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Optical Fiber Sensor based Impact Detection System for Aircraft Structures

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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. The Japan Airbus SHM Technology for Aircraft Composites (JASTAC) has been instrumental in guiding this development activity. This paper summarizes the achievements over the years on the development of Impact Detection System (IDDS), with the emphasis on the joint achievements between Airbus and Kawasaki Heavy Industries.

1 INTRODUCTION

The application of composite materials to primary aircraft structure has contributed to the structural weight reduction, but has mixed effect on the maintenance cost. Well-designed composite primary structures are less susceptible to fatigue failures and corrosion, and the scheduled maintenance can be reduced. On the other hand, composite materials are more susceptible to impact which creates internal damages that can only be detected through detailed non-destructive inspection (NDI). This necessitates periodic detailed NDI of all the areas that have a possibility of impact damage.

Structural health monitoring (SHM) system capable of detecting impact damages can reduce the maintenance cost by focusing the detailed NDI on the regions of detected impacts. The authors have developed an optical fiber sensor based SHM system intended to be on-board the aircraft and operated during flight and ground operations [1]. The system will continuously monitor the strains due to operations and detects occasional impact events.

The Japan Airbus SHM Technology for Aircraft Composites (JASTAC) has been instrumental in guiding this development activity. The JASTAC program provided the foundation to discuss the potential SHM use case scenarios, define technical readiness level (TRL) evaluation tasks, and verification test of the SHM system using actual aircraft structures.

The achievements over the years on the development of Impact Detection System will be summarized here, with the emphasis on the joint achievements between Airbus and Kawasaki

Heavy Industries.

2 OUTLINE OF IMPACT DAMAGE DETECTION SYSTEM

The damage detection system is shown in Figure 1. Impact Damage Detection System (IDDS) detects impact event, location and energy level using optical fiber sensors installed in the airframe. Impact locations are detected from the arrival time difference of strains obtained with the multiple Fiber Bragg Grating sensors (FBG) sensors. Impact damage level can also be estimated with the strain level or power spectrum density of the strain responses.

The summary of the environmental durability tests of the sensors bonded to the composite structures are shown in Table 1. The tests were performed under the wide range of environmental conditions expected on the typical aircraft operation. The IDDS has demonstrated sufficient durability under aircraft environment conditions.

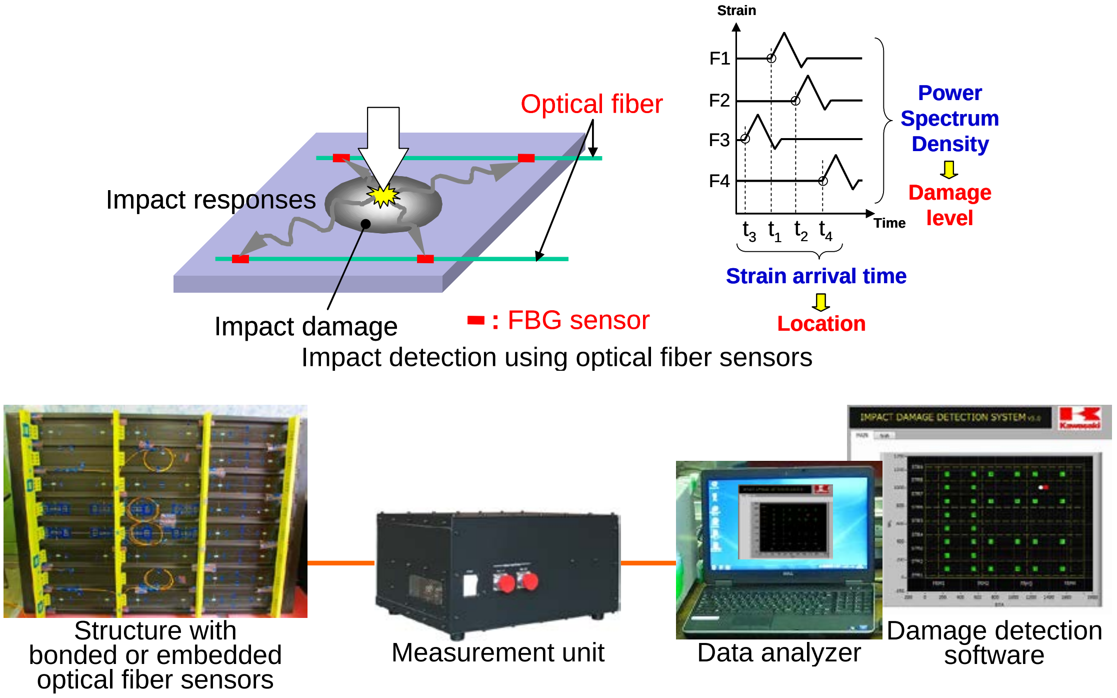


Figure 1: Impact Damage Detection system

Table 1: Environmental durability test summary

Requirement	Status	Requirement	Status
High Temp	Complete	Hydraulic Fluid	Complete
Low Temp	Complete	Solvent	Complete
Altitude/Pressure	Complete	Toilet Fluid	Complete
Over Pressure	Complete	Insecticide	Complete
Decompression	Complete	Disinfectant	Complete
Temperature Variation	Complete	Fire Extinguishing Fluid	Complete
Humidity	Complete	Salt Spray	Complete
Fire Resistance (Flammability)	Complete	Xenon (QUV)	Complete
Water Immersion	Complete	Static Test	Complete
Kerosene	Complete	Fatigue Test	Complete
Fatigue Test on Actual Aircraft Structure	Complete		

3 BLUNT OBJECT IMPACT DETECTION

Blunt object impact (BOI) [2] damage due to ground support equipment (GSE) is a major safety issue since the damage is less apparent than the typical impact damage.

BOI detection test was performed to demonstrate the capability to detect the blunt impact event with the FBG sensors. The BOI test setup is shown in Figure 2. BOI was applied at various locations to evaluate various deformation modes and to assess sensor sensitivity, with the aim of finding a robust method of detecting BOI. For example, shear tie is one of the critical structural elements, but was found to be less suited for detection.

The BOI test measurements are shown in Figure 3. The strain response of the skin is localized and lacks the initial peak observed in the typical impact detection. The large bending strain of the frame is easy to monitor with the FBG sensors, and can be correlated to the impact energy. The strain of the shear tie was found to be difficult to measure and too localized for impact detection. The strains of the frames correspond well with those of the shear ties. Therefore, monitoring the strain of the frame was found to be the most effective for BOI detection.

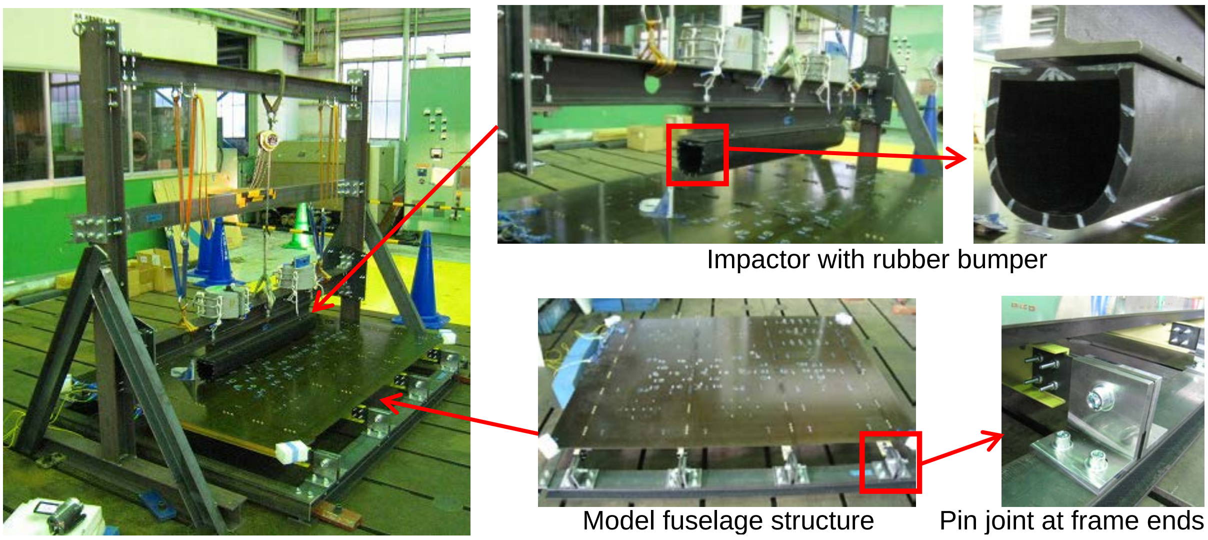
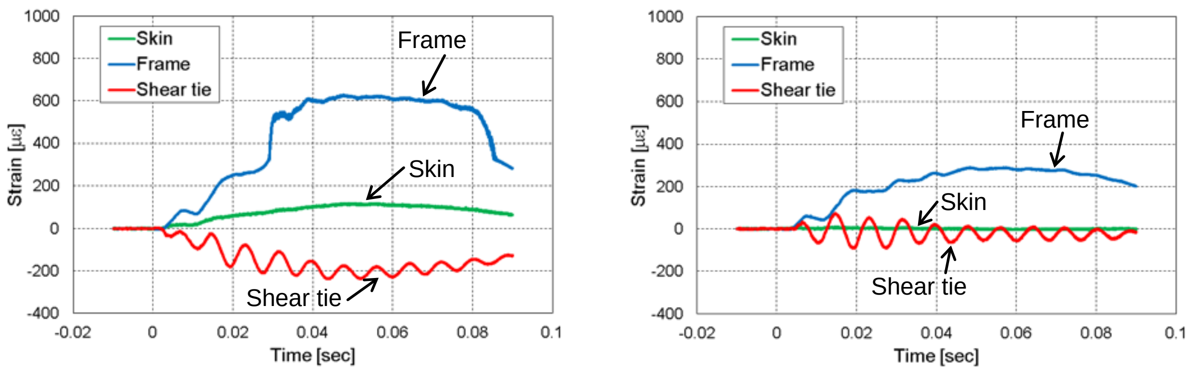


Figure 2: BOI test setup



(a) Impact near the sensors (b) Impact away from the sensors

Figure3: Example of the BOI strain response

4 FULL-SCALE SHM DEMONSTRATION TEST

As a part of the JASTAC joint research program, SHM technology verification test using the full-scale structural tests of the A350 XWB were performed to validate the impact detection reliability and the durability of the IDDS.

The test performed in 2015 demonstrated that the network of optical fiber sensors can be installed in the actual aircraft structure. In this test, the strain responses for the non-damage impacts applied on the test structure were collected. The test also verified that the strain history of the actual aircraft structure subject to fatigue loading can be measured with the same network of sensors.

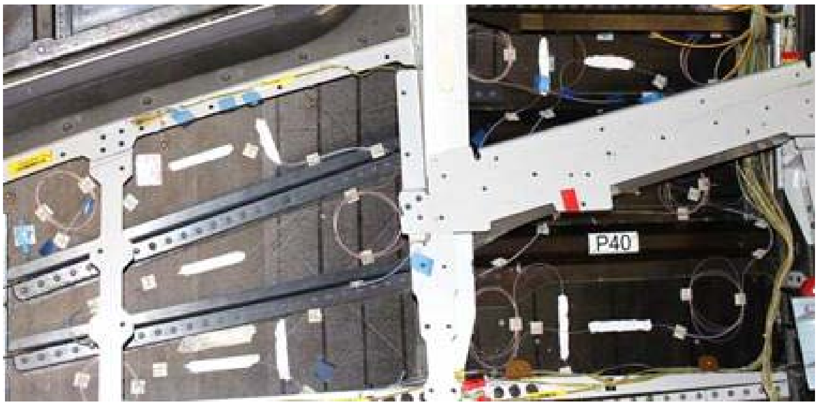
The test performed in 2016 verified that the impact damage on the actual aircraft structure can be detected. The test also verified the durability of the sensor network.

4.1 Durability of the sensor network installation

The durability of the sensor network installed on the fatigue test article was verified by inspection of the installed sensor network which experienced more than a year of fatigue loading.

Figure 4 shows the two sensor installation locations. Three sensor lines (built of multiple FBG sensors and connecting optical fiber cables) were installed in two locations near the door of the fuselage structure. A sensor line was installed in Location 1, which is below the passenger door and is of a typical aircraft fuselage configuration. Two more sensor lines were installed in Location 2, which is below the bulk cargo door and surrounded by large metal reinforcements.

(a) Location 1



(b) Location 2

Figure 4: Sensor installation locations

One purpose of the verification test in 2016 is to verify that the sensing lines are not damaged physically or functionally by the fatigue loading.

From the visual and optical response inspections, no damage or degradation were found in the sensing line in Location 1. In Location 2, two fiber breaks were found, which were apparently due to handling and not due to the fatigue loading. The sensing lines in Location 2 were repaired to bypass the two fiber breaks.

Figure 5 shows the test measurement overview.

Figure 6 shows the example of the sensing line installation.

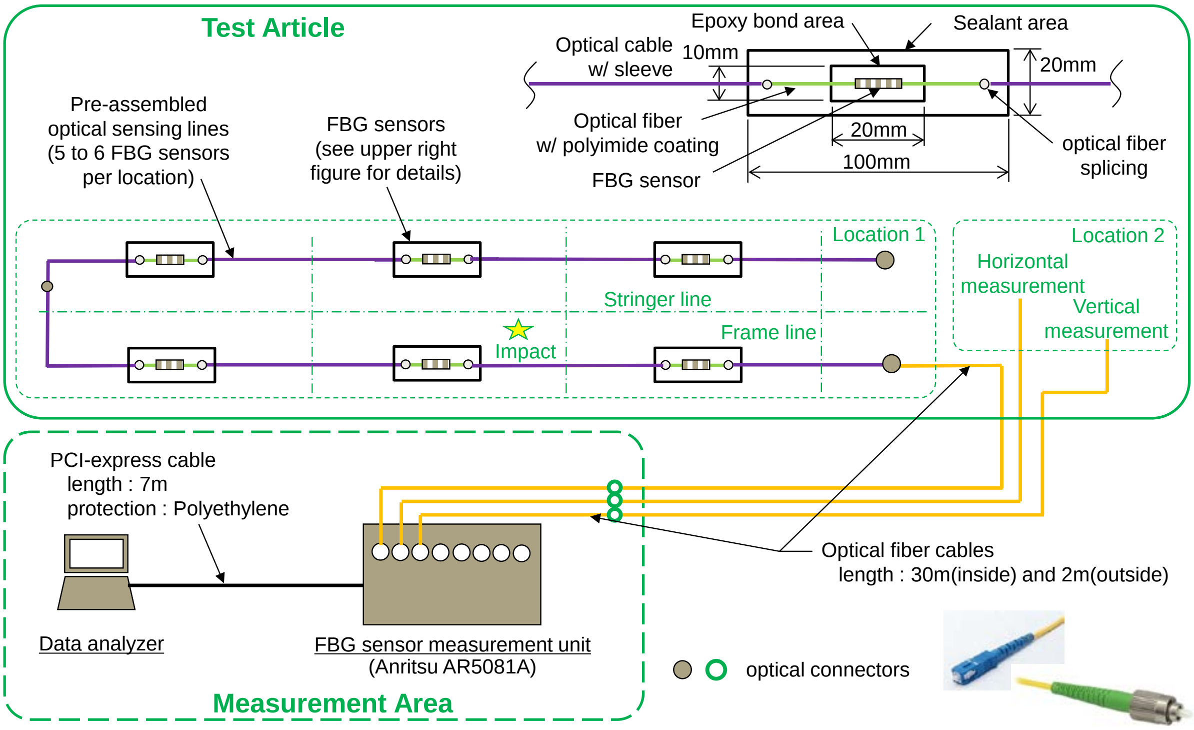


Figure 5: Test measurement overview

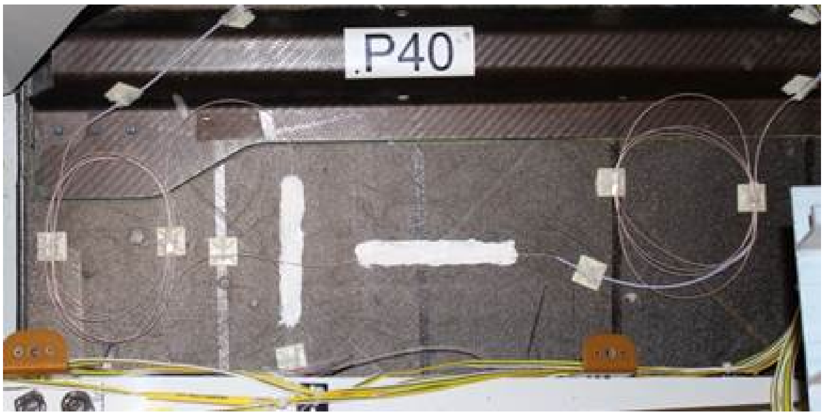


Figure 6: Example of the sensing line installation

4.2 Evaluation of the detection reliability on the actual aircraft structure

In the damage detection test, 28 impacts at three levels of impact, namely the non-damage, BVID (Barely Visible Impact Damage) and VID (Visible Impact Damage) impacts were applied from the outside using the Airbus mobile impactor.

Three sensing lines at two different locations were measured at the same time, to imitate the actual IDDS application using multiple sensing lines. The strain responses were measured at the sampling rate of 100 kHz using the FBG measurement unit AR5081A by Anritsu.

In Location 1, which represents typical composite fuselage configuration, and in Location 2, which represents highly reinforced configuration, the impacts were clearly detected using the FBG sensors in the same location. On the other hand, the FBG sensors reasonably away from the impact location did not show erroneous strain response that could lead to false positive error. The example of the impact strain response measurement is shown in Figure 7.

In both Locations 1 and 2, the FBG sensors aligned in the stringer directions provided sufficient strain response for the impact detection. FBG sensors aligned in the frame directions were more sensitive to the strain response, demonstrating that the FBG sensor direction is another parameter that can be selected based on the structural configuration.
In all cases, the strain response was clearly detectable even for the non-damage impact level, which was much lower than the BVID or VID energy levels.

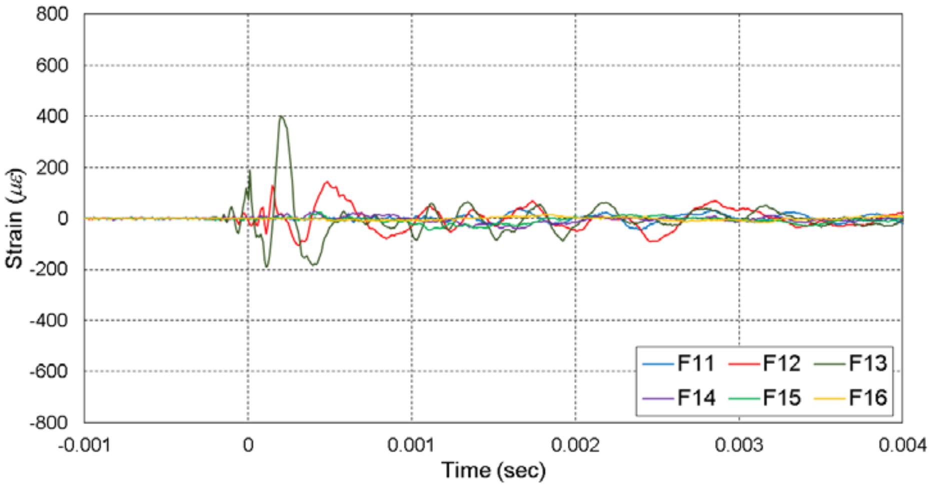


Figure 7: Example of the impact strain response measurement
(at impact location I41, below the BVID level)

Impact locations were detected using the IDDS software by analyzing the impact strain response measurements. Figure 8 shows the actual impact location and that predicted by the IDDS software.

The conclusion of the impact detection test is that the IDDS can detect impact on the actual aircraft structure in much the same manner as the numerous laboratory tests performed up-to-date. Also note that the 28 impact tests were detected 100% with no false negative and no false positive errors.

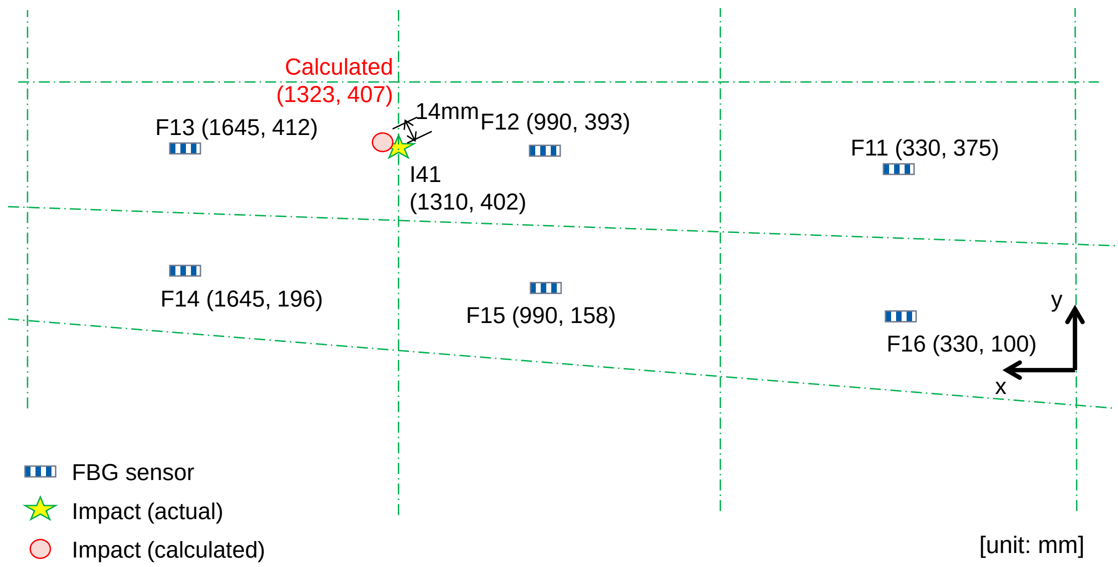


Figure 8: Actual and predicted impact locations
(at impact location I41, below the BVID level)

4.3 Durability evaluation of the sensors subject to fatigue load

The durability of the sensor network subject to fatigue loading, imitating the actual airframe load, was demonstrated during the impact detection test and through the detailed measurement of the signal changes before and after more than a year of fatigue loading.

Although two sensors were repaired before the tests, the remaining sensors functioned flawlessly in detecting the impacts. Also, the sensors reasonably away from the impact did not measure erroneous signals.

To evaluate the loss of measurement accuracy due to fatigue, the individual sensor's center wavelengths before and after the fatigue loading were compared. Table 2 shows the center wavelength of the FBG sensors in Location 1. The change in the center wavelength is negligible after more than a year of fatigue loading. Note that the fatigue test was performed in a controlled environment and the effect of temperature can be assumed to be minimal.

Table 2: Center wavelength change after more than one year of fatigue test

Sensor ID	Center wavelength [nm]		Change in wavelength [nm]
	year 2015	year 2016	year 2016 - year 2015
F11	1532.2	1532.2	-0.06
F12	1539.9	1539.9	0.06
F13	1552.0	1551.9	-0.09
F14	1544.0	1544.0	-0.01
F15	1555.8	1555.9	0.02
F16	1564.0	1564.0	-0.01

5 LIFE CYCLE MONITORING TEST

The authors have studied the life cycle monitoring concept [3] in which the same sensor network is used to monitor the composite part during the fabrication phase in addition to the operation phase. This is possible only with the optical fiber sensors that can withstand the high temperature and pressure of the composite fabrication. Another benefit of the optical fiber sensor is that it can measure the minute strain changes over a course of several decades, as opposed to the electrical strain gages which can only measure relative strain changes while it is activated.

Life cycle monitoring concept was evaluated using the foam core sandwich structure imitating a major structural element. Following tests, spanning from manufacturing to operation, were performed.

(1) Cure monitoring within the autoclave
(2) Impact detection during in-plane and out-of-plane cyclic loads
(3) Crack propagation detection

5.1 Cure monitoring within the autoclave

The foam core sandwich panel before cure is shown in Figure 9. In this specimen, 16 FBG sensors were embedded between the CFRP face sheets and the foam core.

Figure 10 shows the example measurement during the cure process monitoring. The strain and temperature changes during the cure process were monitored using the FBG sensors. Local cure condition can be evaluated by the FBG sensors embedded in each critical location of the specimen. Residual stress can also be estimated using these measurements.

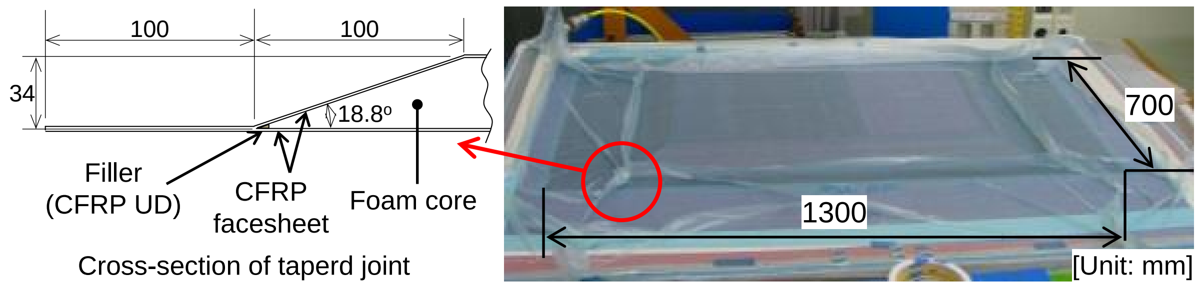


Figure 9: Foam core sandwich panel before cure

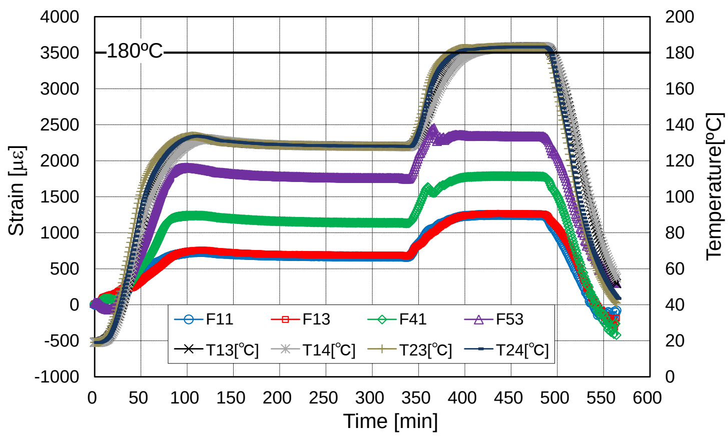


Figure 10: Example of the cure process monitoring

5.2 Impact detection during in-plane and out-of-plane cyclic loads

The impact test setup is shown in Figure 11. Impacts were applied during the in-plane and out-of-plane fatigue loading.

Figure 12 shows the impact response during the fatigue loading. Impacts during the fatigue loading can be detected by the same FBG sensors used in the cure process monitoring. Strain response due to impact and those due to external loading were easily separable using the frequency filter.

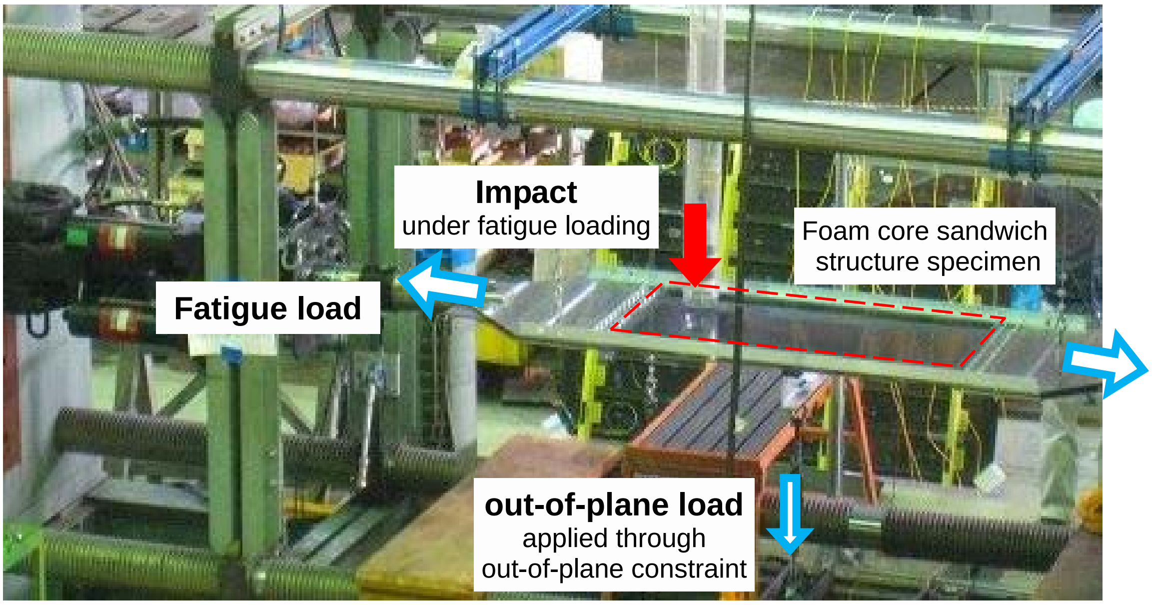


Figure 11: Impact test setup

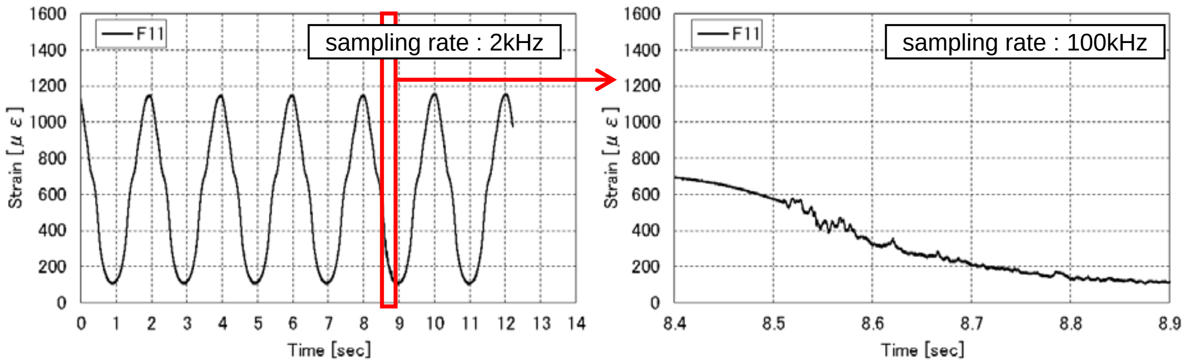


Figure 12: Example of the impact response during fatigue loading

5.3 Crack propagation detection

Figure 13 shows the strain measurement at the unloaded condition performed as the crack propagation monitoring. Impact damages were introduced to the specimen to propagate the internal crack in the core and in the core and facesheet interface. The change of residual strain was observed when the core crack propagated near the FBG sensors. Therefore, FBG sensors can be used to detect internal crack propagation at the unloaded condition.

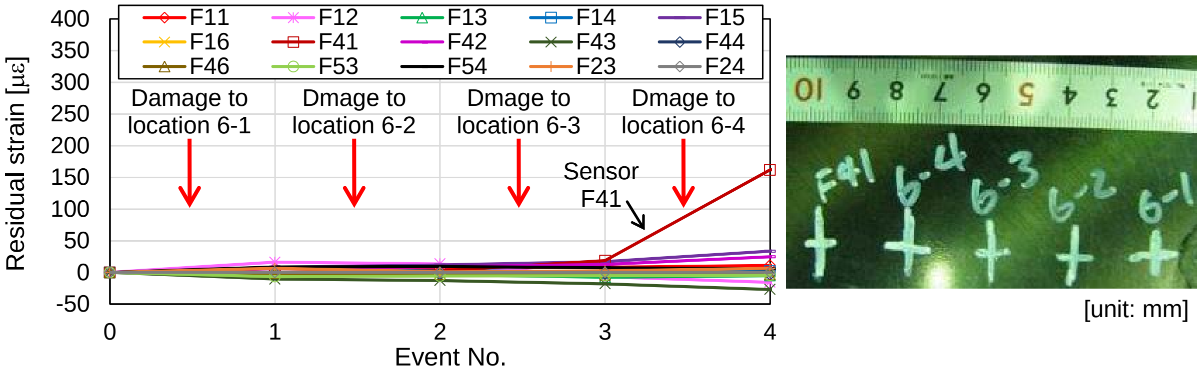


Figure 13: Example of the crack propagation monitoring test

6 CONCLUSIONS

The achievement on the development of the Impact Damage Detection System (IDDS) was summarized in this paper.

The IDDS was subject to wide range of environmental durability tests and also verified through the numerous tests including the full-scale SHM demonstration test in collaboration with Airbus. The test demonstrated the durability of the sensing lines and the impact detection capabilities of the IDDS.

Detection of the blunt object impact, also an important potential application for the IDDS, was tested, and the effective detection method was defined.

The life cycle monitoring concept was verified by using the foam core sandwich panel specimen with the embedded sensors. The test demonstrated that the same set of sensors can be used for cure process monitoring, impact damage detection and crack propagation detection.

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