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Statistical Damage Detection of Laminated CFRP Beam Using Electrical Resistance Change Method

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Abstract. Statistical diagnosis using electrical resistance changes is performed to detect a delamination crack in a CFRP beam. This method enables to reduce data required for damage identification. First, a new measuring method of multiple electrical resistance changes is proposed to perform statistical diagnosis. The proposed method measures electrical resistance changes of multiple segments in a CFRP beam although electrical interference must be considered when multiple voltages are charged at once. Next, statistical diagnosis is performed on loading to the CFRP beam. A delamination crack is detected by the change of relative relationship between multiple electrical resistance changes due to damage occurring. As a result, the monitored states of the CFRP beam are diagnosed exactly by the proposed damage detection system.

Introduction

A damage detection system of CFRP structures is demanded to improve reliability of them. The damage detection system is mainly divided into two functions: data sensing and damage identification from the data. As one of the data sensing techniques, author's group has proven the effectiveness of electrical resistance change method (ERCM) [1-3]. In the ERCM, carbon fibers of the CFRP composites are used as sensors by making use of their electrical conductivity. Electrical resistance changes when the CFRP structure deforms as well as damages occur. The electrical resistance changes are measured by means of making electrodes on the surface of CFRP laminates without expensive sensors. Generally, ERCM requires a large number of experiments or finite-element computations to obtain the relationship between the measured electrical resistance changes and damages. To reduce the required cost for damage identification, statistical diagnosis is proposed here. In the statistical diagnosis, multiple sensors are attached on a target structure and relationship between the outputs from the sensors is obtained. Damages are detected from the change of the relationship due to damage occurrence in the structure. Statistical diagnosis requires data in intact state of the target structure, and it judges automatically occurrence of damage with statistical tools [4]. Our research group has proven the effectiveness of the statistical diagnosis by means of applications of a CFRP beam and of a ventilation jet fan in a tunnel [5,6]. In the present study, the statistical diagnosis is applied using the ERCM to reduce the required experimental cost. Since the statistical diagnosis requires relationship between multiple outputs measured simultaneously, a new method is developed to measure electrical resistance changes of multiple segments. After this, the statistical diagnosis is performed to detect a delamination crack in CFRP beam.

Electrical Resistance Change Method

Schema of measuring method. In the present study, a target structure is a cross-ply laminated CFRP beam type specimen. Electrodes are made on the surface of a CFRP laminate to measure electrical resistance. Since the electrical resistance change due to deformation and damage is small, a bridge circuit and an amplifier is used to measure the electrical resistance change. The electrical resistance between two electrodes constitutes one of four resistors of the bridge circuit. To measure multiple electrical resistances simultaneously, electric current interference between adjacent circuits must be reduced. As shown in Fig. 1(a), the electric currents between the GND electrodes interfere when we use a serial connection of each circuit. The electrical currents of the bridge B and the bridge C interfere with each other in those segments. To solve the problem of electrical interference, a new connection method is proposed. As shown in Fig. 1 (b), each segment is put between two GND electrodes.

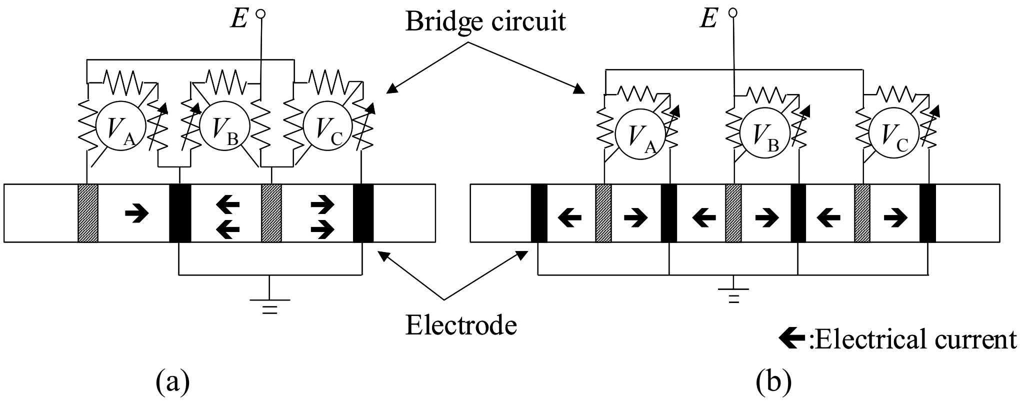

Fig.1 Measurement method of multiple electrical resistance changes

Experiments and results. To verify the effectiveness of the proposed measurement method, electrical resistance changes due to elastic deformation are measured. Specimen configuration is shown in Fig. 2. Stacking sequence of the CFRP laminates is $[0_2/90_2]$s. Seven electrodes are made on the single surface of a CFRP beam by means of electrical copper plating, and the specimen is connected to three bridge circuits as shown in Fig. 1(b). The beam type specimen is gripped at one end like a cantilever. The bending load is applied to the free end of the beam and the electrical resistance changes due to bending strain changes are measured. To confirm the effectiveness of the new method, electrical resistance changes are measured simultaneously using the proposed method. After the measurements, an electrical resistance change of a segment B is measured and compared to the result simultaneously measured. The comparison results are shown in Fig. 3. The two results fit with each other. These results show that there is no interference of electrical currents in the proposed method.

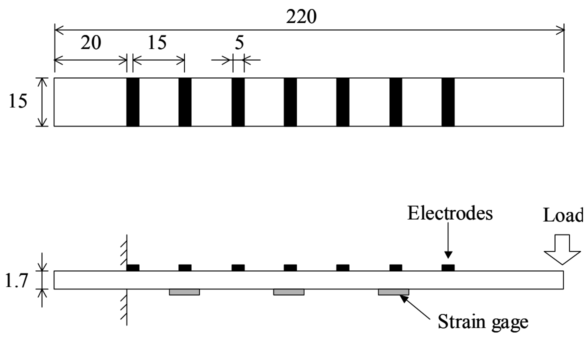

Fig.2 Specimen configuration

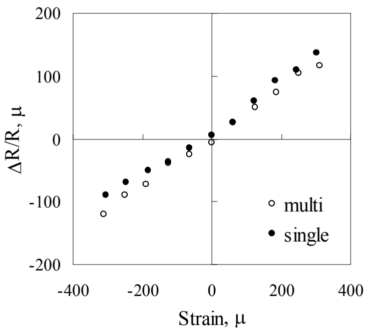

Fig.3 Comparison of multiple and single

Statistical diagnosis

Outline. The damage detection procedure has two steps: a training step and a monitoring step. At the training step, data are monitored in the initial intact state structure, and relationships are made with response surfaces. This response surface made from the intact state is named an initial response surface. After making the initial response surfaces, a monitoring step starts. At the monitoring step, the sampled data of the target structure are also related with each other using a response surface, the response surface is named monitored response surfaces. Then the monitored response surface is compared with the initial response surface by means of F-test. If the similarity of the two response surfaces is accepted by the F-test, it means the monitored state is the same as the intact state. If the similarity is rejected, the monitored state is different from the initial state, and the target structure is regarded as damaged.

Evaluation of similarity. The similarity of the two response surfaces is evaluated by F-statistics. F-statistics is calculated from the residual sum of squares of response surfaces as following equation.

$$F_0 = \frac{SSE_0 - (SSE_1 + SSE_2)}{SSE_1 + SSE_2} \times \frac{n - 2p}{p} \tag{1}$$

where, *SSE* means the residual sum of squares of a response; *SSE* with subscript 1 and 2 mean *SSE* of the initial response surface and monitored response surface, respectively. *SSE* with subscript 0 means *SSE* of the response surface with all data. n and p are parameters of response surface. If the two response surfaces are similar with each other, probability distribution of F_0 value follows $F(p,n\text{-}2p)$. To improve the reliability of similarity test, F_0 value is calculated many times and average of F_0 is evaluated. The similarity is accepted when the average of F_0 lies in following range.

$$E(F_0) - z\frac{\sigma(F_0)}{\sqrt{r}} < \overline{F}_0 < E(F_0) + z\frac{\sigma(F_0)}{\sqrt{r}} \tag{2}$$

where, $E(F_0)$, $\sigma(F_0)$, and r are expectation of F_0, a standard variation of F_0 and repeated times, respectively. z is limit level determined from level of significance, which is set to 5% in this study.

Results of diagnosis. The statistical diagnosis is performed using the data of the electrical resistance changes here. For the training step, the electrical resistance changes are measured with bending loading in the initial intact state. 3000 sets of data are obtained; sampling frequency is 100Hz and sampling time is 30s. The response surface is created using the 25 sets of data selected from the 2000 sets randomly. In the present study, response surface is a quadratic polynomial shown as following.

$$x_B = \beta_0 + \beta_1 x_A + \beta_2 x_C + \beta_3 {x_A}^2 + \beta_4 {x_C}^2 + \beta_5 x_A x_C \tag{3}$$

After this, the data are measured for monitoring mode. The first monitored data are measured in undamaged state. After that, a delamination crack is made in the same specimen by means of an interlamina shear test as shown in Fig. 4. The size of delamination is about 8mm. After the delamination creation, the monitored data are measured again. 30000 data sets are obtained for each monitored state and divided into 10 files. The response surface of monitored state is created in the same way as the initial state and F_0 value is calculated for 10 files in each monitored data. The average of F_0 is obtained from calculations of 100 times. The results are shown in Fig. 5. The abscissa is monitored data number and the ordinate is average of F_0. In the undamaged data, all averages of F_0 are plotted near the region of acceptance. On the other hand, all averages of F_0 are away from the region of acceptance in damaged state. These results show that the proposed damage detection system detects delamination exactly.

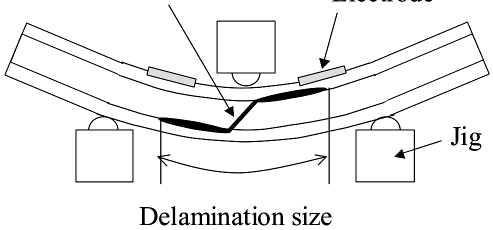

Fig. 4 Schema of delamination

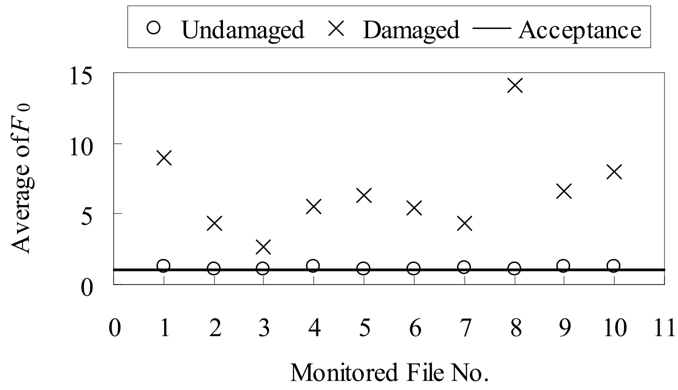

Fig. 5 Results of diagnosis

Conclusion

Present study proposes the simple damage detection system of CFRP structure. The effectiveness of the new simultaneous measurement method of multiple electrical resistance changes is experimentally confirmed. After this, the statistical diagnosis using the electrical resistance changes is performed and the method detected a delamination crack successfully.

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