EXPERIMENTAL IMPACT FORCE IDENTIFICATION OF CFRP STIFFENED PANELS

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Abstract

An experimental identification method of impact force location and history acting on CFRP laminated plates is presented. The relation between force histories and strain responses is first determined experimentally 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 is identified using measured strain responses based on the mathematical programming method. The validity of the present identification method has been verified through the impact test of CFRP laminated plate with embedded PZT piezoelectric sensors and CFRP stiffened panel using biaxial strain gauges attached on the surface of the panel. The method is also applied to the impact force identification of CFRP plate involving impact damages such as delamination.

1 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 [2-8]. 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.

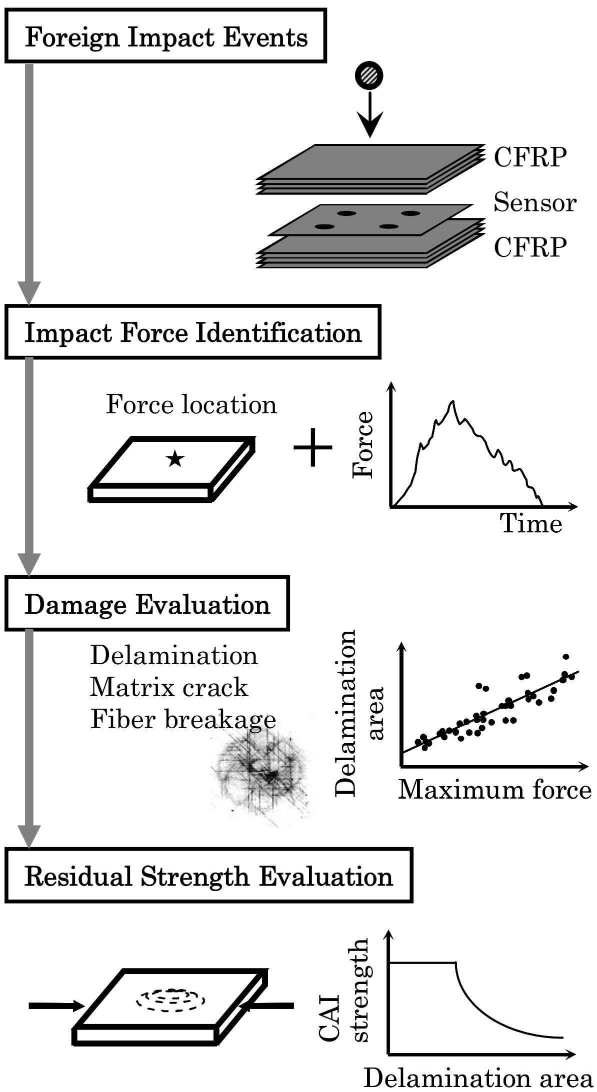


Fig. 1 Schematic view of damage monitoring

The present paper discusses a feasibility of a damage monitoring method of CFRP structures based on impact force identification as shown in Fig. 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 the impact test of CFRP flat plate and CFRP stiffened panel with an impulse hammer. The method is also applied to the drop-weight impact test of CFRP plate.

2 Identification Method

2.1 Force-Strain Relation

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

$$\{\tilde{\varepsilon}\} = [G(x_f, y_f, x_o, y_o)]\{\tilde{f}\} \tag{1}$$

where the strain and force histories are expressed at a discrete time, and $[G(x_f, y_f, x_o, y_o)]$ 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_i 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 components of a transform matrix, $\{g\}$, is 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 measurement errors in the determination of $\{g\}$. Then the components of the transform matrix can be obtained by applying the least-squares method [8]:

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

In CFRP laminated plates, we use PZT piezoelectric sensors embedded in the plate as strain sensors. When we consider a thin circular PZT element attached on or embedded in structures, the output voltage V_{PZT} is proportional to the summation of in-plane strains, $\varepsilon_x + \varepsilon_y$ as follows [4]:

$$V_{PZT}(t) = G_{PZT}\{\varepsilon_x(t) + \varepsilon_y(t)\} \tag{6}$$

where G_{PZT} is the sensitivity of PZT element as a strain sensor. The sensitivity of PZT sensors is calibrated using strain gauges through an impact test.

2.2 Force Identification

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

$$\underset{\{\tilde{f}\}}{\text{minimize}}\quad F = \sum_{i=1}^{m} \left\| \{\tilde{\varepsilon}_i\} - [G_i]\{\tilde{f}\} \right\|^2 \qquad \text{subject to}\quad \{\tilde{f}\} \geq 0 \tag{7}$$

where $\{\tilde{\varepsilon}_i\}$ is the strain responses measured by the i-th sensor located at (x_{oi}, y_{oi}), $[G_i]$ is the transform matrix relating $\{\tilde{\varepsilon}_i\}$ to $\{\tilde{f}\}$, and m is the number of sensors. The constraint in Eq. 7 is to ensure the force to be compressive all the time. Then the force history identification is achieved by solving Eq. 7 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 (x_e, y_e), 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:

$$\underset{x_e, y_e}{\text{minimize}} \quad E = \sum_{i=1}^{m} \frac{\left\| [G_i]\{\tilde{f}_e\} - \{\tilde{\varepsilon}_i\} \right\|^2}{\left\| \{\tilde{\varepsilon}_i\} \right\|^2} \qquad (8)$$

Eq. 8 is solved by a nonlinear programming method [9]. In the minimization process, the force history $\{\tilde{f}_e\}$ is updated using Eq. 7 for each force location.

3 Identification Test

3.1 Identification System

To verify the identification method stated in the previous section, the impact test for CFRP laminated plate and stiffened panel has been performed. The impact test system and the specimen utilized in this study are shown in Figs. 2 and 3, respectively. The impact test system consists of a measurement part and identification codes as shown in Fig. 2. The former part consists of a sensor network and several signal conditioners. The present study utilizes the SMART Layer developed in Stanford University as a part of the sensor network as shown in Fig. 3. The specimen is cantilevered and impacted by an impulse hammer. The strain response is measured using four PZT sensors for laminated plates.

The identification task is carried out intermittently. When the impact force is applied and the strain responses are induced, a trigger signal is sent to the computer from the oscilloscope. After receiving the trigger signal, the computer imports the strain responses from the oscilloscope, then identify the impact force and monitor the strain responses again. In this test, the measurement time and the sampling time are 10.0×10^{-3} second and 1.0×10^{-4} second, respectively. The force history is also measured from the output of impulse hammer in order to verify an identified force history.

3.2 Impact Test for CFRP Laminated Plates

The material properties of the specimen are shown in Table 1. In order to determine the sensitivity of the PZT sensors, the calibration is performed by comparing the output voltage of the PZT sensor with the output of the biaxial strain gauge located at the same point. The sensitivity G_{PZT} in Eq. 6 was determined by comparing the maximum and minimum peak values of the output voltages [4].

Fig. 4 shows the impact points used to determine the transform matrix in Eq. 1 where the number of sensors is 4. The transform matrix is constructed for each combination of impact point and sensor point through four times of impact tests with an impulse hammer. The transform matrix is interpolated at points except impact points using a shape function similar to one used in a finite element method.

Table 1. Material properties of CFRP plates

Stacking sequence	Material properties of unidirectional lamina
$[45_2/-45_4/45_2]_s$ $[0_2/45_2/-45_2/90_2]_s$	E_1= 114 GPa, E_2= 9.20 GPa G_{12}= 5.49 GPa ν_{12}=0.30, ρ=1550 kg/m^3

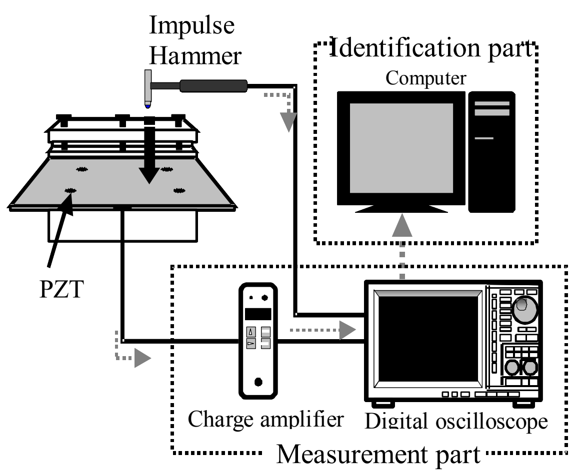


Fig. 2. Impact test system

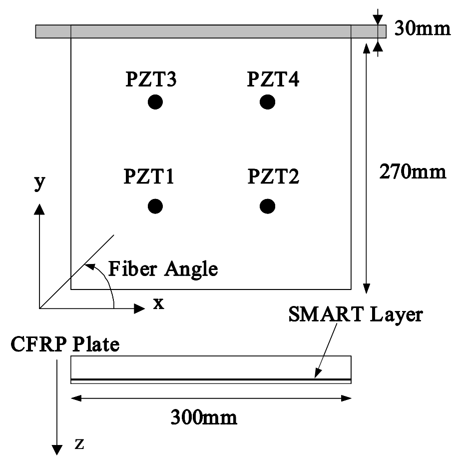


Fig. 3 CFRP specimen with PZT sheet

3.3 Identification Results

The impact force is identified using the output of four PZT sensors embedded in CFRP laminates. The force location is determined by Eq. 8. Fig. 5 shows the identification results of the force location for $[45_2/\text{-}45_4/45_2]_s$ laminate and $[0_2/45_2/\text{-}45_2/90_2]_s$ laminate.

In Fig. 5, each circle involves the true (measured) and identified force locations. The average errors of the force location were 2.7 mm for $[45_2/\text{-}45_4/45_2]_s$ laminate and 3.1 mm for $[0_2/45_2/\text{-}45_2/90_2]_s$ laminate, respectively. These are around 1% of the plate size in length. The location error in the present method is smaller compared with 8.5 mm for $[45_2/\text{-}45_4/45_2]_s$ laminate and 4.1 mm for $[0_2/45_2/\text{-}45_2/90_2]_s$ laminate in the previous method based on FEM modeling [4] since the present method can avoid the modeling error in the construction of the transform matrix.

Fig. 6 shows the identified force histories at the points B and C for $[45_2/\text{-}45_4/45_2]_s$ plate, respectively. In these cases, the force locations are identified near the true ones, and therefore the identified force histories agree well with the true ones.

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

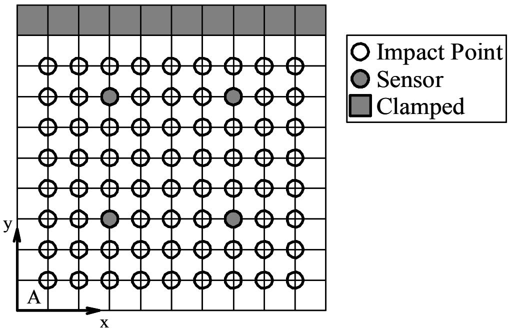
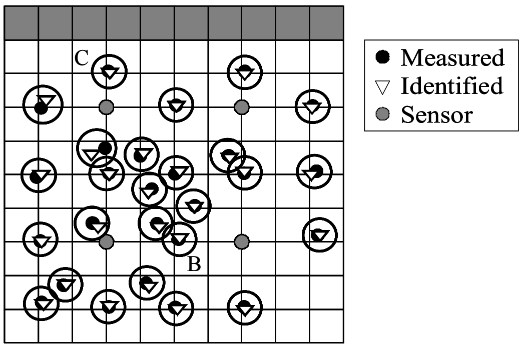
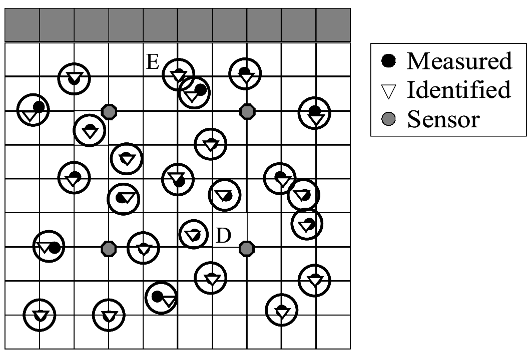


Fig. 4. Impact points used to determine a transform matrix

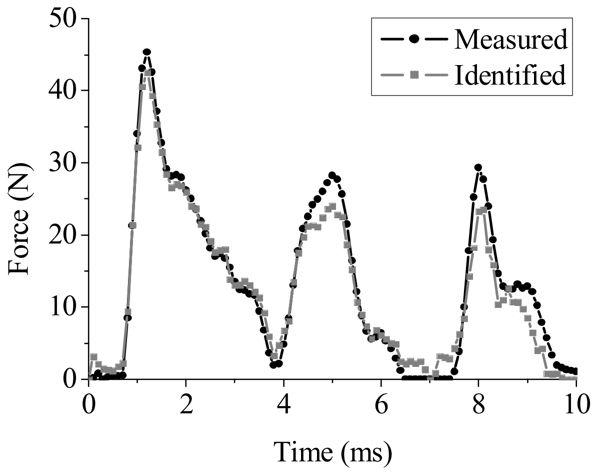


(a) $[45_2/\text{-}45_4/45_2]_s$ laminate

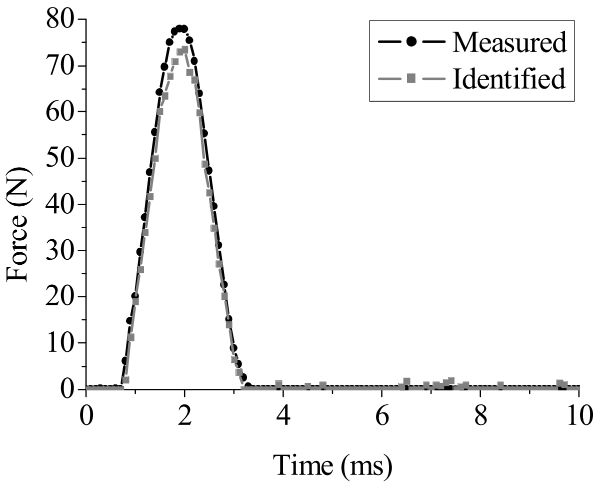


(b) $[0_2/45_2/\text{-}45_2/90_2]_s$ laminate

Fig. 5. Identified force locations for CFRP laminated plates



(a) Point B



(b) Point C

Fig. 6. Identified force histories for $[45_2/\text{-}45_4/45_2]_s$ laminate

3.4 Impact Test for CFRP Stiffened Panel

Next we consider Carbon/PEEK stiffened panel as shown in Fig. 7. The laminate sequence of stiffener and skin are $[45/\text{-}45/\text{-}45/45/0_4/90/45_3]_s$ and $[45/\text{-}45/\text{-}45/45/0/90]_s$, respectively. The impact points and the sensor locations are shown in Fig.8 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.

3.5 Identification Results

The force location is determined by Eq. 8. Fig. 9 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, and those are 1% of the panel length or 3% of the region A in Fig. 7. The location error at the point B with the stiffener is 11.5 mm and that at the point C without the stiffener is 3.2 mm. The difference of location errors with and without the stiffener is not so large.

Figs. 10 and 11 show the identified force histories in the case of the points B and C for CFRP stiffened panel. The identification error of force history at the point B is a little large since the location error is relatively large. On the contrary, the identification error of force history at the point C is small, and the force history as well as the force location is accurately identified.

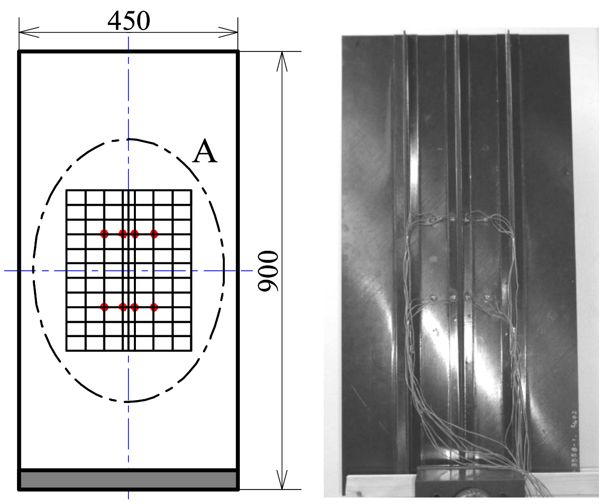


Fig. 7. Impact test of CFRP stiffened panel

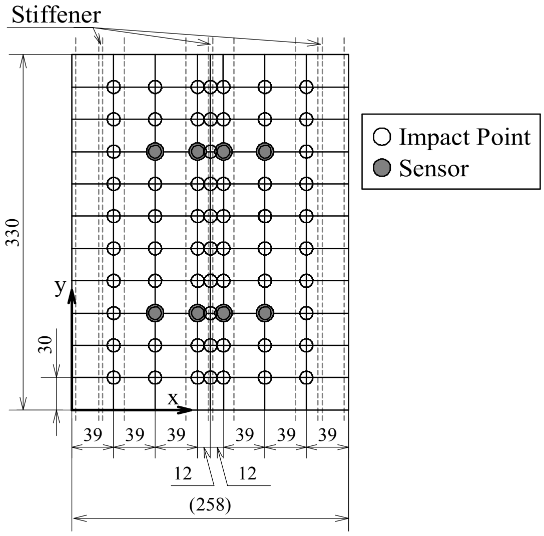


Fig. 8. Impact points and sensor locations (enlargement of the region A in Fig. 7)

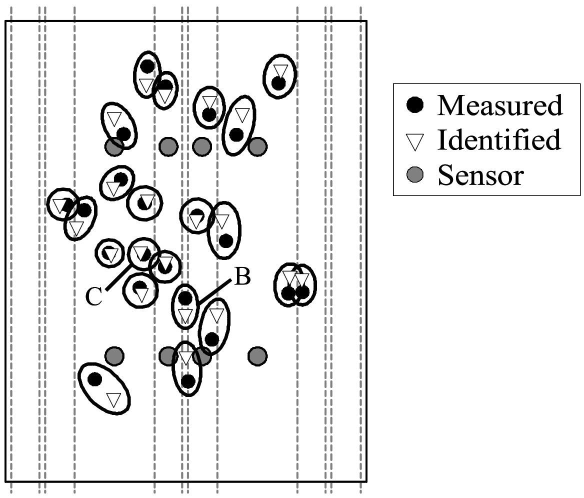


Fig. 9. Identified force location for CFRP stiffened panel

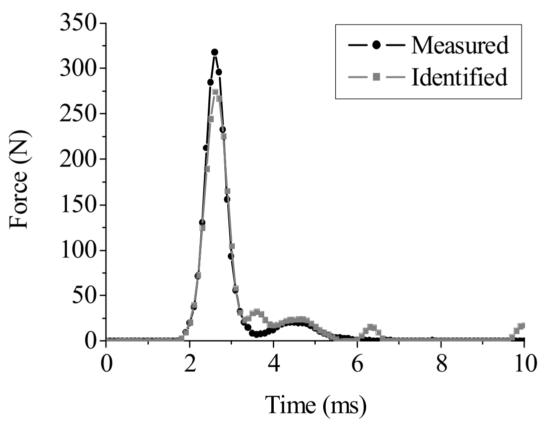


Fig. 10. Identified force history for CFRP stiffened panel (Point B)

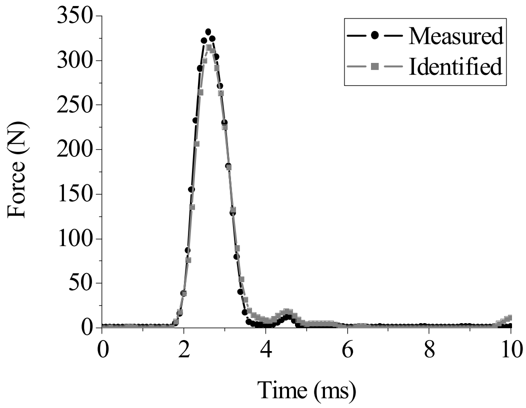


Fig. 11. Identified force history for CFRP stiffened panel (Point C)

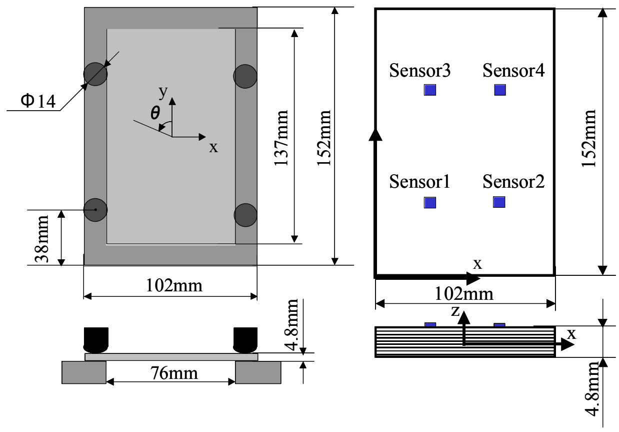


Fig. 12 Specimen of drop-weight impact test

4 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 is induced within the laminate.

Fig. 12 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 4.7 kg and 15.8 mm, respectively. The center of the plate is impacted by drop-weight. Four biaxial strain gauges are attached on the upper surface of the plate. As energy levels in an impact test, 3.0 J, 4.8 J and 7.2 J were used where there was no damage in the laminate for the case of 3.0 J impact energy. By employing the experimental transform matrix for the impact case of 3.0 J, the impact force is identified using measured strains for the impact cases of 4.8 J and 7.2 J.

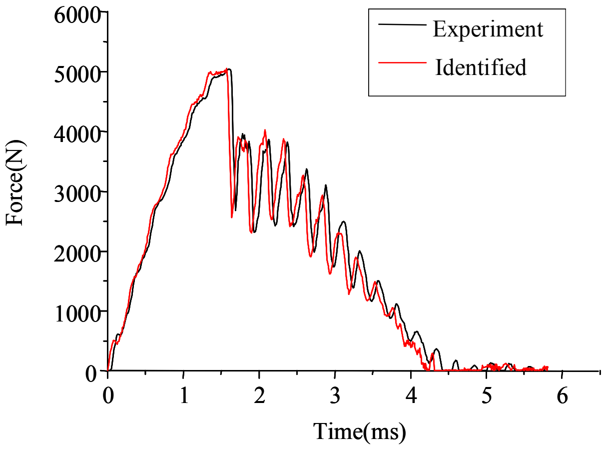
Figs. 13 and 14 show the identified impact force histories for 4.8 J and 7.2 J cases, respectively. The identified force histories agree well with the true ones. The damage areas by ultrasonic C-scan are also shown in the figures. The diameter of the damage area is 16mm for 4.8 J case and 27 mm for 7.2 J case, respectively, and is not so large in both cases. When 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 or strength as well as the damage state as shown in Fig. 1, using an analytical or experimental database of CFRP structures.

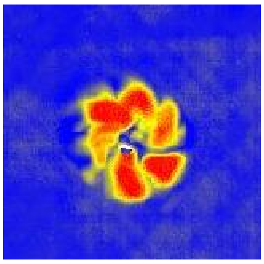
5 Conclusions

In this paper, the experimental identification method of the impact force location and force history is developed. The validity of the present method is verified through impact tests for the CFRP flat plates and the stiffened panel, and a drop-weight impact test of CFRP laminated plates. The knowledge from these results is summarized as follows:

(1) The accurate force location and force history can be identified using the present experimental identification method for both of CFRP flat plate and stiffened panel.
(2) The present force identification method is based on the experimental transform matrix to relate the impact force and the measured strain. Thus the method can be applicable easily to complicated structures such as composite wing and fuselage structures.
(3) The present force identification method using a transform matrix of a healthy structure can be applicable to the case of that a small size of impact damage is induced.
(4) Using identified force location and force history, evaluation of the impact damage and the residual strength of composite structures is possible in real-time.

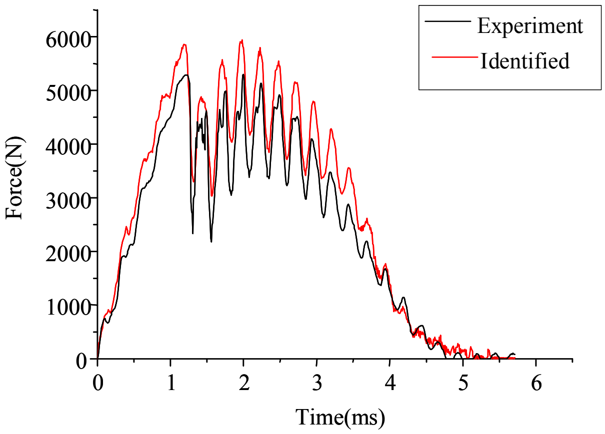


(a) Impact force history

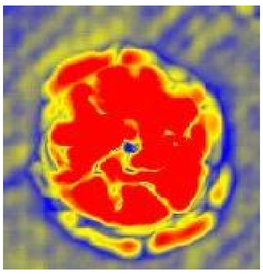


(b) Ultrasonic C-scan (diameter=16 mm)

Fig. 13. Identified force history for 4.8 J case



(a) Impact force history



(b) Ultrasonic C-scan (diameter=27 mm)

Fig. 14. Identified force history for 7.2 J case

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References

[1] Ishikawa, T., Sugimoto, S., Matsushima, M. and Hayashi, Y. "Some experimental findings in compression-after-Impact (CAI) tests of CF/PEEK (APC-2) and conventional CF/Epoxy flat plates". Comp. Sci. Tech., Vol.55, pp 349-363, 1995.

[2] Wu, E., Yeh, J. C. and Yen, C. S. "Identification of impact forces at multiple locations on laminated plates". AIAA J., Vol.32, pp 2433-2439, 1994.

[3] Seydel, R. and Chang, F. K. "Impact identification of stiffened composite panels". Smart Mater. Struct., Vol.10, pp 354-369 & 370-379, 2001.

[4] Fukunaga, H., Matsumoto, S. and Hu, N. "Real-time impact force identification of CFRP structures using piezoelectric sensors". Proc. 24th ISTS, pp 286-291, 2004.

[5] Tajima, M., Matsumoto, S. and Fukunaga, H. "Impact force identification of CFRP laminated plates using PZT piezoelectric sensors". Trans. Japan Soc. Mech. Eng., Part A, Vol.70, pp.1566-1573 & 1747-1754 (in Japanese), 2004.

[6] Hu, N. and Fukunaga, H. "A new approach for health monitoring of composite structures through identification of impact force". J. Advanced Science, Vol.17, pp 82-89, 2005.

[7] Hu, N., H. Fukunaga, S. Matsumoto, B. Yan and X. H. Peng. "An efficient approach for identifying impact force using embedded piezoelectric sensors". Int. J. Impact Engineering, Vol.34, pp 1258-1271, 2007.

[8] Fukunaga, H. and N. Hu. "Experimental impact force identification of composite structures". Proc. Third European Workshop on Structural Health Monitoring 2006, A. Guemes ed., DES Tech Pub., pp 840-847. 2006

[9] Vanderplaats, G. N. and Sugimoto, H. "A general purpose optimization program for engineering design". Computers Structures, Vol.24, pp 13-21, 1986.