Damage Monitoring of CFRP Structures Based on Impact Force Identification

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ABSTRACT:

A damage monitoring method based on an impact force identification is proposed for CFRP structures under impact force. An experimental identification method of impact force is developed. The relation between force histories and strain responses is determined by using measured force histories and the corresponding strain responses at the discrete points. By employing this relation, the location and history of impact force acting on CFRP stiffened panel is identified using measured strain responses. The method is also applied to the impact force identification of CFRP laminated plates involving impact damages under a drop-weight impact test. It is shown that the identified force history agrees well with the experimental one even when the impact damage is induced, and the damage monitoring method based on impact force identification is promising as a real-time health monitoring of CFRP structures.

INTRODUCTION

External impact events give severe damage to composite structures and may cause a catastrophic fracture of structures. The mechanical properties of composite structures such as compression-after- impact (CAI) strength [1] may degrade severely after external impact events. Modern techniques of structural health monitoring are a possible resort to insure the safety of composite structures. The identification of the external impact forces is important for structural health monitoring and has been investigated by many researchers [2-7]. For instance, Wu et al. [2] reported the identification results of impact forces on various plates based on the relation between the impact force and the strain response. Seydel et al. [3] identified the location and history of the impact force acting on stiffened composite panels. The authors [4-7] proposed a technique to identify the location and history of impact forces based on a finite element method. However, it is difficult to construct a precise analytical model on complicated structures such as aircraft wings and fuselages. Then it is important to develop the impact force identification method using only experimental data without resorting to an analytical model.

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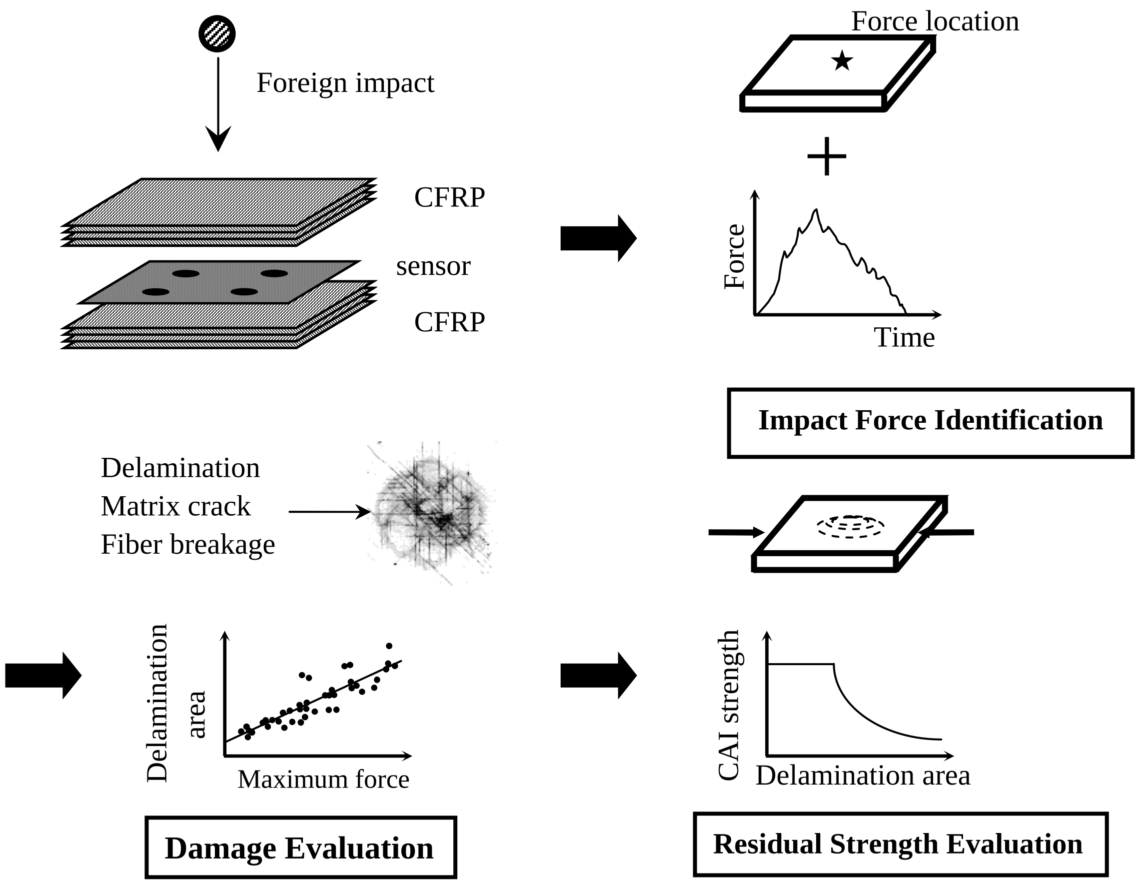


Figure 1: Schematic view of damage monitoring.

The present paper discusses a feasibility of a damage monitoring method of CFRP structures based on impact force identification as shown in Figure 1. Especially this paper examines an experimental identification method of impact forces acting on CFRP structures. The experimental relation between force histories and strain responses is first determined by using measured force histories and the corresponding strain responses. The location and history of impact force is identified based on this relation. The validity of the present identification method has been verified through an impact test of CFRP stiffened panel with an impulse hammer. The method is also applied to a drop-weight impact test of CFRP laminated plates involving impact damages.

EXPERIMENTAL IMPACT FORCE IDENTIFICATION

In the low-velocity impact event, the relation between the impact force history acting at the location (x_f, y_f) and the strain response observed at the location (x_o, y_o) can be expressed in the following algebraic equation:

$$\{\tilde{\varepsilon}\} = \left[G(x_f, y_f, x_0, y_0)\right]\{\tilde{f}\} \quad (1)$$

where the strain and force histories are expressed at discrete time, and $\left[G(x_f, y_f, x_o, y_o)\right]$

is a transform matrix composed of the Green's function at each time, which is a lower triangular matrix [2] as follows:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_n \end{Bmatrix} = \begin{bmatrix} g_1 & & & & \\ g_2 & g_1 & & 0 & \\ g_3 & g_2 & g_1 & & \\ \vdots & \vdots & \vdots & \ddots & \\ g_n & g_{n-1} & g_{n-2} & \cdots & g_1 \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_n \end{Bmatrix} \tag{2}$$

where $\{g\}$ is a component of a transform matrix which is determined by the force location and the observation point of strain only, and is not influenced by the force history.

Eq. (2) is transformed into the following equation:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_n \end{Bmatrix} = \begin{bmatrix} f_1 & & & & \\ f_2 & f_1 & & 0 & \\ f_3 & f_2 & f_1 & & \\ \vdots & \vdots & \vdots & \ddots & \\ f_n & f_{n-1} & f_{n-2} & \cdots & f_1 \end{bmatrix} \begin{Bmatrix} g_1 \\ g_2 \\ g_3 \\ \vdots \\ g_n \end{Bmatrix} \tag{3}$$

Eqs. (2) and (3) can be expressed as follows:

$$\{\tilde{\varepsilon}\} \equiv [G]\{\tilde{f}\} = [F]\{g\} \tag{4}$$

The component of a transform matrix, $\{g\}$, can be determined using the force histories $\{\tilde{f}\}$ and measured strain responses $\{\tilde{\varepsilon}\}$ in an impact test with an impulse hammer. Several times of tests are performed to avoid the measurement errors in the determination of $\{g\}$. Then the component of a transform matrix can be obtained by applying the least-squares method [8]:

$$\min_{\{g\}} H = \sum_{k=1}^{K} \left\| \{\tilde{\varepsilon}\} - [F]\{g\} \right\|^2 \tag{5}$$

As the transform matrix in Eq.(1) is determined, the impact force acting on CFRP structures is determined using measured strains at the multi-point sensors in the case that the force location is known [4]. The force history can be identified using a minimization problem as:

$$\underset{\{\tilde{f}\}}{\text{Minimize}} \quad F = \sum_{i=1}^{m} \left\| \{\tilde{\varepsilon}_i\} - [G_i]\{\tilde{f}\} \right\|^2 \tag{6}$$
$$\text{subject to} \quad \{\tilde{f}\} \geq 0$$

where $\{\tilde{\varepsilon}_i\}$ is the strain responses measured by the *i*th sensor located at (x_{0i}, y_{0i}), $[G_i]$ is the transform matrix relating $\{\tilde{\varepsilon}_i\}$ to $\{\tilde{f}\}$, and *m* is the number of sensors. The constraint in Eq. (6) is to ensure the force to be compressive all the time. Then the force history identification is achieved by solving Eq. (6) by means of the quadratic programming method in this study.

Another issue is the determination of the force location. In the force history identification at the assumed location, we can have a force history denoted by $\{\tilde{f}_e\}$. Then an error vector, which indicates the deviation between the estimated strains and measured strains, can be defined. The force location is determined by solving a minimization problem as follows:

$$\underset{x_e, y_e}{\text{minimize}} \quad E = \sum_{i=1}^{m} \frac{\left\| [G_i]\{\tilde{f}_e\} - \{\tilde{\varepsilon}_i\} \right\|^2}{\left\| \{\tilde{\varepsilon}_i\} \right\|^2}. \qquad (7)$$

Eq. (7) is solved by a nonlinear programming method [9]. In the minimization process, the force history $\{\tilde{f}_e\}$ is updated using Eq.(6) for each force location.

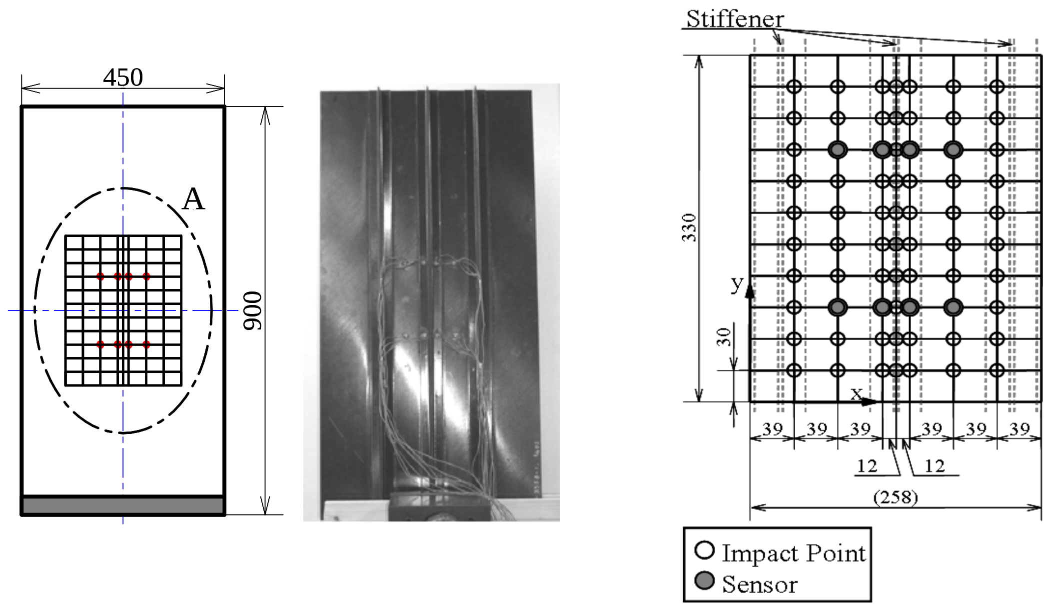
IDENTIFICATION RESULTS

Impact Force Identification of CFRP Stiffened Panel

To verify the identification method stated in the previous section, the impact test for Carbon/PEEK stiffened panel has been performed as shown in Figure 2. The impact point

Table 1: Laminate sequence of CFRP stiffened panel.

Laminate Sequence	
Stiffener	Skin
$[45/-45/-45/45/0_4/90/45_3]_s$	$[45/-45/-45/45/0/90]_s$



a) CFRP stiffened panel (b) impact points and sensor locations (enlargement of the region A in (a))

Figure 2: Impact test of CFRP stiffened panel.

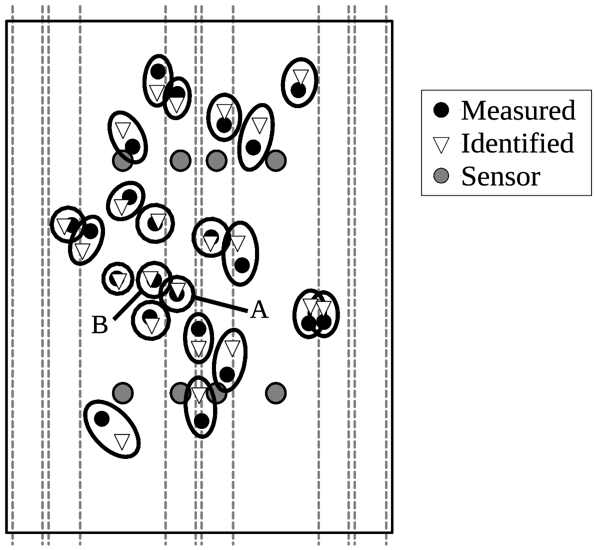
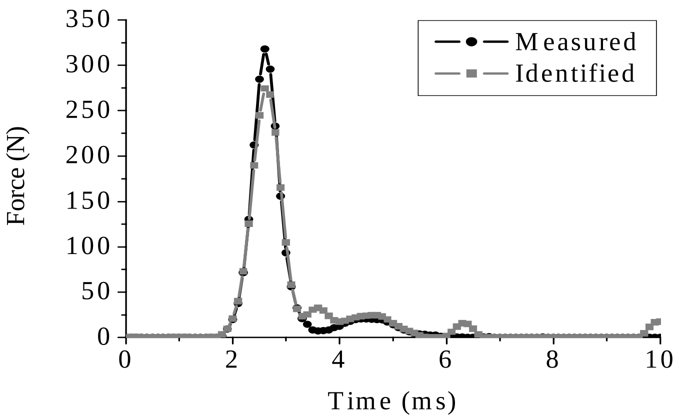
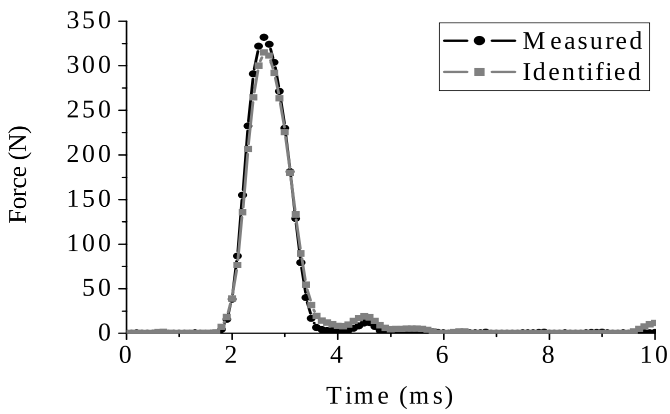


Figure 3: Identified force location for CFRP stiffened panel.



(a) point A



(b) point B

Figure 4: Identified force histories for CFRP stiffened panel.

and the sensor location are also shown in Figure 2 where the impact point with the impulse hammer is located at the skin side and the strain responses are measured by using 8 biaxial strain gauges attached on the surface of the stiffener side. The transform matrix is determined using the measured force histories and strain responses in an impact test with an impulse hammer. Table 1 shows laminate sequence of the stiffener and skin in the stiffened panel.

The force location is determined by Eq.(7). Figure 3 shows the identification results of the force location. Each circle involves the true (measured) and identified force locations. The average errors of the force location were 9.2 mm. The location error at the point A with the stiffener is 11.5mm and that at the point B without the stiffener is 3.2mm. The difference of location errors with and without the stiffener is not so large. Figure 4 shows the identified force histories in the case of points A and B for CFRP stiffened panel. The identification error of force history at the point A is a little large since the location error is relatively large. On the contrary, the identification error of force history at the point B is small, and the force history as well as the force location is accurately identified.

In the present force identification, it takes a few seconds to identify the location and history for each case. Almost identification time is required in the force location identification.

Impact Force Identification in Drop-Weight Impact Test

In the present identification method, we assume that there is no damage in structures, and we use a transform matrix of a healthy structure. We consider the impact force identification in a drop-weight impact test where the impact damage such as delamination is induced within the laminate.

Figure 5 shows the specimen of CFRP laminated plates used in drop-weight impact test where the laminate configuration of CFRP plates is $[(45/0/-45/90)_4]_s$, and the mass and the tip radius of an impacter is 4.7kg and 15.8mm, respectively. Four biaxial strain gauges are attached on the upper surface of the plate. As energy levels in an impact test, 3.0J, 4.8J and 7.2J were used where there was no damage in the laminate for the case of 3.0J impact energy. By employing the experimental transform matrix for the impact case of 3.0J, the impact force is identified using measured strains for the impact cases of 4.8J and 7.2J.

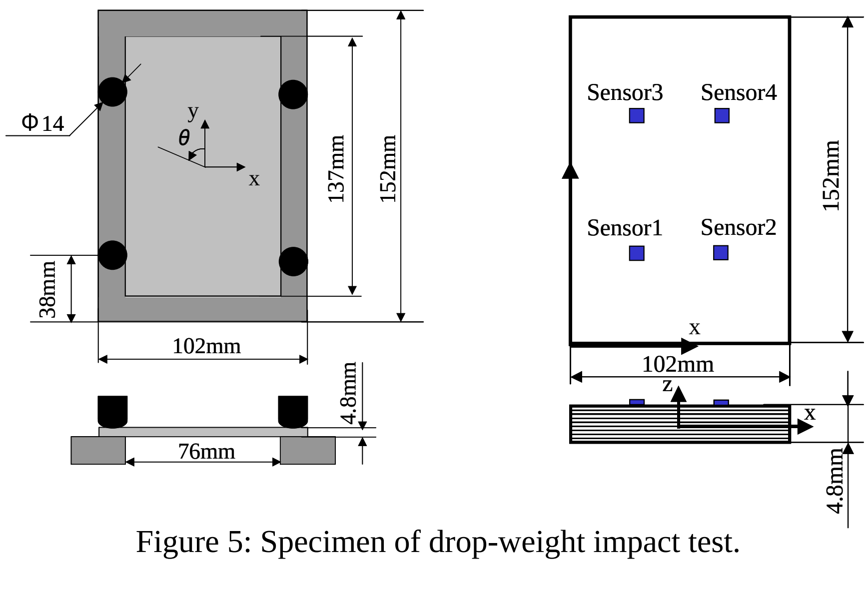


Figure 5: Specimen of drop-weight impact test.

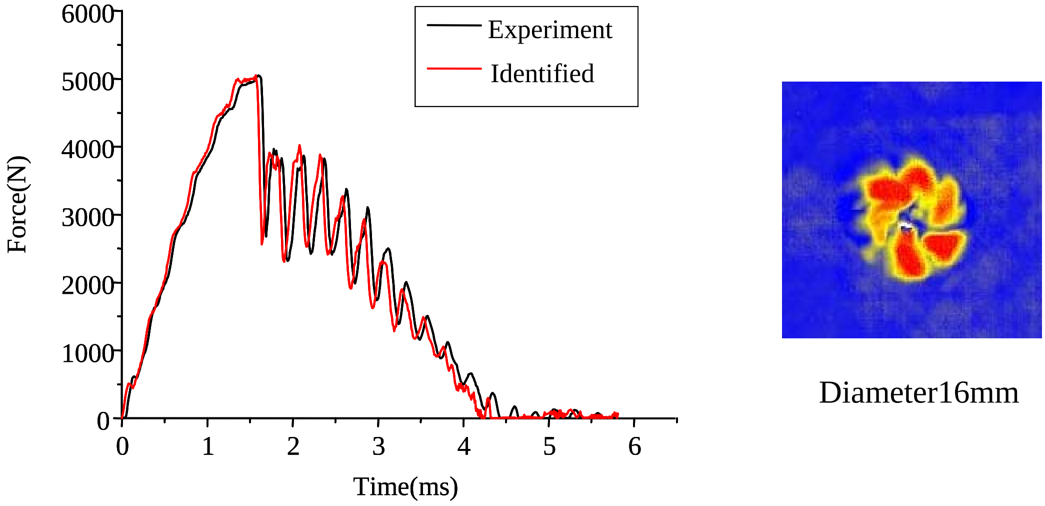


Figure 6: Identified force history for 4.8J impact energy.

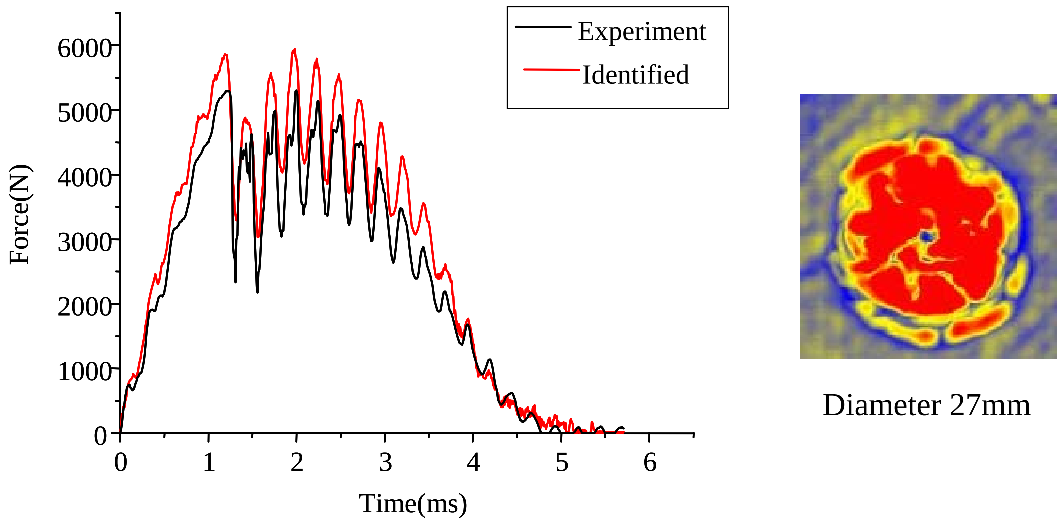


Figure 7: Identified force history for 7.2J impact energy.

Figures 6 and 7 show the identified impact force histories for 4.8J and 7.2J cases, respectively. The identified force histories agree well with the true ones. The damage area by ultrasonic C-scan is also shown in the figures. The diameter of the damage area is 16mm for 4.8J case and 27mm for 7.2 J case, respectively, and is not so large in both cases. When impact damage is not so severe and the damage extent is not so large, we can identify the force history using a transform matrix of a healthy structure.

Real-time monitoring of the impact events is one of the most important health monitoring. The present method of the force identification gives the location and history of the impact force acting on composite structures. We can get the information of impact events in real time since it takes only a few seconds to identify impact events. When we can know the location and history of the impact force, we can evaluate the residual strength as well as the damage state as shown in Figure 1, using an analytical or experimental database of CFRP structures.

CONCLUSIONS

In this paper, the method to identify the impact force location and force history is developed by using an experimental transform matrix relating the force history to the strain response. The validity of the present identification method has been verified through an impact test of CFRP stiffened panel with an impulse hammer, and a drop-weight impact test of CFRP laminated plates. The knowledge from these results are summarized as follows:

(1) The accurate force location and force history can be identified using the present experimental identification method. The present method is applicable to more complicated structures such as aircraft wings and fuselages since we use only experimental data for identification.

(2) The present force identification method using a transform matrix of a healthy structure can be applicable to the case of a small size of impact damages. Using identified force location and force history, evaluation of the impact damage and the residual strength of composite structures is possible in real-time.

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