Energy-absorbing behavior of laminated plate structures with multiple delaminations

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ABSTRACT

The concept of an energy-absorbing laminated plate structure with artificially introduced multiple delaminations is proposed for use in crashworthiness design. Experimental investigation was performed to study an impact performance of delaminated laminates subjected to axial compression, where achieving a high energy absorption performance is examined by using failure initiation technique. Although buckling load decreases with the introduction of delaminations, postbuckling behavior is altered to more desirable energy-absorbing characteristics. Delaminations can thus be used to improve the impact performance of laminated plate structures.

INTRODUCTION

Laminated plate structures have recently been widely used in aerospace and other structures in which structural efficiency is greatly required. These structures have advantages for tailoring and laminating to fit the specific design requirements. A common failure mode in laminated structures is delamination which usually results in the reduction of structural load capacity[1],[2].

In the case of applications of advanced composite materials, high specific moduli and specific strengths of composite materials play a key role up to failure. However, from the view point of crashworthiness design, the relatively brittle nature of advanced composite materials causes difficulties in meeting the required safety performance. The methods of achieving a high energy absorption performance have been studied by many investigators[3]–[8].

In the present study, the concept of an energy-absorbing laminated plate structure with artificially introduced multiple delaminations is proposed for use in the crashworthiness design. Experiments were performed to verify an impact performance of laminated plates containing multiple delaminations which initiate
failure modes. As a result, buckling load decreases with the introduction of artificial multiple delaminations, and the postbuckling behavior is altered to more desirable energy-absorbing characteristics. Delamination can thus be used for reducing the axial rigidity of a laminated plate structure, but it does not prevent the structure from supporting further load so long as no delamination propagation occurs. The concept of the present study is applicable to any laminated plate structures where the crashworthiness is one of the major concerns.

EXPERIMENTAL PROCEDURE

Test specimens with Young's modulus 153 GPa are composed of unidirectional Carbon–fiber/Polyether–ether–ketone(PEEK). The laminated plates consist of nine layers bonded together so that no slip can occur between them. Each laminated plate of thickness 1.125mm contains three parallel plane delaminations at a depth 0.375mm from the surface of the plate as shown in Figure 1(a). The plate has a constant width between two lateral edges and it is subjected to uniform compressive axial load at the clamped ends. The model shown in Figure 1(b) represents a part of box beams used in thin-walled plate structures. Each initial delamination extends over the length 50mm and runs across the entire width of the plate.

![Figure 1: Schematic diagram of a plate with multiple delaminations.](image)

Each test plate has 1 cm of margin at both sides and ends. The test plate was supported by rods on both sides where steel bars of circular cylinder were used for fixing the plate. The upper and lower ends were firmly fixed to the rigid frame by using bolts. Adjustments in the upper end fixtures were made before loading to assure uniform compression. A dial-gage was fabricated to measure
the end shortening. Eight strain gages were mounted on each side of the test plate to check deformation (buckling modes) of the plate during loading. Note that initial imperfection was not measured beforehand. The energy absorption tests in which specimens were placed in a universal testing machine and loaded in a static manner, were conducted on non-delaminated and delaminated plates.

RESULTS AND DISCUSSION

The objective of the present model tests was to examine the actual energy absorption behavior of delaminated plates and to study the effect of artificially introduced delaminations. A total of 6 specimens were tested with one pattern of initial delaminations as shown in Figure 1. One of the typical experimental results for delaminated and non-delaminated plates are shown in Figure 2, in which the circles represent the results of non-delaminated plate, and the filled circles represent those of delaminated plate. In order to evaluate the postbuckling behavior of non-delaminated and delaminated plates, a large displacement analysis was performed on the basis of the finite element method. In the analysis, it is assumed that the fracture toughness of the material is sufficient enough to resist the growth of the delamination even if finite deformation occurs. Moreover, the initial imperfection given by the linear buckling analysis is applied to initiate out-of-plane displacement mode of the plate. Qualitative agreement between the analytical and experimental values seems to indicate energy absorption capability of delaminated plates. As mentioned before, it is observed that the presence of artificial delamination in the plate reduces the buckling load although the prebuckling behavior is identical. The axial rigidity of the delaminated plate is smaller than that of the non-delaminated plate in the realm of the postbuckling region, and this may be considered to produce a preferable effect within an energy-absorbing structure. Figure 3 shows the corresponding deflection modes of the typical test plate. These results show that the delaminated plates exhibit preferable energy absorption capability by showing the increase of deformation capacity.

![Figure 2: End shortening of non-delaminated and delaminated plates.](image-url)
Although there were no visible evidence whether initial delaminations grow or not, it is believed that the delamination growth will produce a preferable effect on the energy absorption so long as the layer bondage is assured. It should be emphasized, however, that problem of energy absorption efficiency requires further study because a knowledge of stress distribution at the delamination front is still lacking.

Existing investigations have revealed that the delamination reduces the buckling load of the laminated plate structure. The prebuckling behavior of the delaminated plate is identical with the non-delaminated plate, which results in the merit that the stiffness of the structure is not affected before the buckling occurs. Hence, by introducing sufficient and pertinent initial delaminations, buckling loads and load-end shortening curves are considered to be controlled as desired.
Figure 5: Relationship between load and end shortening (Type A).

Figure 6: Relationship between load and end shortening (Type B).

Figure 7: Relationship between load and end shortening (Type C).
In order to investigate the effects of prescribed delamination patterns on the load—end shortening curves, Aluminium plates (E=70.2 GPa) of thickness 0.9mm containing three parallel plane delaminations at a depth 0.3mm from the surface of the plate were tested. Although the length of each individual delamination at Types B and C may be different, each one must be uniform across the width of the plate as shown in Figure 4. Test apparatus and test procedure are the same as those of the Carbon—fiber/PEEK composite specimens. The experimental results are presented in Figures 5, 6 and 7, in which the corresponding deflection modes are shown. Appreciable differences in energy absorption performance could not be seen from Figures 5, 6 and 7. It may be said that laminated plates with equal size initial delaminations improve the impact performance of laminated plate structures.

CONCLUDING REMARKS

Experimental studies were conducted to evaluate the energy absorption behavior of laminated plates with multiple delaminations loaded in axial compression. The results of the present studies may be summarized as follows:
1) The concept of energy—absorbing laminated structures with artificially introduced multiple delaminations is proposed for the possible application in crashworthiness design.
2) Buckling and subsequent postbuckling response of the laminated plates with multiple delaminations is considerably different from that of the same plates with no delaminations.
3) The preferable characteristics of energy—absorbing laminated structures is confirmed both experimentally and numerically.
4) Energy absorption behavior may be controlled intentionally, but further studies will be required in the practical design procedure for laminated plate structures.

REFERENCES

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