W for UD-CFRP

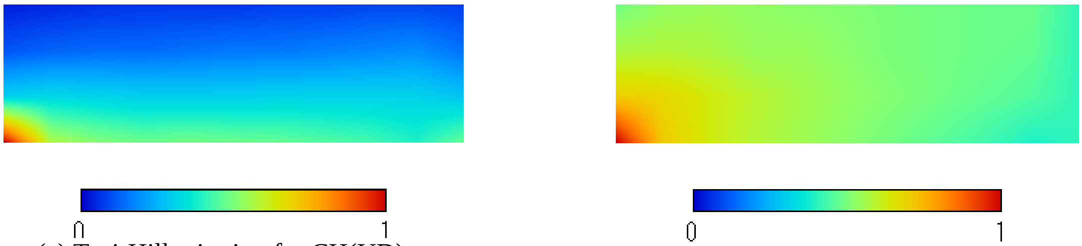
Fig.11 depicted the comparison between Tsai-Hill criteria and the fiber stress concentration factor normalized by the highest value of the DH(UD) or CH(UD) for the CFRP region without the resin region, respectively. The coefficient of correlation between the Tsai-Hill criteria and the fiber stress concentration for DH(UD) was 0.984. On the other hands, the coefficient for CH(UD) was 0.515. It is implied that the numerical simulation based on Monte-Carlo approach including the strength distribution is necessary for the prediction of the first failure point for CH(UD) because of the low and extended stress concentration.



(a) Tsai-Hill criterion for DH(UD)



(b) Normalized stress concentration for DH(UD)



(c) Tsai-Hill criterion for CH(UD)   (d) Normalized stress concentration for CH(UD)

Figure 11. First failure point prediction according to Tsai-Hill criteria and stress concentration of fibers

4 Bolted joint strength properties

The relation between the bearing strength and the circular hole diameter ration *W/D* for the plain-woven CFRP laminates was shown in fig. 12. The bearing strength σ_b was estimated by equation (1).

$$\sigma_b = \frac{P_f}{Dt} \qquad (1)$$

Where, P_f is the failure load, which was defined as the first drop load as shown in fig.13 in the present study. Furthermore, the fracture aspect for DH(PW) was shown in fig. 14. From these figures it was found that the bearing strengths of DH(PW) were less than those of CH(PW) due to the occurrence of global buckling failure in the case of DH(PW). As mentioned above, the proposed pin-inserting open-hole method with non-cut fibers is superior to the conventional drilling method in the double-lap pin joint strength, as well as tensile strengths of UD and PW specimens. Thus, it is concluded that it is a quite promising method for the practical joint system.

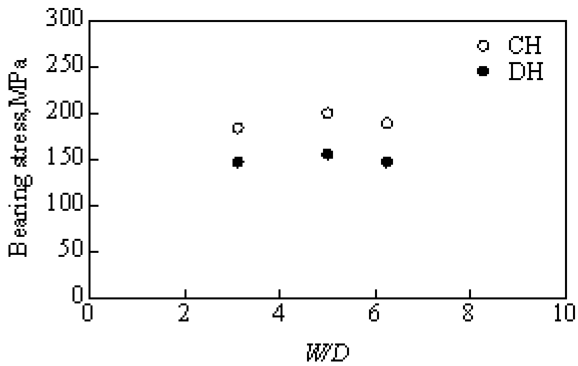


Figure 12. Relation between bearing strength and circular hole diameter ratio for PW-CFRP

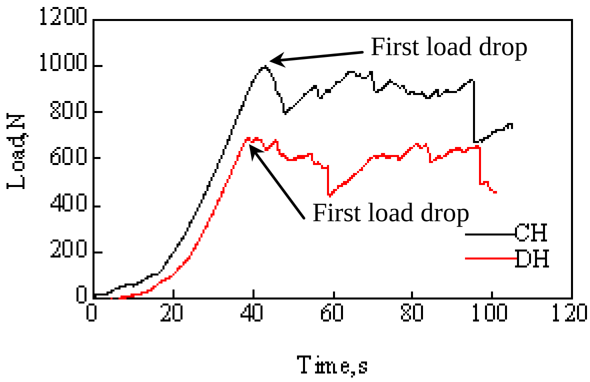


Figure 13. Relation between load and time for DH(PW) and CH(PW) at *D*=5.0mm

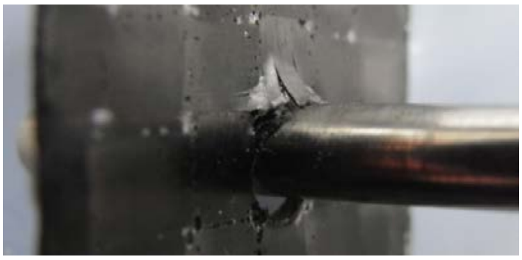


Figure 14. Fracture aspect of DH(PW) at D=4.0 mm

5 Conclusions

The open-holed CFRP structure with non-cut fibers was newly proposed in order to reduce the stress concentration to the fibers around open-hole. In this method, not only the fiber continuity is maintained around the hole by inserting a pin in a specimen, but also the fiber volume fraction increases locally in the vicinity. Tensile properties of the unidirectional and plain-woven CFRP laminates were investigated. The results showed that the open-hole CFRP structure with non-cut fibers proposed here was superior to the conventional drilling open-holed CFRP. Furthermore, the stress concentration to the fibers around the open-hole was estimated for unidirectional CFRPs by the finite element analysis. It was clarified that the stress concentration was quantitatively less in the case of non-cut fibers, as compared with that of the conventional drilling open-holed structure. Finally, the bearing strength of double-lap pin joint between the plain-woven CFRP and metal plates was experimentally investigated. The bearing strength of the non-cut fiber specimen showed a relatively high value as compared to that of the conventional one. It is concluded that the proposed open-holed CFRP structure with non-cut fibers would be applicable for the practical joint system.

Acknowledgements

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References

[1] Davim J.P., Reis P., Antonio C.C. Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up. *Composite Science and Technology*, **64**, pp. 289-297 (2004).

[2] Kortschot M.T., Beaumont P.W.R. Damage mechanics of composite materials: I-Measurements of damage and strength. *Composite Science and Technology*, **39-4**, pp. 289-301 (1990).

[3] Coats T.W., Harris C.E. A progressive damage methodology for residual strength predictions of notched composite panels. *Journal of Composite Materials*, **33**, pp. 2193-2224 (1999).

[4] Russo A., Zuccarello B. An accurate method to predict the stress concentration in composite laminates with a circular hole under tensile loading. *Mechanics of Composite Materials*, **43**, pp. 359-376 (2007).

[5] Carlesson L. A., Pipes R. B. *Open hole tensile strength of laminates, Experimental characterization of advanced composite materials*. Technomic publishing company, Lancaster (1997).

[6] Whitney J.M., Nuismer R.J. Stress fracture criteria for laminated composites containing stress concentrations. *Journal of Composite Materials,* **8**, pp. 253-265 (1974).

[7] Belmonte H.M.S., Ogin S.L., Smith P.A. A physically-based model for the notched strength of woven quasi-isotropic CFRP laminates. *Composites* : *Part A*, **35**, pp. 763-778 (2004).