Detectability Assessment of Optical Fiber Sensor Based Impact Damage Detection for Composite Airframe Structures

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DETECTABILITY ASSESSMENT OF OPTICAL FIBER SENSOR BASED IMPACT DAMAGE DETECTION FOR COMPOSITE AIRFRAME STRUCTURE

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ABSTRACT

Airframe structures, especially composite structures, are prone to damage by tool drops, bird strikes, hailstones, etc. The authors have developed an optical fiber based impact damage detection system for composite airframe structure since 1998. In this method, impact locations are measured with the signals of multiple Fiber Bragg Grating (FBG) sensors. In case of aircraft implementation, impact information should be detected under the actual vibration condition, and both detection capability for impact localization and damage level should be improved. This paper presents the detectability assessment result from the impact tests under a simulated vibration condition. In addition, study of optimal FBG sensor direction for localization and review of damage level detection method are conducted to enhance the accuracy of detection.

KEYWORDS : *Optical fiber sensor, Fiber Bragg grating (FBG), Impact damage, Composite airframe structure*

INTRODUCTION

Application of composite materials to aircraft structures has grown significantly due to its high specific strength and modulus, and its fatigue capability. However, the airframe structures, especially composite structures, are prone to damage by tool drops, bird strikes, hailstones, ground support equipments etc. These foreign object impact damages are the major cause of undetectable internal damage and can become major safety hazards. Although such impact damage is taken into account in the airframe design, it is very important to detect the damage as early as possible and to repair the damaged area as required to maintain airworthiness.

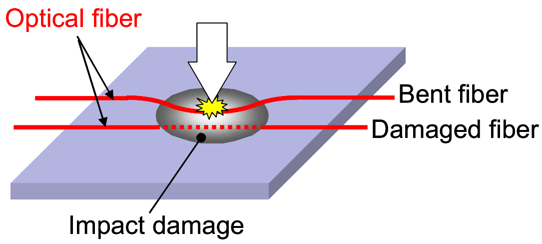
The authors have performed the fundamental research of the impact damage detection method based on multiple Fiber Bragg Grating (FBG) sensors since 1998 in collaboration with the University of Tokyo and RIMCOF (SOKEIZAI Center at present) [1]. From 2006, Kawasaki Heavy Industries, LTD. (KHI) has conducted more practical studies toward real aircraft application with the focus on the impact localization due to its technical maturity and applicability. KHI assessed the impact detectability through series of impact tests using several types of specimens ranging from coupon to component levels following the building block approach. Although the localization errors were within acceptable level, there is still room for improvement [2].

This paper presents the detectability assessment result from the impact tests under a simulated vibration condition, and the study on the optimal FBG sensor direction. The aim of the latter study is to achieve higher localization accuracy, and was studied through the impact tests using stiffened panel with FBG sensors aligned in three directions (in effect, similar to a rosette type strain gage). In addition, damage level detection method is reviewed to enhance the accuracy.

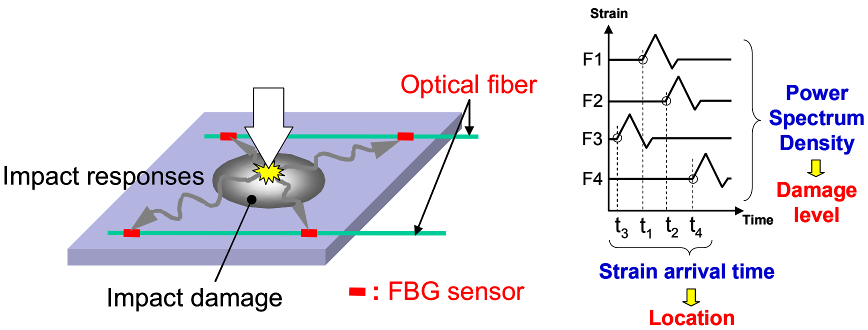
1. Outline of Impact Damage Detection Method

The damage detection methods are shown in Figure 1. IDDS detects impact damage with two types of measurement methods, namely, (a) optical intensity measurement before and after impact events by multi-mode fibers and (b) strain measurement with multiple FBG sensors. In method (a), impact damage can be detected with the optical intensity change associated with the extent of the impact damage such as matrix crack, delamination, or local deformation in the vicinity of the dent. In this method, all part of the optical fibers work as crack detectors. In method (b), impact locations are detected from the arrival time difference of strains obtained with the multiple FBG sensors. Impact damage level can also be detected with the power spectrum density of the strain responses.

This paper focuses on the method (b) and presents the R&D results regarding this method.



(a)Optical intensity measurement method



(b)Strain measurement method with multiple FBG sensors

Figure 1: Impact Damage Detection Method

2. Reliability Assessment with Simulated Vibration Condition

The impact tests under vibration were performed to assess the impact detectability of IDDS under simulated vibration condition. In this test, a quasi-isotropic Carbon Fiber Reinforced Plastics (CFRP) stiffened panel shown in Figure 2 was used. The panel has three T-shape stringers. The size of the skin is 600x630x3mm. One optical fiber with 4 FBG sensors was bonded on the stringer side surface of the specimen. The sensor directions were aligned parallel with the stringers. The diameter of bonded optical fiber is 125 micro meter. The applied vibration condition was vertical random vibration of 5.83 Grms with the frequency range of 10Hz to 2000Hz. This condition is based on RTCA DO-160, Section 8, Category R, which is applicable to the fuselage of fixed wing turbojet airplane. The stiffened panel was set to the shaker by the test fixture as shown in Figure 3. Impacts were applied using an impact hammer under the random vibration. The impact load was approximately 1.5kN, which did not cause any impact damage.

Typical strain response is shown in Figure 4. Also shown is the impact load signal measured by the load cell built in the impact hammer. This strain history involved the responses due to both impact and simulated random vibration. The strain history before impact was obtained by pre-trigger for 20msec before impact occurrence. The impact induced response can be readily separated. This indicates that strain arrival time can be extracted from the strain response using a properly designed filter.

New algorithm to obtain strain arrival time under vibration condition was developed taking advantage of the frequency differences between impact and vibration. The strain frequency of vibration is less than 2000Hz whereas the strain frequency due to impact is higher than 2000Hz. Band-pass filter is available for detecting the first strain response due to impact under the random noise condition. The new algorithm is implemented to the LabVIEW based impact damage detection software developed by KHI. The typical localization result is shown in Figure 5. The localization error is 60.7mm, which accuracy is sufficient for narrowing down the impact zone, and visually locating the actual impact location. Therefore, IDDS can be used to supplement zone inspection to identify possible impact damage.

Figure 2: CFRP stiffened panel for simulated vibration test
(Looking from stringer side)

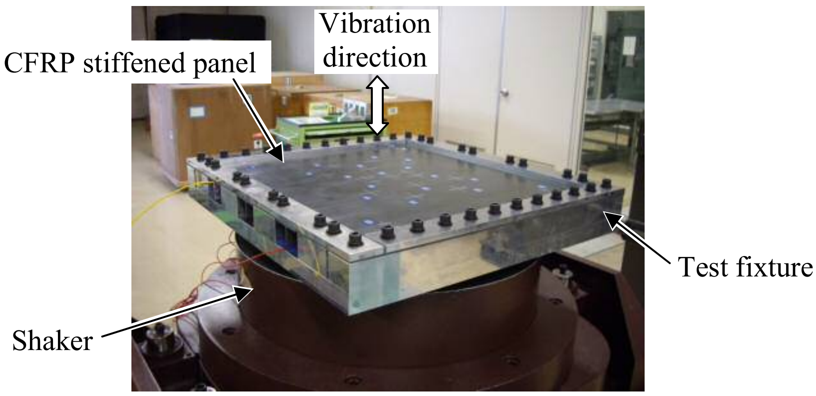
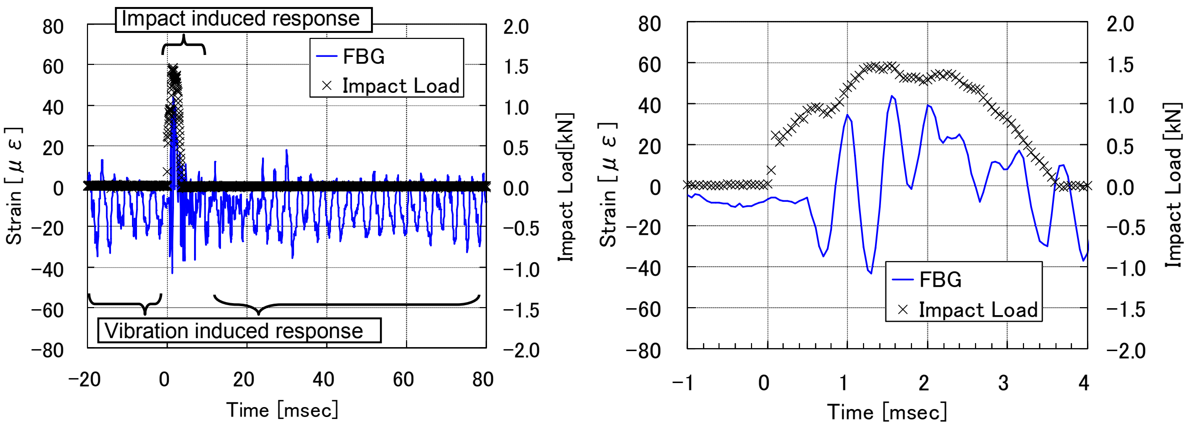


Figure 3: Setup of simulated vibration test



(a) -20msec ~ 80msec (b) -1msec ~ 4msec (near the impact event)

Figure 4: History of strain response and impact load under random vibration

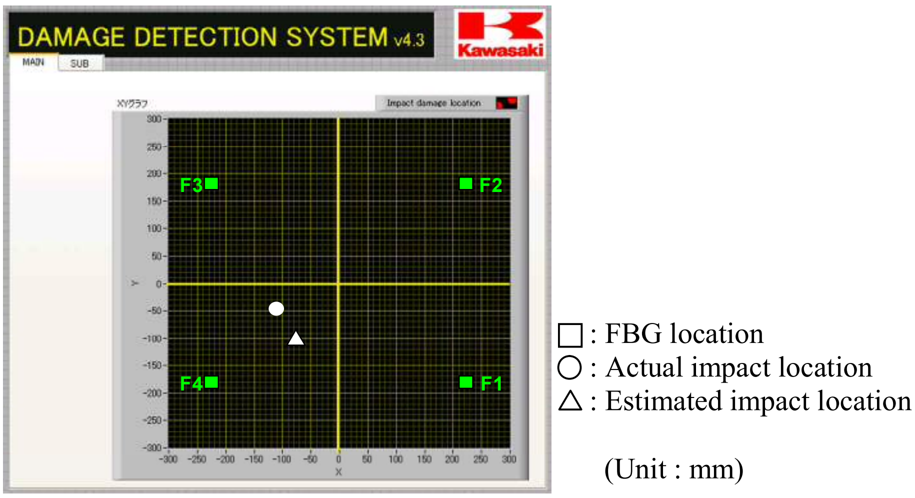


Figure 5: Localization result of impact location under random vibration

3. Optimal Sensor Direction Assessment Suitable for Impact Localization

In the study on the optimal FBG sensor direction, impact tests were performed for three types of FBG sensor alignment patterns using a CFRP stiffened panel imitating an actual aircraft structure as shown in Figure 6. This stiffened panel consists of quasi-isotropic CFRP skin, 9 CFRP T shaped stringers, 4 aluminium frames and 32 aluminium shear ties. The frames were fastened to the skin via shear ties. The size of the skin is 1800x1300x3mm. 12 FBG sensors were bonded on the stringer-side skin surface. The diameter of the bonded optical fibers are 125 micro meter. The arrangement of FBG sensors is similar to a rosette type strain gage, aligned in the stringer direction, frame direction (perpendicular to the stringer) and at 45-degree direction as shown in Figure 7. FBG sensor signals were obtained at 800kHz sampling rate using high speed FBG measurement system AR5011A developed by Anritsu corporation in Japan. Localization errors were compared between three types of FBG alignment patterns and suitable sensor direction for impact localization was evaluated. 16 impacts were applied to the web and stringer foot of the stiffened panel, as shown in

Figure 8. Applied impact energy range from 50 to 80 J causing barely visible impact damage (BVID) or higher level damage.

Localization results are summarized in Table 1. The average localization error estimated by stringer direction FBG sensors is 86.2mm. In contrast, the average localization error for frame direction case is 52.8mm, which has higher accuracy than the stringer direction case. This result indicates that the FBG sensors oriented in the frame direction is more sensitive to impact and is suited for impact localization. However, authors believe that the localization accuracies in both cases are sufficient for narrowing down the impact zone. In practical application, FBG direction should be determined taking into account the ease of optical fiber installation. In order to install the optical fibers in the frame direction, optical intensity loss due to micro-bending of optical fiber at the stringer has to be considered. However, in case of the hat stringer used in B787 and A350, optical fibers can be easily installed along the hat stringer surface.

Figure 6: CFRP stiffened panel
(Looking from stringer side)

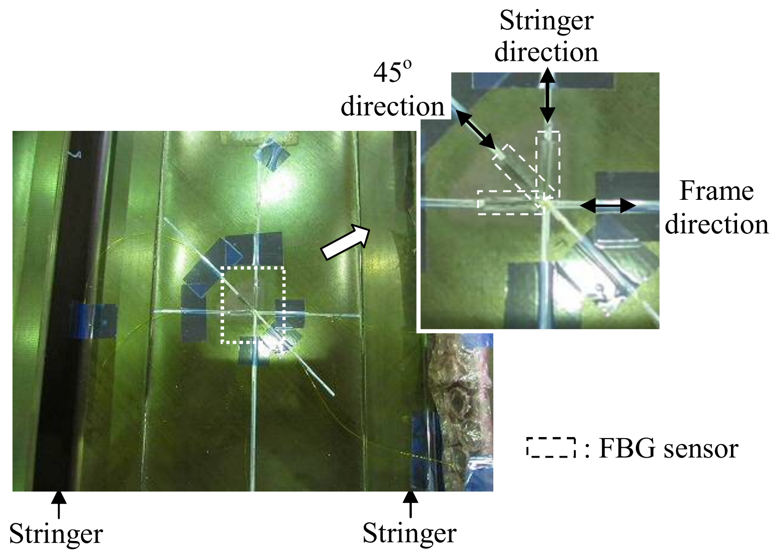


Figure 7: Arrangement of FBG sensors similar to rosette gage pattern

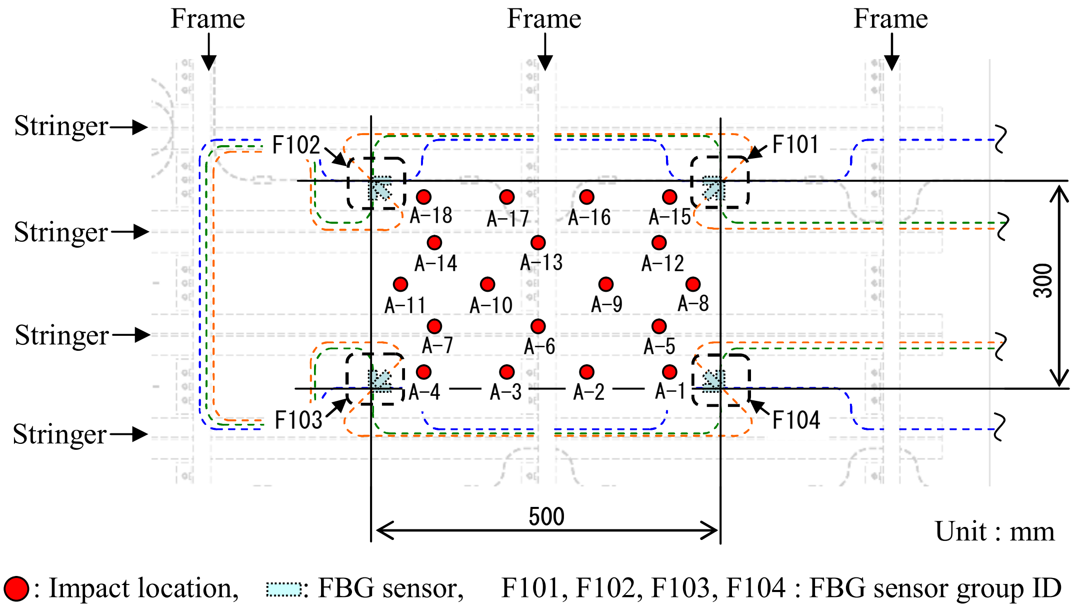


Figure 8: Impact and FBG sensor locations of impact test
(Looking from the impact side)

Table 1: Localization results of the impact test

Impact location ID	Impact location	Impact energy [J]	Dent depth after 24H [mm]	Localization error [mm]	
				Stringer direction sensor	Frame direction sensor
A-6	Stringer	50	0.14	41.4	31.0
A-13	Stringer	50	0.16	80.7	35.4
A-9	Web	75	0.16	33.5	39.2
A-10	Web	75	1.33	14.4	33.4
A-8	Web	75	0.23	*	*
A-11	Web	70	0.15	*	*
A-2	Web	75	0.22	60.2	21.2
A-17	Web	75	2.71	115.0	47.8
A-3	Web	75	0.21	102.3	18.8
A-16	Web	75	1.18	76.1	44.3
A-5	Stringer	80	0.18	58.2	67.3
A-14	Stringer	80	0.19	124.9	103.5
A-7	Stringer	80	0.18	154.6	92.2
A-12	Stringer	80	0.19	142.3	60.0
A-1	Web	50	0.15	109.2	68.0
A-18	Web	50	0.14	89.9	74.0
A-4	Web	50	0.13	96.1	69.7
A-15	Web	50	0.14	80.2	39.4

*Detection failure due to sensor disbond

4. ACCURACY ENHANCEMENT OF IMPACT DAMAGE LEVEL DETECTION

While impact damage detection system can estimate impact damage level, improvement is necessary if the system is to supplement the conventional non-destructive inspection such as ultrasonic inspection. Ultrasonic inspection technique is effective in detecting internal damages of composite materials and widely used in aircraft industries. However, the technique is labor-intensive and costly. In addition to the information of impact event and location, in-flight information on impact damage level from the structural health monitoring system is helpful to maintain airworthy operation.

The novel FBG sensor monitoring system of 800kHz sampling was used in the previously mentioned impact test. In this study, high frequency domain of power spectrum density (PSD) obtained by 800kHz sampling was studied in detail to extract useful signals for estimating impact energy or impact damage level. Figure 9 shows the typical PSD distribution estimated from the 800kHz sampling data by Burg method. In this example, PSD shows multiple peaks which is thoroughly distributed in wide frequency range, indicating that there is no useful signal to estimate impact energy or damage level.

PSD integrals averaged by 4 FBG sensors parallel to the stringer are summarized in Table 2. Here, web-impact results are shown as typical. Integral calculation was performed in each 1kHz interval to understand the trend of PSD regarding impact energy, dent depth or impact damage area. The magnitude of the PSD integrated from 0Hz to 1kHz is not proportional to the impact energy. The closest FBG sensor to an impact location tends to respond strongly even for low impact energy. This indicates that the largest PSD appearing in the frequency range of 0Hz to 1kHz is caused by the largest 1st mode deformation of the structure. Therefore the PSD integrated from 0Hz to 1kHz is not suited for the impact energy estimation. The integral value from 1kHz to 2kHz is comparatively proportional to the impact energy, more so than the integrated value from 0Hz to 1kHz. When plotted against dent depth, magnitude of PSD integrated from 1kHz to 2kHz is proportional to the dent depth distribution, as shown in Figure 10. Impact damage area is also proportional to the PSD integral. This indicates that the PSD integral over 1kHz is more suited for estimation of dent depth and/or damage area, more so than the impact energy.

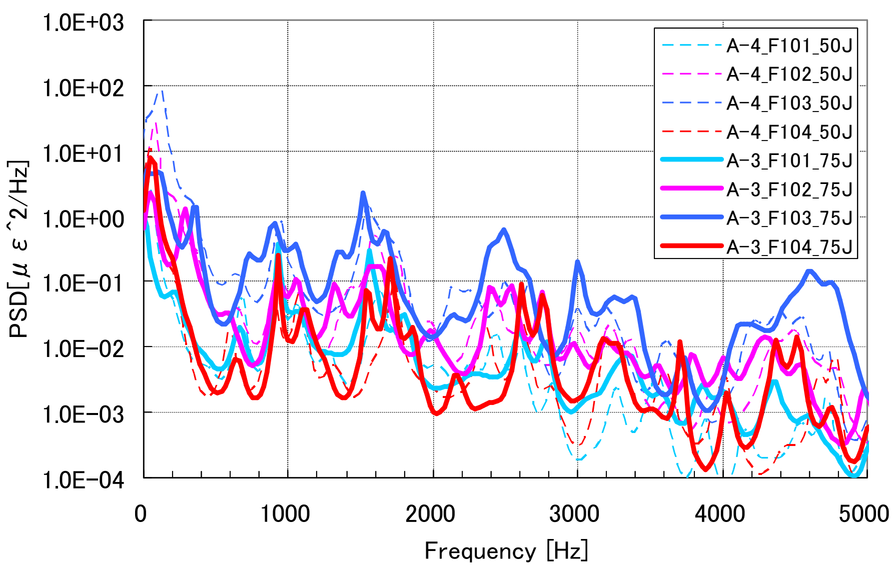


Figure 9: Typical PSD distribution obtained by FBG sensors parallel to stringer

Table 2: Averaged PSD integral for web impact case (FBG sensor parallel to stringer)

Impact ID	Impact energy [J]	Dent depth [mm]	PSD integral [$\mu\varepsilon^2$] (Averaged by 4 FBGs)	
			0 ~ 1kHz	1 ~ 2kHz
A-1	50	0.15	1397.1	25.6
A-2	75	0.22	410.3	35.5
A-3	75	0.21	228.5	51.3
A-4	50	0.13	1394.0	45.0
A-15	50	0.14	2182.5	24.2
A-16	75	1.18	233.1	92.3
A-17	75	2.71	332.5	150.4
A-18	50	0.14	1665.3	28.0

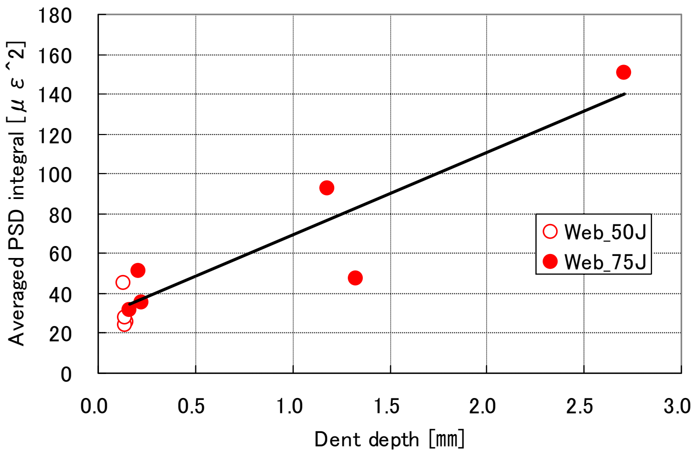


Figure 10: Relation between the dent depth and the averaged PSD integral (1kHz~2kHz)

CONCLUSION

In this study, impact location detectability was assessed from the impact tests under a simulated vibration condition. In addition, new arrangement of the optical sensors and improved signal processing technique have demonstrated the potential for localization and damage level detection improvement. Further improvement in this field will enhance the value of the impact damage detection system in estimating the structural health monitoring of the composite airframe.

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