Key Engineering Materials Vols. 353-358 (2007) pp. 1427-1430
online at http://www.scientific.net
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Online available since 2007/09/10

Monitoring of Delamination of the CFRP Beam by the Smart Structure System Using the SI-F Method

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Keywords: Structural Health Monitoring; Smart Structure; Delamination and SI-F Method.

Abstract. The structure with the sensor and the actuator is called *Smart Structure*. Installation of the sensor and the actuator to the structure enables the automatic damage detection. In this paper, a novel damage detection method called "*SI-F method*" is applied to the Smart Structure to detect the delamination in the CFRP beam. The artificial delamination in the CFRP is introduced by the out-of-plane bending. CFRP beam will be exited by the PZT actuator, and the strain of the surface will be measured by the strain gauge. As the result, the delamination is successfully detected by varying the condition of the excitation.

Introduction

Previously, the integrity of the structure involving the power plant or the aircraft was estimated by in service inspection (ISI) using the visual inspection or the kinds of nondestructive test, such as CT, PT, etc. However, the cost of the ISI is remarkably high and those structures must be suspended during the inspection. Moreover, due to the highly qualified personnel they require, these inspections might not be possible immediately after a major event such as earthquake. Therefore, in recent years, global attention is attracted to the structural health monitoring (SHM) in various engineering fields. SHM is the technology to detect the damage in the structure on real time. SHM will be usually performed only with the sensor installed to the structure. By adding the actuator to the structure, it is possible to detect the damage in the structure automatically and to raise the accuracy of the damage detection. The structure with the sensor and the actuator called the Smart Structure. The smart structure system is able to utilize not only to the new structures but also to the aged structure.

Although numerous researchers had developed the damage detection algorithm ever, previous damage detection algorithms are not able to apply to the aged structure, since those techniques require the construction of the complex physical model, or the experimental data from the fracture test. A reasonable damage detection algorithm called *SI-F method*, which detects the damage without using either physical model or experimental data, was suggested by Iwasaki et al, in 2002[1]. The SI-F method is suitable for detection of the delamination of the laminated CFRP plate because this method doesn't need the modeling and/or fracture test.

In the present study, the SI-F method is applied to the smart structure. PZT actuator and the strain gauges are attached on the surface of the CFRP beam. And presented system is applied to detect the delamination of the specimen in the laboratory environment to demonstrate its feasibility. The artificial delamination is introduced by out-of-plane bending, and occurrence of the delamination is detected by the change of the surface strain distribution.

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Procedure of the Damage detection using the SI-F method

By the SI-F method, damages are detected by judging the statistical difference of data of intact state and present state. The difference between the normal data and present data will be judged by the difference of the correlation among the output of the sensors equipped. The correlation among the sensor output will be identified by the response surface methodology. The normal response surface (NRS) will be obtained from data acquired in intact state, and the detection response surface (DRS) will be obtained from data acquired in present state. By testing the similarity between the NRS and the DRS using the F-test, it is possible to estimate the damage occurrence in the structure. If the hypothesis of the similarity were rejected, damage would be detected. Otherwise, integrity of the structure would be proved.

Response surface methodology. The response surface methodology (RSM) is employed for process optimization in the field of quality engineering[2]. The response surface is the approximation function that expresses the relationship between the response and the predictors as follows:

$$y = f(x_1, x_2, \cdots, x_p) + \varepsilon \tag{1}$$

where, y is a response, x_i is predictors, ε is regression error and p is the degree of freedom of the response surface. In general, 1st or 2nd degree polynomial is used for response surface. In the SI-F method, Response surface is applied to identify the correlation among sensor output. By using the response surface, it is possible to detect the damage of the structure of interest accurately regardless of the change of the boundary condition.

F test. The similarity of the NRS and the DRS is tested by the F test that is generally used for test of the similarity of the two distributions. By assuming the regression error of each response surface is independent, and has the same variance, the test statistic F_0 is defined as follows:

$$F_0 = \frac{SSE_0 - (SSE_1 + SSE_2)}{(SSE_1 + SSE_2)} \frac{n-2p}{p} \tag{2}$$

where SSE describes the residual sum of squares of the response surface. Subscript 0 means the response surface with all data. Subscript 1 and 2 mean the NRS and DRS respectively. If two response surfaces are similar, the test statistic F_0 follows the theoretical F-distribution of degree of freedom (p,n-2p). Thus critical limit for the hypothesis of similarity is defined as follows:

$$F_0 > F^{\alpha}{}_{p,n-2p} \tag{3}$$

Delamination detection of the CFRP beam

Specimen and experimental setup. The prepreg used to produce the specimen is PYROFIL #380 produced by Mitsubishi Rayon Co. ltd. The laminates with a staking sequence of $[0/90]_s$ were fabricated by the autoclave process. The curing temperature is 403[K], the curing time was 90[min] and the pressure was 0.7[MPa]. The thickness of the specimen is about 1.0[mm]. Figure 1 shows that the experimental setup.

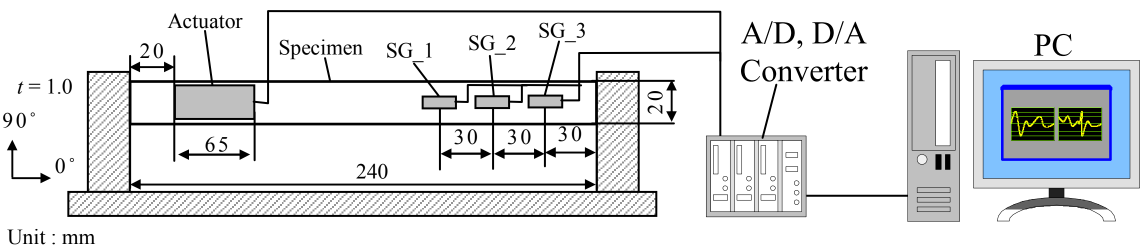


Fig.1 Experimental setup

The CFRP beam was fixed both ends, the bimorph type transducer was attached to one end, and conventional strain gauges were attached to the other end. Generally, when the stiffness of the node decreased, shape of the deformation is changed a lot. Since the position of node and loop is shifted by changing the vibration mode using the actuator, it will be possible to improve the damage detection accuracy over each location of the damage by exciting the specimen under two or more vibration modes. The artificial delamination is introduced by the out-of-plane bending at the center of CFRP beam. In the present study, the length of the delamination is 15mm.

Experimental condition. The experimental conditions are listed in Table1. The 1st and 2nd natural frequency of the specimen is 151[Hz] and 311[Hz] respectively. Therefore the excitation frequencies are determined as resonance frequency at 1st and 2nd mode as listed in table 1. Data is acquired 3 seconds at each excitation conditions after completing the transient response.

Table 1 Experimental condition

Wave type	Sine wave
Excitation frequency f_e [Hz]	150, 310
Sampling rate f_s [Hz]	10000

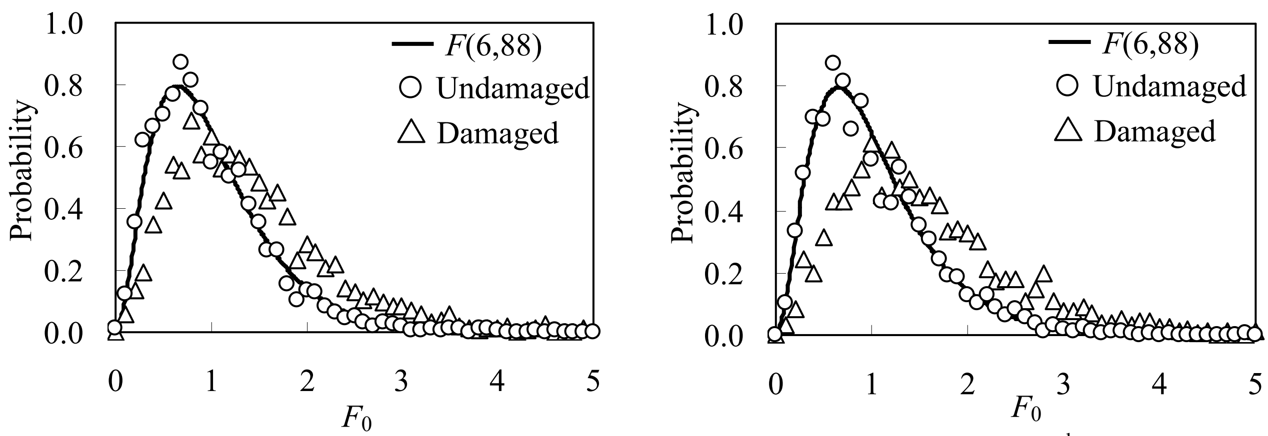
Procedure of the signal processing. The specification of the response surface is listed in Table 2. In this case, the probability distribution of F_0 in the intact state may follow $F(6,88)$. Each measured signals are filtered with the band pass filter. The range of the band pass frequency is $f_e \pm 50$ [Hz]. The NRS and the DRS are derived using the 50 of data sets arbitrary extracted from each data group. The similarity test is repeated 2000 times to obtain the experimental probability distribution of F_0.

Table 2 Specification of the response surface

Order	2
Degree of freedom p	6
Number of data n	100

Results and discussion

Probability distribution of F_0. Figure 2 shows the experimental probability distribution of F_0 in the undamaged state and the damaged state under each excitation conditions and the theoretical probability distribution of $F(6,88)$. As shown in Fig.2, each experimental distribution of undamaged state follows the theoretical probability distribution, and each experimental distribution of damaged state deviated from the theoretical probability distribution.



(a) f_e = 150Hz (1st resonance) (b) f_e = 310Hz (2nd resonance)

Fig.2 Probability distribution of F_0

Accuracy of the damage detection. Although both of experimental distributions of damaged state deviated from the theoretical distribution, the degree of deviation is not constant as shown in Fig.2. In order to quantify the degree of deviation, average of experimental distribution was calculated as the indicator of the accuracy of damage detection. Fig.3 shows the average of experimental distribution of F_0 and the theoretical average of $F(6,88)$. As shown in Fig.3, the accuracy of the damage detection under the secondary resonance mode is higher than the accuracy of the damage detection under the primary resonance mode. It can be explained from the mode of vibration. In this case, the delamination is located on the center of specimen, and in the secondary resonance mode, the node would be also located on the center of the specimen. Therefore, the shape of the deformation in the secondary resonance mode was changed a lot due to the reduction of the stiffness at the node.

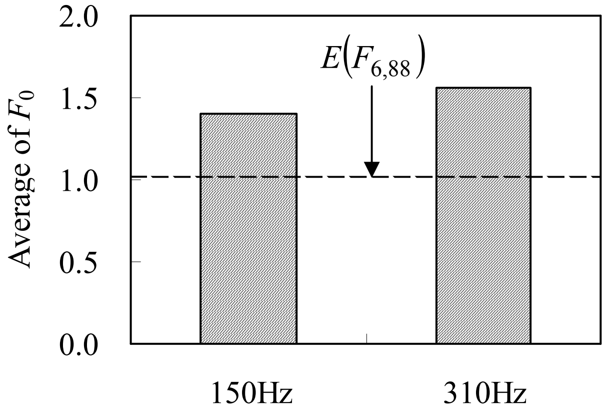


Fig.3 Average of the probability distribution

Conclusion

Utilization of the SI-F method to smart structure system enables automatic damage detection without physical modeling and/or fracture test. As an example of the proposed system, the delamination detection of the CFRP beam was carried out. Results obtained are as follows.

(1) By adding the excitation using actuator, it is possible to detect the delamination of the CFRP located on far from sensor.

(2) Location of the node and the loop of the beam shifts due to changing the vibration mode, it is possible to detect the damage accurately by exciting the structure in the optimum condition over each position of the damage.

References

[1] A.Iwasaki, A.Todoroki, T.Sugiya, S.Izumi, S.Sakai, Unsupervised statistical damage diagnosis for structural health monitoring of existing civil structures, Smart Mater. Struct. 14 (2005), pp.154-161

[2] Raymond M. Myers, Douglas C. Montgomery: Response Surface Methodology 2nd Edition (Wiley-Interscience Publications, United States of America 2002)