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Damage detection in composite laminates using coin-tap method

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The coin-tap test has the ability to indicate damage in a structural element due to a localized change of stiffness. The change in vibration signature may be detected by ear or more precisely by measurement of the dynamic contact force. In this paper, a coin-tap test method for discriminating between measurements made on sound and delaminated structures is present. It has been shown that the characteristics of contact force history during a tap are changed by the presence of defect beneath the surface of the structure. For structurally radiated noise, the sound field is directly coupled to the structural motion. Therefore, Impact response analysis should be performed. And the delamination model is used to analyze the impact response analysis. Experimental results for delaminated composite structure are presented and correlations between simulation and measured data are shown. It is shown that coin-tap test is useful and practical diagnostic tool for detecting localized delamination in composite laminates.

1 Introduction

The use of laminated composite structures has many potential applications in a variety of engineering fields. However, they are mostly used in a laminated form with relatively weak interlaminar interfaces which are vulnerable to transverse loads such as impacts arising from a falling mass. The presence of delaminations can cause significant degradation of the structural response characteristics [1]. The coin-tap test is one of the oldest methods of non-destructive testing and it is regularly used for testing laminated structures. The test requires an operator to tap each point of the structure to be inspected with a coin, and listen to the resulting sound radiated by structure. When a structure is struck with a hammer, the characteristics of the impact are dependent on the local impedance of the structure and on the hammer used. Damage such as an adhesive disband and fatigue damage results in a decrease in structural stiffness, and hence a change in the nature of impact [2]. Adams showed that it is possible to produce a version of the coin-tap test which depends on the measurement of the force input to the test structure during the tap [3]. There are two kinds of coin-tap test method. One is based on the impact force histories that produced when the structure is struck. And the other is based on sound pressure histories. The first one requires the time histories of the force input to the test structure to be captured, and this can be done via transducer in tapping head so no transducer need be attached to the structure. The second requires the time histories of the sound that radiated from the structure. The sound based coin-tap test requires the Fourier transform of the sound pressure histories to be computed and compared with a standard from a sound structure. It is shown that the two kinds of coin-tap test are useful and practical diagnostic tool for detecting localized delamination in composite laminates. In this paper, an impact force based non-destructive method is proposed. This method is using the difference between measured impact force histories of healthy structure and delaminated structure. For structurally radiated noise, the sound field is directly coupled to the structural motion. Therefore, impact response should be analyzed. Generally, the finite element method on the impact response of the laminate has been known to require long computation time. Shivakumar et al. did not use the finite element method to analyze the impact response of the laminate but used the spring-mass model to efficiently predict the impact force history [4]. In their study, the contact energy due to local indentation as well as transverse shear energy and bending energy of plate are considered, and they reported that the contact energy can be neglected in the impact by relatively low velocity foreign object on a flexible or thin plate. However, their study was restricted to circular laminates with transversely isotropic material properties. Choi proposed the spring element model using linearized contact law. In their study, they have shown that the linearized contact law approach could be applied to low-velocity impact response analysis problem with using general purpose FEM software [5]. In this study, to use the spring-mass model, hammer shaped impactor is modeled by concentrated mass. And to investigate the impact response on delaminated laminates, gap elements are used to avoid the overlap and penetration between the upper and lower sub-laminates at delamination region. The use of three-dimensional elements to predict the impact response of delaminated composite structures is inconvenient because of a quite number of elements necessary to obtain numerical solutions. In this study, 2-D finite elements are used in delaminated area. In this study, from the impact response analysis results, sound pressure is computed.

2 Impact response analysis

Fig.1 shows the FEM model for impact response analysis using general – purpose FEM software. The mass of impactor is lumped at the end of the spring mass, and the other end of spring element is attached to laminate at impacted location. After FEM analysis we can extract the compressive force history acting at the spring. In present study, MSC/NASTRAN was used as general-purpose FEM software. In FEM modeling 4-node plate element was used and transient dynamic analysis was performed with the initial condition, which is that initial speed of the lumped mass was loaded as impact velocity.

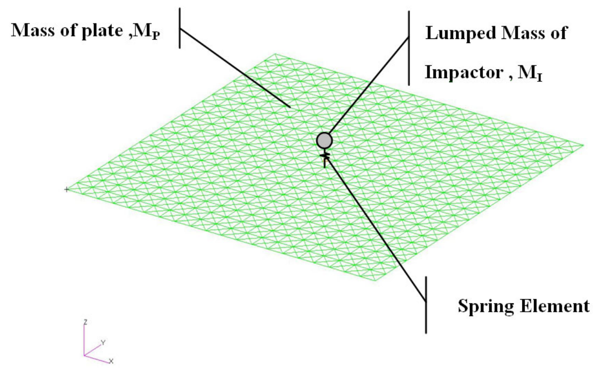


Fig. 1 Spring - mass model using general-purpose FEM software

2.1 Simplified spring – mass model

Fig.2 shows the FEM model for impact response analysis for hammer shaped impactor. The hammer shaped impactor is modeled by solid elements and beam elements. The use of three-dimensional elements to model the hammer shaped impactor is inconvenient because of a quite number of elements necessary to obtain numerical solutions. And it is time consuming work if the hammer shape is complicate. So the hammer shaped impactor is simplified by concentrated mass to use spring – mass model. The equivalent concentrated mass is determined as followed procedure.

$$R_c \sin\theta \times \tan\theta = \frac{1}{2} I_0 \dot{\theta}^2 \qquad (1)$$

$$v_i = \dot{\theta} \times R_i$$

Where R_c is the center of impactor, θ is rotated angle from neutral position, I_0 is the mass moment of inertia of impactor with respect to rotation center, v_i is the impact velocity of impact position and $\dot{\theta}$ is the angular velocity of impactor. The equivalent impactor mass is computed as followed.

$$\frac{1}{2} I_o \dot{\theta}^2 = \frac{1}{2} m_e v_i^2 \qquad (2)$$

Where m_e is the equivalent mass of impactor.

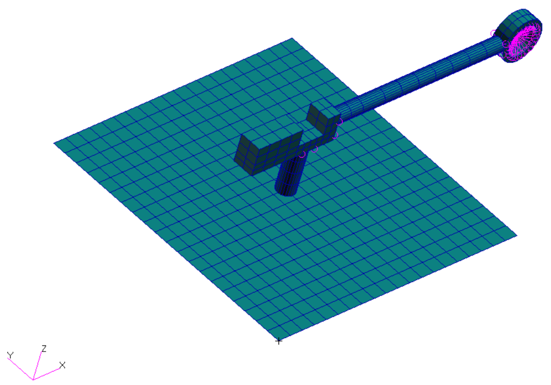
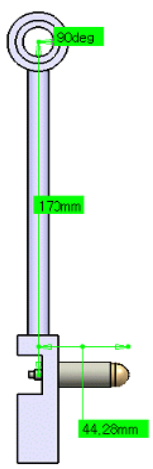


Fig. 2 Detail finite element model of impactor

2.2 Verification of spring – mass model

The configuration of impactor for type 1 and physical properties are shown in Fig.3. Equivalent mass is 0.092 kg that computed by Eq. (2).



- Material : Aluminum
- Impactor mass : 0.1237 kg
- Center of mass (R_c)
  : 127 mm
- Mass moment of inertia (I_0)
  : 2670 kg mm^2
- Center of percussion (R_i)
  : 170.0 mm

Fig.3 Configuration of impactor for type 1 and physical properties

The analysis model of the laminate is 19 × 19 cm, and the boundary condition of the plate has four edges clamped. The laminate has a lay-up $[0/90]_{2s}$. And the material properties are shown in table 1. A comparison of impact force histories between detail FEM model and simplified spring - model when the impact velocity is 0.954 m/sec is shown in Fig.4. As shown from the figure, the impact force history obtained by simplified spring - model provided accurate result.

Table 1 Material properties

Material properties of lamina	E_1 = 132 GPa, E_2= 8.0 GPa G_{12}=G_{13}=G_{23}= 3.74 Gpa ν_{12} = 0.3 ρ =16 kg/m3 Thickness = 0.14 mm
Material properties of impactor	E = 207 Gpa ν =0.3

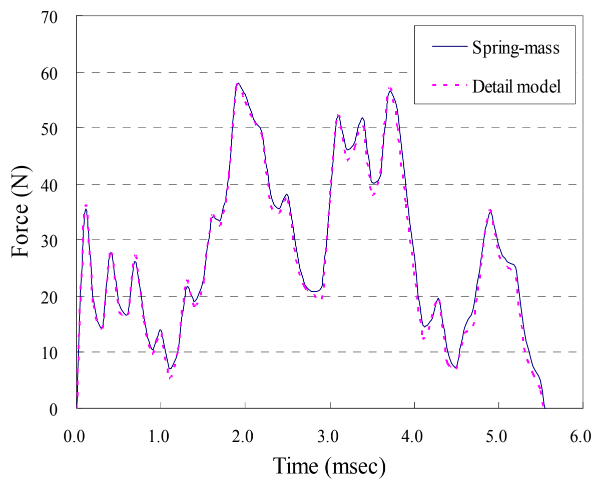


Fig. 4 Comparison of impact force histories between detail model and simplified spring – mass model

2.3 Comparison with experimental result

To compare the experimental result, a pendulum type tapping test system set up by the author is used. Fig.5 shows the schematic diagram of tapping system and test fixture. The test model of the laminate is 19 × 19 cm, and the boundary condition of the plate has four edges clamped. The laminate has a lay-up $[0/45/0/-45/0/-45/0/45/90]_s$. In Fig. 6, the impact force history given by simplified spring-mass model and experimental one are shown. The type 1 impactor is rotated 30 degrees upward from vertical line. and then released. In this case, the impact velocity is 0.954 m/sec.

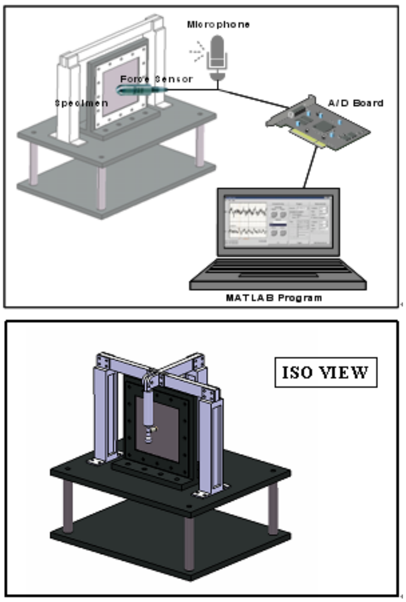


Fig. 5 Test fixture and tapping system

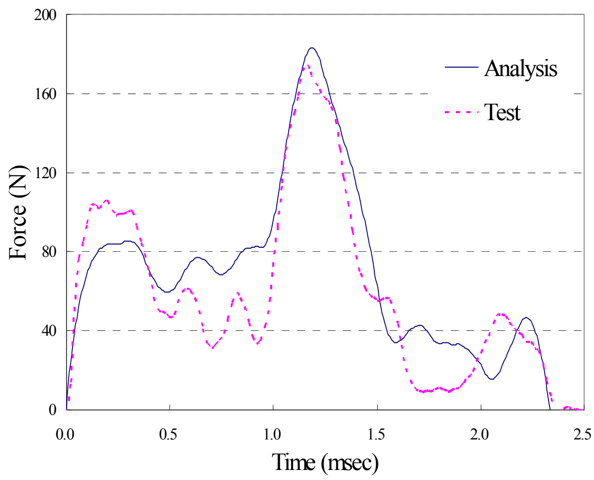
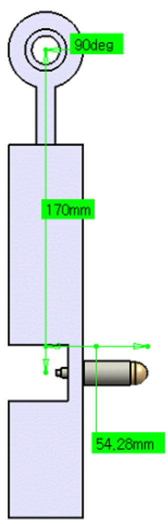


Fig. 6 Comparison of impact force histories between experimental result and simplified spring – mass model for type 1 impactor



- Material : Steel
- Impactor mass : 1.218 kg
- Center of mass (R_c) : 133 mm
- Mass moment of inertia (I_0)
  : 27642 kg mm^2
- Center of percussion (R_i)
  : 170.0 mm

Fig.7 Configuration of impactor for type 2 and physical properties

The configuration of impactor for type 2 and physical properties are shown in Fig.7. Equivalent mass is 0.956 kg that computed by Eq. (2). In Fig. 8, the impact force history given by simplified spring-mass model and experimental one are shown. The type 2 impactor is rotated 15 degrees from vertical line. and then released. In this case, the impact velocity is 0.478 m/sec.

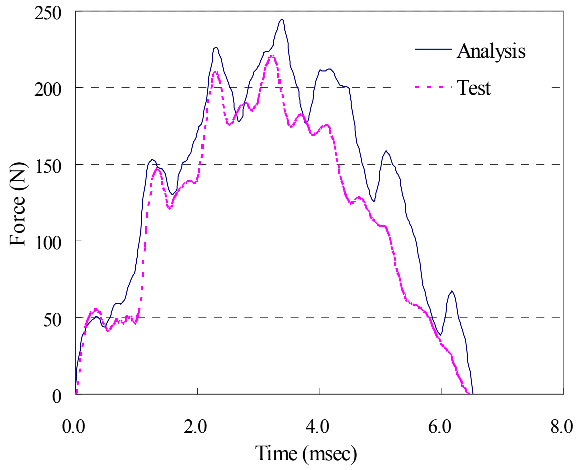


Fig. 8 Comparison of impact force histories between experimental result and simplified spring – mass model for type 2 impactor

3 Delamination model

To prevent the overlap and penetration, non-linear finite element analysis was performed using MSC/NASTRAN to determine the impact response of graphite/epoxy composite specimens.

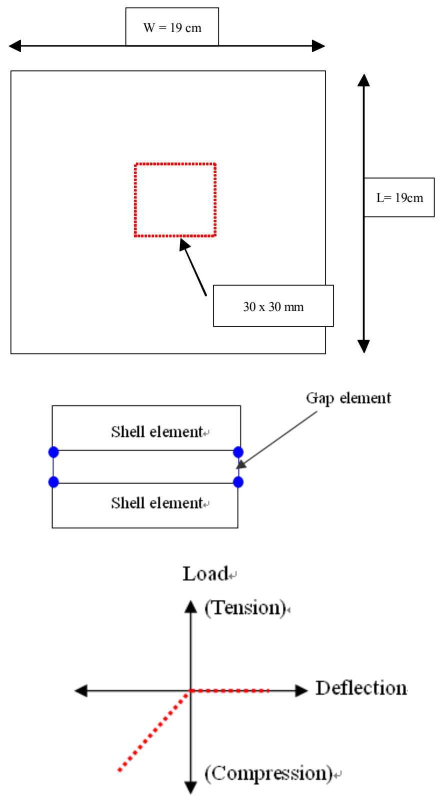


Fig.9 Configuration of laminate with a delamination and gap element stiffness curve used to connect shell element

4-node shell elements and gap elements were used to model delamination. The gap elements are inserted along the delamination interface surfaces for preventing penetration of the upper and lower sub-laminates during impact analysis process. Fig.9 shows the schematic of the delamination modeling. A comparison of impact force histories with and without delaminated is shown in Fig.10 when the laminate has a lay-up $[0/90]_{2s}$. And type 1 impactor is used. Impact response analysis has performed when the impact velocity is 0.954 m/sec. From the results, we could know that maximum impact force is decreased by the presence of delamination. This result would be expected because plates with delaminations should be less stiffness than undamaged plates. The larger delaminations produced the greatest decrease in impact force histories and increase in contact time duration.

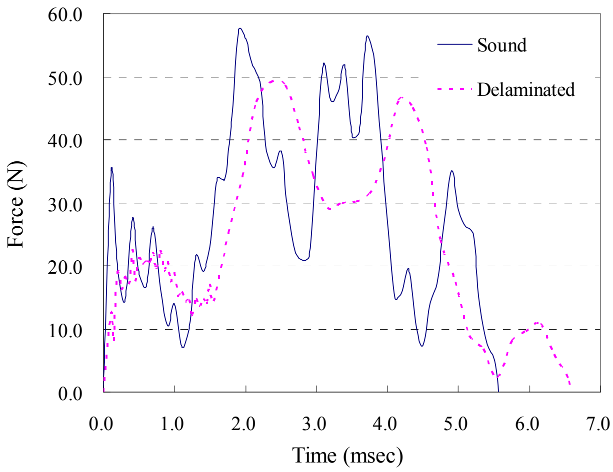


Fig. 10 Comparison of impact force histories between without and delamination

4 Conclusion

In this paper, the physical basis of the coin-tap test has been demonstrated. And the simplified spring – mass model has been proposed to model hammer shaped impactor. From the test result, we could know that simplified spring - mass model provides the appropriate solution. The numerical results show that the change of maximum impact force is related to stiffness reduction. And a delamination model is used to numerically explore the effect of delamination. The numerical results show that there is strong correspondence between the extent of delamination (or local stiffness reduction) and reduction in impact force. The final goal of this research is to provide useful tool for detecting the damage in composite structures.

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