Investigation of the Probability of Detection of Our SHM System

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ABSTRACT

We have been developing a structural health monitoring (SHM) system for evaluating structure integrity in aircraft composite structures De-bonding in the bondline, which is a kind of the most critical damages in composite structures, can be diagnosed by evaluating changes in Lamb waves generated and detected by our hybrid sensing system. In our sensing system, a macro fiber composite (MFC), which is one of the piezoelectric devices, is used as an actuator to generate Lamb waves, and a fiber Bragg grating (FBG) optical fiber sensor is used as a sensor to detect the propagating Lamb waves.

In order to achieve the implementation of our SHM system to commercial aircraft, we have been investigating a lot of issues, such as probability of detection (PoD), environmental influences, installability of the SHM system, system compatibility to aircraftystem and structures, and so on. PoD assessment is one of the indispensable subjects in order to apply a SHM technique as one of the non-destructive inspections (NDI) for actual commercial aircraft. And both of the durability of the hybrid sensor systems and the influences of environmental conditions on detected Lamb waves, which affect the precise diagnosis of structural integrity, should be investigated. Moreover, consideration of the installability and compatibility of the SHM systemto aircraft, in which the academic investigations are not included so much unfortunately, are absolutely required to achieve commercial applications.

In this paper, we propose an appropriate assessment procedure of PoD of SHM technologies that can diagnose damage initiation and its growths, being different from the conventional NDI, such as ultrasonic inspection.

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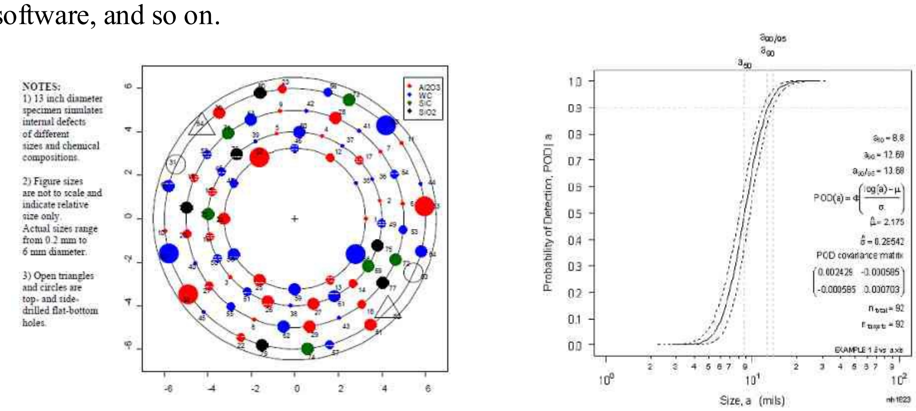
INTRODUCTION

SHM techniques have been widely investigating for some decades because they are candidate techniques that can contribute to improve safety and reliability and to reduce life cycle costs, of a lot of industrial products. In order to achieve implementation of SHM techniques to commercial aircrafts, a lot of subjects, probability of detection (PoD), installability of the SHM system, SHM system compatibility, environmental influences and durability, certification by regulatory agencies, and so on, must be considered and solved. Especially, PoD assessment is one of the most crucial topics in the aircraft industry, in which safety and reliability are the first priority.

Regarding conventional NDI procedures for aircraft structures, such as ultrasonic inspection and eddy current inspection, we have to comply with a guideline "the NDI technique can demonstrate with a 90 percent probability and a 95 percent confidence level" in JSSG-2006 [1] in order to fulfil the required reliability. Therefore, we have to assess whether a NDI procedure can fulfil the abovementioned requirement or not in its development phase. Commonly the PoD assessments for aircraft are carried out referring to the handbook, MIL-HDBK-1823 [2]. Moreover, in order to ensure safety and reliability and to minimize human errors, personnel who inspect the structural integrity of aircraft by a NDI procedure must be certified in accordance with the specification, NAS 410[3].

In the PoD assessment of conventional NDIs, we can use target specimens in which flaw sizes are pre-determined, PoD(a) curves, shown in figure 1 [2], mh 1823 POD software, and so on.



(a) UT internal target specimen (b) Example of PoD(a) curve

Figure 1. Ultrasonic testing internal target specimen.

SHM techniques can be considered as next generation nondestructive evaluation techniques and one of the great advantages of SHM techniques is to monitor and diagnose initiation and growths of damage by permanently installed sensors automatically, which is absolutely different from conventional NDI techniques. Because evaluation targets of SHM techniques are not the same as those of conventional NDI, we have to consider an appropriate procedure to assess the PoD of SHM techniques, referring to abovementioned manner. In this report, we proposed and discussed a novel assessment procedure for PoD of SHM systems.

DESCRIPTION OF OUR SHM TECHNIQUE

One of the monitoring targets of our SHM system is de-bonding in bondlines of composite structures. Our SHM system, shown in figure 2, can measure Lamb waves propagating into a CFRP structure from a MFC actuator to a FBG sensor.And our SHM system can evaluate the de-bonding length by analyzing a difference of time of flight (ToF) of a certain Lamb wave mode between intact state and each de-bonding growth state.

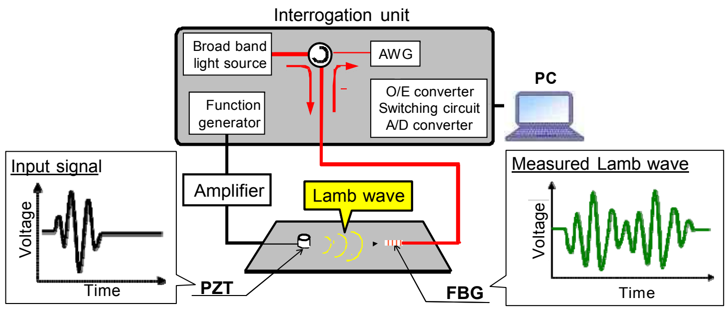


Figure 2. Overview of our SHM system.

PROPOSED EVALUATION PROCEDURE

Conventional PoD assessment procedure,described in MIL-HDBK-1823, can't be applied to our SHM system. There are two major reasons that we can't. One is that the procedure does not consider the cases in which a damage size changes gradually. The other is that it is very difficult or very time-consuming to control de-bonding length in CFRP bondlines. Consequently, we propose an appropriate assessment procedure of our SHM system as follows.

First, data collection is carried out in order to assess PoD of our SHM system. Basically, tests for data collection should be carried out taking the actual in-service situations into consideration. Therefore, initiation and growths of de-bonding of bondlines in CFRP structures are introduced to the test specimens. However, evaluations herein are the first step to develop a novel assessment procedure, fundamental test specimens were tested in the laboratory conditions.

Second, the relationship between the responses of our SHM system and the actual de-bonding lengths is obtained from the collected data.

Third, threshold values are determined at the entire de-bonding length using the equation (1) [4] in order to consider the 90 percent detectablity with the 95 percent confidence. In the equation (1), b_{th} is threshold value of de-bonding length derived with our SHM system, μ and σ are average and standard deviation of b at actual de-bonding length "a_i", respectively. k_B corresponds to one-sided B-basis tolerance limit factor.

$$b_{th} = \mu +/- k_B\sigma \qquad (1)$$

Because one-sided B-basis tolerance limit corresponds to "90 percent detectability with the 95 percent confidence", candidate de-bonding lengths between upper and lower threshold values at a measured response of our SHM system are identified. Because the interval between upper and lower threshold values at a measured response corresponds to the scatter of our SHM system and the interval includes the influence of B-basis tolerance factor, the interval might become smaller when we carry out a larger numbers of tests. In case of actual use of our SHM system, we have to make our system avoid the false-negative indication. Therefore, lower threshold value is selected as actual de-bonding length by our SHM system. Figure 3 describes the outline of the process in which we determine the threshold values and actual de-bonding length with scatter of our SHM system.

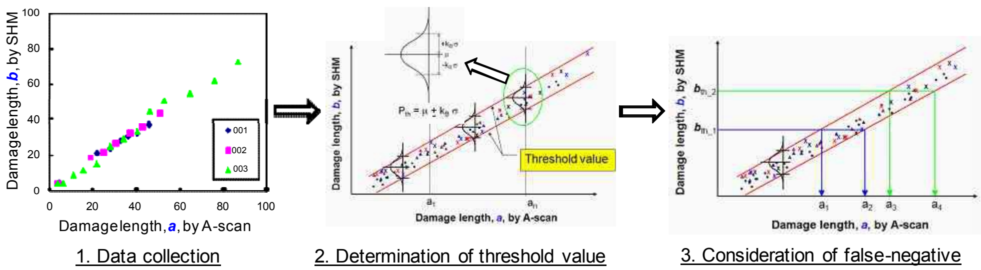


Figure 3. Outline of determination of threshold values and actual debonding length.

After finishing abovementioned processes, in order to assess the $PoD_{90/95}$ of our SHM system, we have to carry out the test by the same procedure. If we can verify that our SHM system can diagnose actual de-bonding length successfully with the 29 test specimens continuously, our SHM system is proven to fulfil the requirement, “the NDI technique can demonstrate with a 90 percent probability and a 95 percent confidence level”.

TEST SPECIMENS FOR PROPOSED PROCEDURE

According to MIL-HDBK-1823, although we have to consider all cases where our SHM system might encounter, such as different environmental conditions, different structures, and so on for the PoD assessment, we conducted several tests as a preliminary evaluation of the proposing procedure using coupon specimens in laboratory conditions. Figure 4 shows the coupon specimen, which simulates the CFRP bonded structures such as a part of skin-stringer stiffened panels.

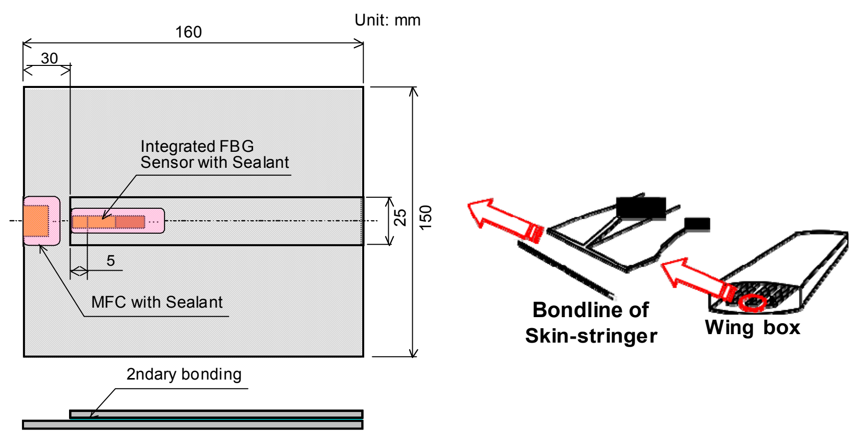


Figure 4. Schema of a fundamental coupon specimen.

A quasi-isotropic CFRP panel was manufactured in autoclave process. A narrow panel, which simulates a stringer, and a wide panel, which simulates skin panel, were cut from the large panel. Then the two types of panel were bonded in secondary bonding process. After that, a FBG optical fibre sensor and a MFC actuator were bonded on the coupon specimen with epoxy type adhesive. In order to simulate the actual use of the sensor and actuator, polysulfide type sealant was applied to the sensor and actuator.

EVALUATION PROCEDURE

In order to collect the data to assess the PoD of our SHM system, de-bonding was introduced to the bondline by saw cut or wedge insertion artificially. Each growth length of the artificial de-bonding is approximately several mm. Growth of the de-bonding was carried out several times in one specimen. Figure 5 described the test procedure. Before introducing de-bonding and after each growth of de-bonding, measurement of Lamb waves and identification of each de-bonding area were carried out by our SHM system and A-scan, which is one of the conventional NDE techniques, respectively. The de-bonding length analyzed by our SHM system is described as "a-hat" in this report, which corresponds to the measured response of a NDE system in MIL-HDBK-1823. On the other hand, the identification results by the A-scan were the standard data, which corresponds to "a", actual flaw size in MIL-HDBK-1823.

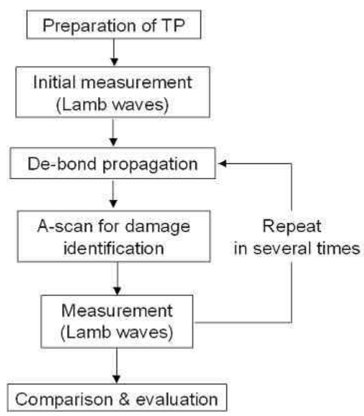


Figure 5. Test sequence in one specimen.

A lot of data will be collected by the above procedure to carry out the reliable PoD assessment and then we will assess and verify the $PoD_{90/95}$ of our SHM system. Unfortunately, we have finished only 5 specimens for determination of the threshold values. Therefore, we discuss abovementioned process herein on the way to accomplishment of our PoD assessment.

RESULTS AND DISCUSSIONS

Figure 6 shows the relationship between de-bonding length identified by A-scan and measured response by our SHM system and all the collected data of 5 specimens were plotted in the same symbol on the graph. The relationship exhibits a good correlation except for the de-bonding length by A-scan between 10 and 20 mm. We have been investigating the detection capability of our SHM system and will continue by collecting and evaluating a lot of data with various types of specimens more precisely.

Because the collected data are so small that we can't apply the proposing assessment procedure in the current situation, we tried to determine the threshold values of our PoD assessment by the similar analysis procedure with the abovementioned procedure.

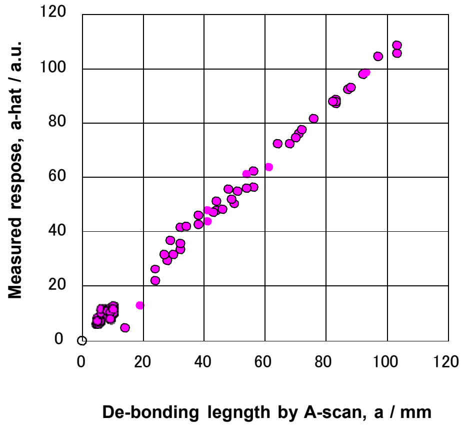


Figure 6. relationships between measured response by SHM and de-bonding length by A-scan.

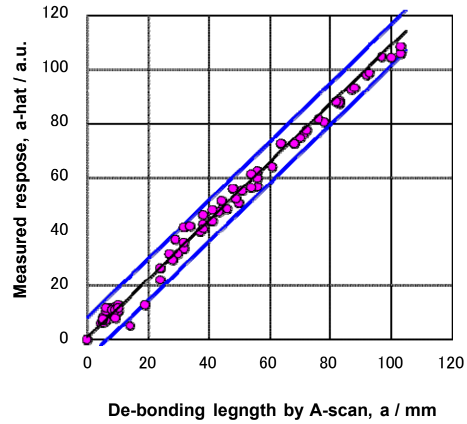


Figure 7. Relationships with regression curve and threshold values.

First, the least squares method was applied to the collected data to obtain the standard data, which are used as the average data for equation (1). A standard deviation was calculated by the equation (2).

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Xi - Xa)^2} \qquad \text{————} \quad (2)$$

In the equation (2), *X*i corresponds to the plotted data in figure 6 and *X*a corresponds to the values that are calculated with the regression curve at each de-bonding length. There are 79 measured points in figure 6. Consequently, k_B in equation (1) is 1.564 according to MIL-HDBK-17-1F. Threshold values were derived the calculated standard deviation and k_B in accordance with equation (1). The regression curve and calculated threshold curves were shown in figure 7. Because the standard deviation was derived from all collected data without any consideration, derived threshold curves don't suit with our SHM technique. It is verified that the scatter in our SHM technique varies with actual de-bonding length. Therefore, we should assess the PoD of our SHM techniqueby assessing the PoD separately in each appropriate interval in thede-bonding length, like the procedure described in previous section.

CONCLUSIONS

Because conventional PoD assessment procedure,described in MIL-HDBK-1823, can't be applied to our SHM system, we propose an appropriate assessment procedure of our SHM system. In the proposing assessment procedure, the threshold values of our SHM technique, in which the scatter of our technique is considered, are determined first. After that, we check the $PoD_{90/95}$ of our SHM technique by statistical method, 29/29 tests method with next 29 specimens.

Unfortunately, we don't have sufficient data to determine and evaluate the threshold values of our proposing procedure. Therefore, we will carry out data collection with a lot of test specimens described in previous section. After that, we will try to assess the PoD of our SHM technique by a statistical method in our future works.

AKNOWLEDGEMENT

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