DAMAGE DETECTION IN CFRP BOLTED JOINTS USING EMBEDDED OPTICAL FIBER STRAIN DISTRIBUTION MONITORING

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Summary Fiber-optic based damage monitoring is proposed for carbon fiber reinforced plastic (CFRP) bolted joints. Optical fibers are embedded along bolt holes and strain change along the optical fiber induced by internal damage is measured by a Brillouin Optical Correlation Domain Analysis (BOCDA), which is a high spatial resolution distributed strain sensing system. Based on the observed damage modes of CFRP bolted joints after bearing failure, effective embedding positions of optical fibers are selected. Then, elasto-plastic finite element analysis simulating the damage propagation in the bolted joint is conducted to calculate the consequent strain change. Verification tests clearly show that damage can be detected using residual strain due to fiber-microbuckling (kinking) damage or permanent deformation of neighboring plies. Furthermore, damage size and direction can be also estimated from the change in the strain distribution.

INTRODUCTION

Current CFRP primary structures include bolted joints which carry significant loads. There are urgent needs to detect internal bearing failures in their initial stage although these failures are barely visible and the number of bolted joints is large. Several methods have been proposed for structural health monitoring (SHM) of CFRP bolted joints. In this paper, we are proposing a fiber-optic BOCDA damage monitoring system to measure the distributed strain distribution along an embedded optical fiber and detect internal failures in bolted joint structures.

OBSERVATION OF DAMAGE EVOLUTION IN CFRP BOLTED JOINTS

Although damage modes in CFRP bolted joints depend on the materials and joint design, bearing failures are normally induced in our current joint design because of the maximum loading capability. Figure 1 shows the CFRP double-lap bolted joints in the present study. Toray T700/2592 prepregs were used to fabricate $[45_2/\text{-}45_2/0_2/90_2]_S$ quasi-isotropic laminates and a hole with 6 mm in diameter was drilled with a ultra-hard solid drill. Three specimens were loaded up to different displacement levels (A, B, and C in Fig. 2), and internal damages were observed firstly by soft X-ray image analysis (Fig. 3) and then by optical observation of damaged sections (Fig. 4). Progressive bearing failures can be clearly observed in Fig. 3. Sectional views in Fig. 4 reveal that the progressive fiber kinking damages are the most pre-dominant failure modes which are associated with matrix failure, delamination and fiber fractures [1]. It is desirable for the SHM sensing system to quantitatively detect such an evolution of fiber kinking behavior. It is well known that optical fibers can be embedded in CFRP laminates with the minimum strength reduction when embedded along carbon fibers in each lamina. Although some breakages are expected in embedded optical fibers when embedded in 0-degree laminas due to fiber kinking, optical fibers embedded in neighbouring 90-degree laminas are expected to be sensitive to plastic deformation induced by fiber kinking in 0-degree laminas. The following elasto-plastic finite element analysis is conducted to validate such a damage detection methodology.

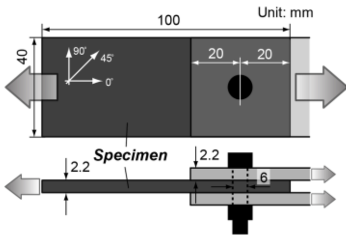


Fig.1 CFRP bolted specimens

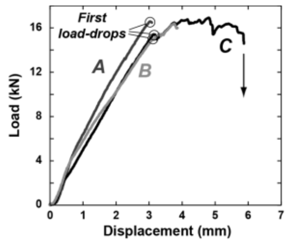


Fig.2 Load-displacement curve

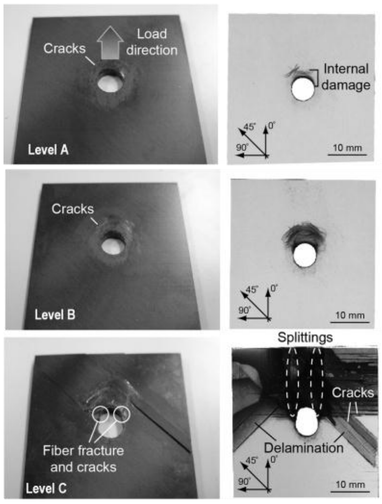
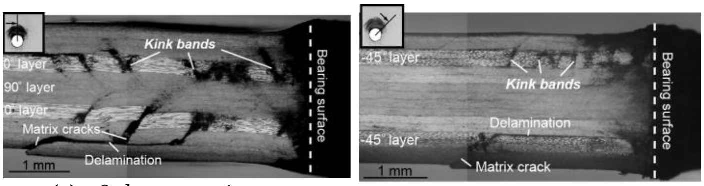


Fig.3 Damage progress observation

ELASTO-PLASTIC FEM ANALYSIS TO PREDICT STRAIN DISTRIBUTION

Three-dimensional (3D) elasto-plastic finite element analysis (FEA) was conducted using the ABAQUS code. The contact analysis was made using the penalty method. The detailed procedure



(a) 0-degree section (b) 45-degree section

Fig.4 Sectional view

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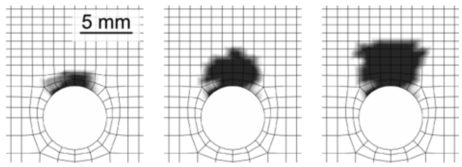
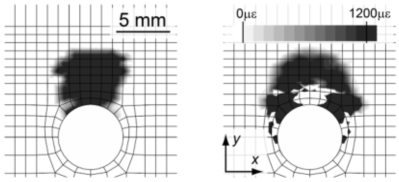
can be found in Ref. [2]. A brief description is presented below.

All damage modes including fiber kinking, fiber tensile fracture and matrix failure were considered in 0-degree and 45/-45-degree laminas. The stress criterion for each failure mode was used for each FE element and the cumulative damage model was used to take into account the stiffness reduction due to each damage mode. Plastic deformation was induced in the 90-degree laminas due to fiber kinkings in neighboring laminas. The elasto-plastic constitutive equation of the 90-degree lamina was obtained using the extended Eshelby's equivalent inclusion model proposed by Tohgo et al. [3] and the experimentally-obtained compressive stress-strain curve of the matrix resin. The anisotropic yield criteria and the J2 flow rule were used with isotropic strain hardening. The incremental displacement was applied at the bolt by each 0.005 mm, and the analysis of the induced damages and the strain distribution was conducted.



(a)0.5mm (b)1.5mm (c)2.5mm

Fig.5 Growth of kinking region in 0 ply



(a)Kinking region (b)Plastic strain ε_{xx}^{p}

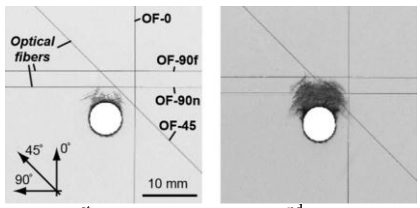
Fig.6 Simulation results at 3mm bolt displacement

The predicted kinking failure growth is shown in Fig. 5. Figure 6 shows both kinking failure region occurring in both 0 and 45-degree plies at 3 mm bolt displacement and the corresponding plastic strain in the fiber direction of the 90-degree ply. Approximately 1,000 με was predicted and sufficiently large enough to be measured by optical fiber strain sensors. Based on the above analysis, three different optical fibers were embedded in 0, 45, and 90-degree plies. 45-degree optical fibers are expected to be sensitive to the fiber kinking in the neighboring -45 ply. 0-degree optical fibers near the hole edge are also expected to be sensitive to the fiber kinking in the neighboring 90 ply.

DISTRIBUTED STRAIN MONITORING AND DAMAGE GROWTH DETECTION

The BOCDA technique [4], a high spatial resolution distributed strain sensing system, was used in our experiments. The special resolution and the sampling interval were 17 mm and 5 mm, respectively. Polyimide-coated optical fibers (150 μm in diameter) were embedded in the following locations: [45/*OF-45*/45/-45_2/0/*OF-0*/0/90_2/*OF-90*/90_2/0_2/-45_2/45_2/], where the number after *OF* is embedding direction. Both optical fibers in 0 and 45 plies were located 3 mm away from the hole edge. Two optical fibers (*OF-90*n and *OF-90*f) were placed in 90 ply, 2.5 mm and 5.5 mm, respectively, away from the hole edge.

The specimen was first loaded up to the load level where some initial damages could be found, and enhanced soft X-ray image and the strain distribution were obtained. Then, the second loading was applied up to the level where the kinking reached the near-by embedded optical fibers in 90 and 45 plies. The results are summarized in Figs. 7 and 8. The 1st loading induced approximately 200 με in all three optical fibers. Since the kinking does not reach the optical fibers, these strains are expected to be elastic residual strains induced by permanent plastic strains in 90 plies. The 2nd loading introduced about 1,000 (1,500 at maximum) and 600 με in 90 and 45 plies, respectively. These strain values quantitatively agreed with the predicted ones. The strain measured in the *OF-90*f in the 1st loading disappeared in the 2nd loading. It can be concluded optical fibers should be embedded in the region where matrix plastic deformation is induced for reliable damage detection. The strain values of 200 με in *OF-0* did not change at different load levels, but this strain can be a good indicator of the kinking damage initiation as well.



(a)1st loading (b) 2nd loading

Fig.7 Enhanced soft X-ray images of damaged CFRP bolted joints

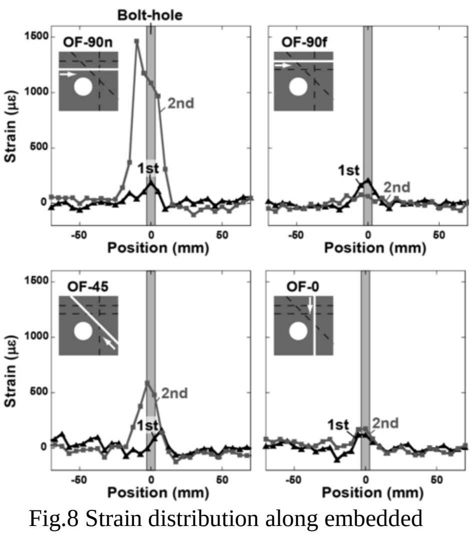


Fig.8 Strain distribution along embedded optical fibers

CONCLUSIONS

A novel fiber-optic damage monitoring system was successfully used to measure the distributed strain distribution along embedded optical fibers and detect internal failures in bolted CFRP joint structures. Plastic strain induced by fiber kinking were well reproduced by elasto-plastic FEA simulating the damage growth in the bolted joint.

References

[1] Nadabe, T., Nishikawa, M., Minakuchi, S., Nakamura, T., Takeda, N.: *J. Japan Soc. Compo. Mater.*, 171-181, 2011. (in Japanese)

[2] Nadabe, T., Nishikawa, M., Minakuchi, S., Nakamura, T., Siivola, J., Takeda, N.: *J. Japan Soc. Compo. Mater.*, in press, 2012. (in Japanese)

[3] Tohgo, K., Kawahara, K., Sugiyama, Y.: *Trans. Japan Soc. Mech. Engineers. A*, **67**-661, 85-92, 2001.

[4] Hotate, K. and Hasegawa, T.: *IEICE Trans. on Electronics*, E83-C-3: 405-412, 2000.