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Damage accumulation in composite laminates during quasi-static transverse loading

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Abstract—A mechanism of damage accumulation in composite laminates subjected to a quasi-static concentrated load is numerically studied by using the finite element method to disclose the impact damage problem. The energy release rate distributions are calculated along the delamination edges in square composite laminates with various stacking sequences. Not only circular delaminations but also more realistic impact damage models are investigated to explain the reason why the typical impact damage must be created. The effects of transverse cracks and stacking sequence on the energy release rate are discussed.

Keywords: Finite element method; delamination; transverse crack; stacking sequence; energy release rate; CAI.

1. INTRODUCTION

In recent years, CFRP composite materials have been used extensively in many engineering applications, such as aircraft and space structures, mainly because of the need to reduce weight. The material is used in the form of laminates for these aerospace applications. But it is known that structures made of composite laminates are susceptible to impact damage, such as delamination, transverse cracking, etc. [1, 2]. It is difficult to detect this impact damage from outside of the structures. Furthermore, such damage can cause severe reduction of compressive strength [3] and, as a result, design loads of the structures are often limited by the degraded compressive performance. Therefore, the mechanism of damage accumulation due to impact must be well understood in order to utilize composite laminated structures to their full advantage.

In this paper, special emphasis is placed on the interlaminar delaminations below the impact point, which usually occur in the form of multiple delaminations. A mechanism of damage accumulation in composite laminates subjected to a quasi-static concentrated load is numerically studied by using the finite element method to disclose the impact damage problem. The energy release rate distributions are calculated along the delamination edges in square composite laminates with various stacking sequences. Not only circular delaminations but also more realistic impact damage models are investigated to explain the reason why the typical impact damage must be created for study. The effects of transverse cracks and stacking sequence on the energy release rate are discussed.

In order to observe the mechanism of the damage initiation and accumulation in the quasi-isotropic composite laminates during static indentation, a transverse concentrated load was applied at the center of glass fiber reinforced composite laminates $[(0_2/45_2/90_2/-45_2)_2]_s$. Details of the experiment will not be shown in the present paper. Only the damage state obtained is shown in Fig. 1. The damage state was quite similar to those of the impact damage reported by many researchers (e.g. ref. [3]). It is reasonable to investigate the damage accumulation problem of laminates during static indentation before studying the impact damage problem.

2. FINITE ELEMENT ANALYSIS

A composite laminate with eight layers analyzed in the present paper is schematically shown in Fig. 2. Firstly we studied the energy release rate distribution along the edges of the circular multiple delaminations in the isotropic plate and cross-ply $[0/90]_{2s}$ and quasi-isotropic laminates $[-45/90/45/0]_s$ to study the effect of the

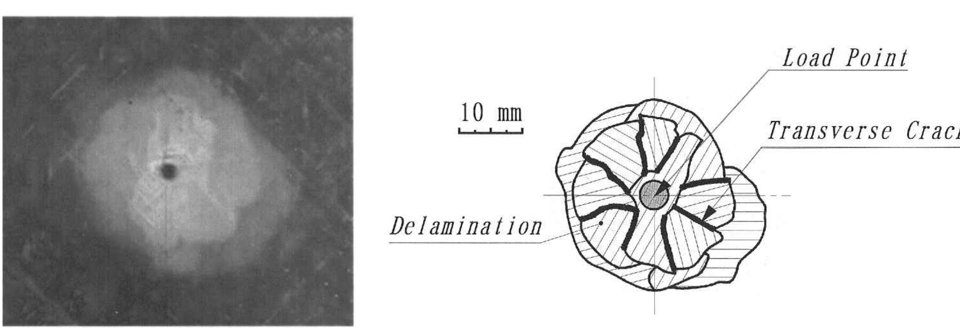


Figure 1. Typical damage shape due to a concentrated static load.

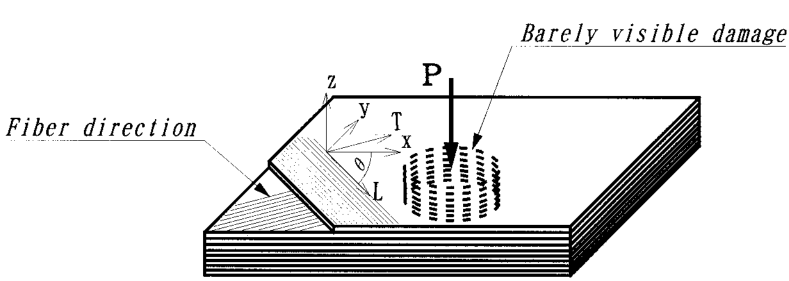
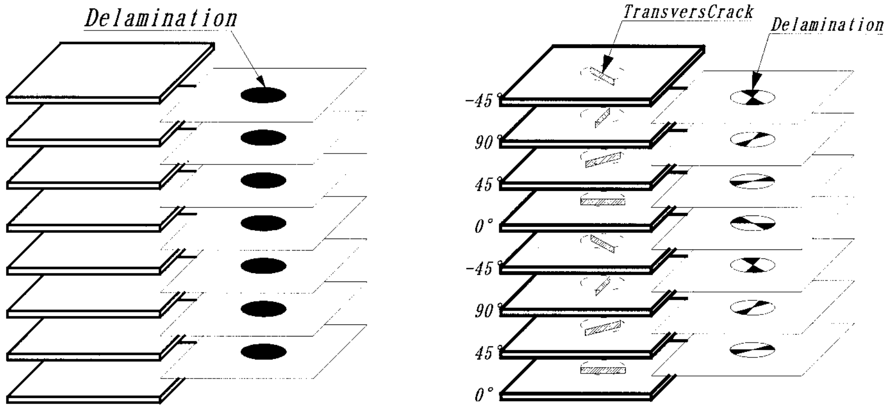


Figure 2. Composite laminate subjected to concentrated load.



(a) Model A (b) Model B

Figure 3. Models of damage analyzed.

fiber orientations on the delamination propagation (Fig. 3a). Then, we studied a damage model made of fan shaped delaminations and transverse cracks in a quasi-isotropic laminate as shown in Fig. 3b. The delaminations are connected each other via transverse cracks and form a circular projected shape.

$$E_x = 56.5\ \text{GPa}, \quad E_y = E_z = 9.15\ \text{GPa}, \quad G_{xz} = G_{yz} = 4.18\ \text{GPa},$$
$$\nu_{xy} = 0.316, \quad \nu_{xz} = \nu_{yz} = 0.262,$$

are chosen for the elastic properties of the lamina, except the isotropic plate ($E = 56.5$ GPa, $\nu = 0.316$). The dimensions of the square plates are 150 mm $\times$150 mm $\times$ 4 mm. All four edges are fixed both in in-plane and out-of-plane directions.

A commercially available finite element program (ABAQUS 5.7) is used. A finite element mesh is shown in Fig. 4. Three-dimensional twenty node isoparametric brick elements are used to model the laminates, except for the center portions of the delaminated layers where 15-node wedge elements are used. The number of elements and nodes is 5520 and 17496, respectively. A static distributed load is applied on the wedge elements at the center of the plate. In order to prevent the delaminated portions from overlapping each other, a spring element having stiffness only in the compression direction is introduced between every double node above and below the delamination. The energy release rate is calculated by using the virtual crack closure technique [4]. Very stiff and very flexible spring elements are set to easily obtain the necessary nodal forces and relative displacements between the corresponding nodes, respectively. Geometrical nonlinearity is considered.

3. RESULTS AND DISCUSSION

The relationships between applied load and center deflection are shown in Fig. 5. The hardening effect due to large deflection, being unclear for the intact plates until

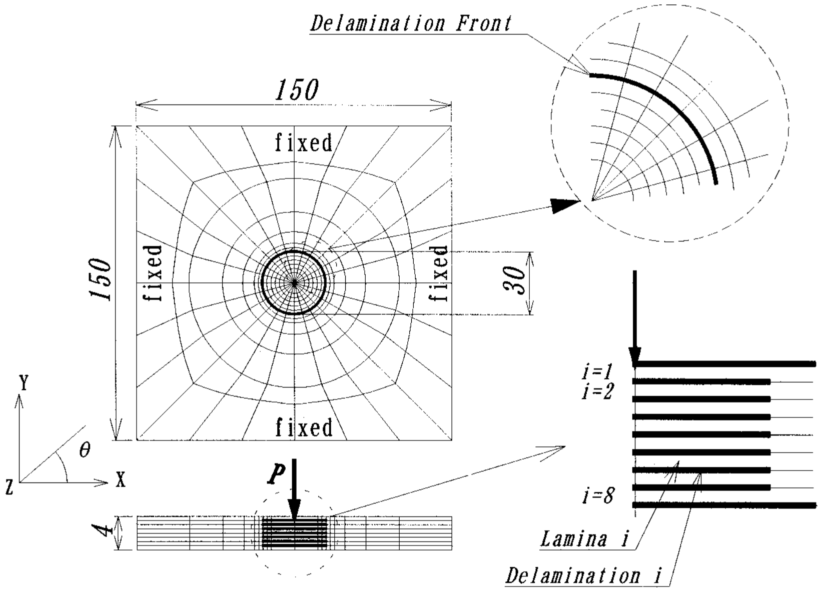


Figure 4. Typical finite element mesh.

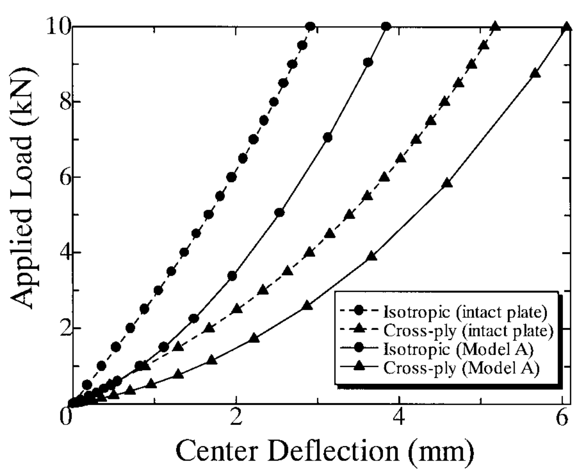
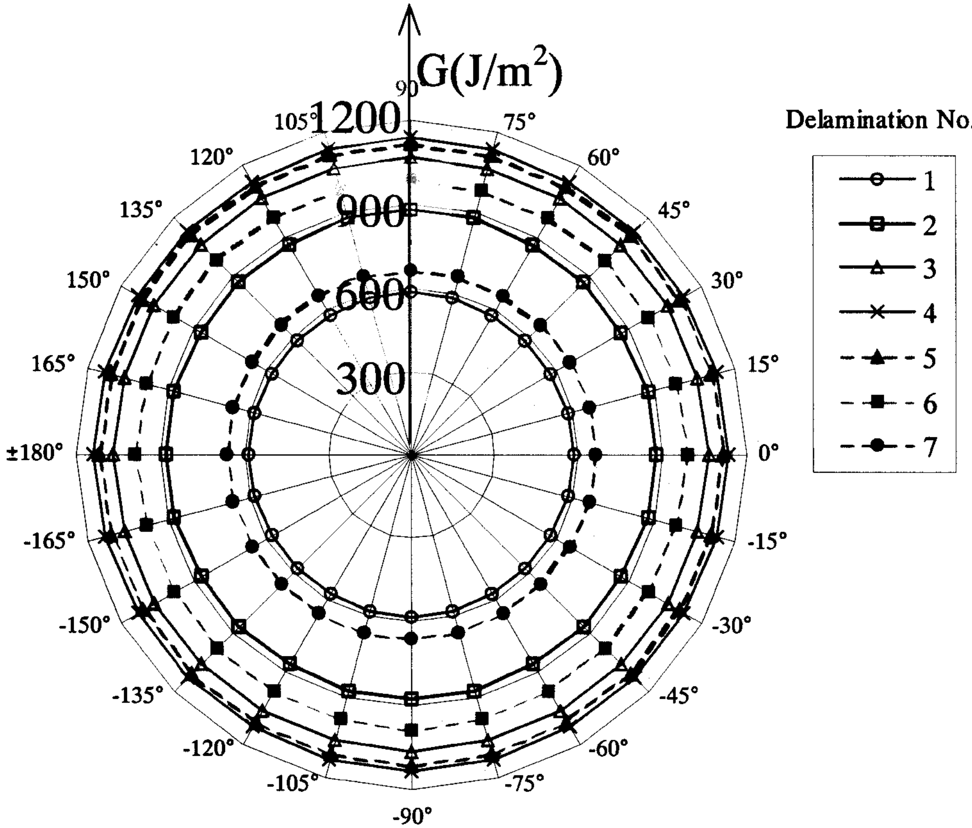


Figure 5. Relationship between applied load and center deflection.

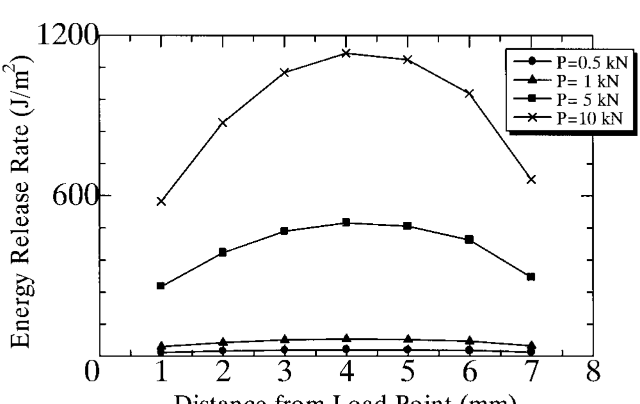
their deflections reach at half the thickness, is extremely significant for the multiply delaminated plate from the low load level. The geometrical nonlinearity must be considered to discuss the instability of the damage in the laminates.

3.1. The case of Model A

We will show the results of the isotropic plate first. The total energy release rate distributions at $P = 10$ kN are plotted in Fig. 6a. At this load level the center of the plate deflects by 3.90 mm and the effect of geometrical nonlinearity is significant



(a)



(b)

Figure 6. Energy release rate distribution at $P = 10$ kN for isotropic plate.

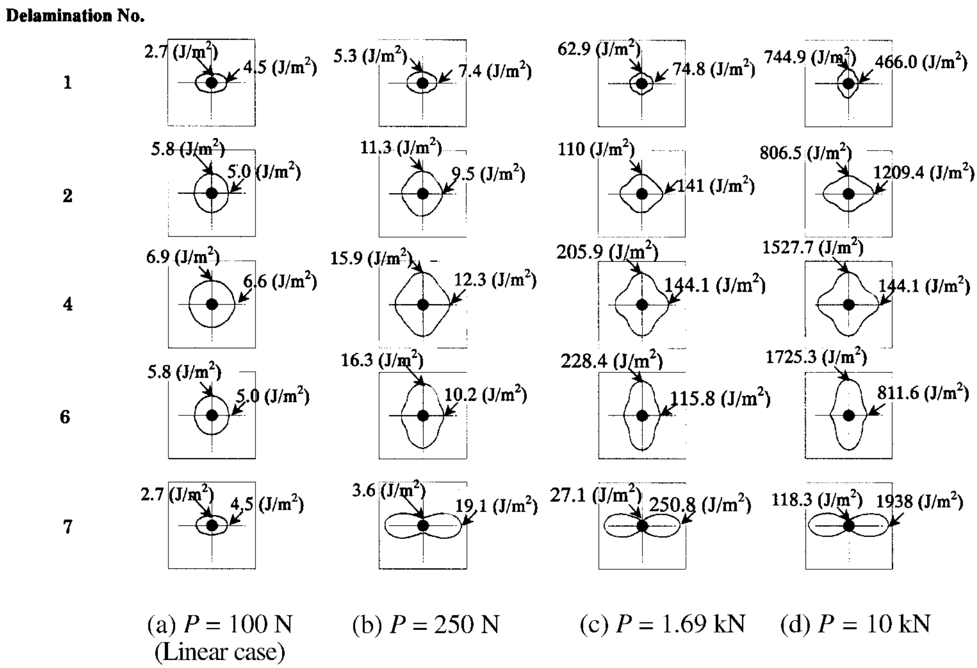


Figure 7. Changes of energy release rate distribution with the increase of the load for cross-ply laminate.

(Fig. 5). The distribution is almost circular and the effect of the square shape plate is insignificant. The energy release rate, being maximum at the middle surface and symmetric about it in the linear case, increases more rapidly at the delamination front near the bottom surface and becomes asymmetric about the middle surface. The tendency is well seen in Fig. 6b where the total energy release rate at the edge of 0° direction is plotted. The mode II component is dominant and the other terms are negligibly small.

The energy release rate distributions at the delamination fronts 1, 2, 4, 6 and 7 for cross-ply laminate and quasi-isotropic laminate are plotted in Figs 7 and 8. The energy release rate of the delamination 6 and 7 is much larger than that of the delamination 1 and 2. The energy release rate is maximum at the fiber direction of the layer outside the delaminations and symmetric about the middle surface at linear case. But the effect of geometrical nonlinearlity being larger with the increase of the load, the direction of the maximum energy release rate changes from the fiber direction of the layer above the delamination to that below the delaminations for the delamination above the middle surface. The distribution of the energy release rate for the delaminations below the middle surface shows deformation in the fiber direction of the layer below the delamination, i.e. outside the delaminations. The maximum values of the energy release rate of the delaminations 6 and 7 are even larger than that of center delamination 4 at middle surface for both laminates, though the energy release rates tend to be large at the middle surface. The tendency

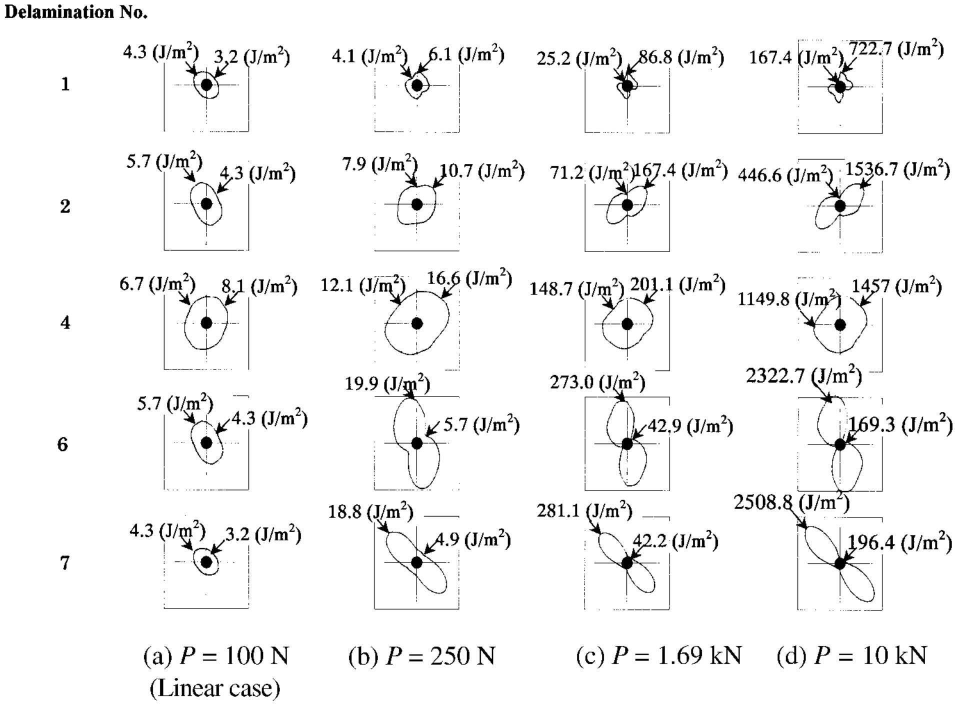


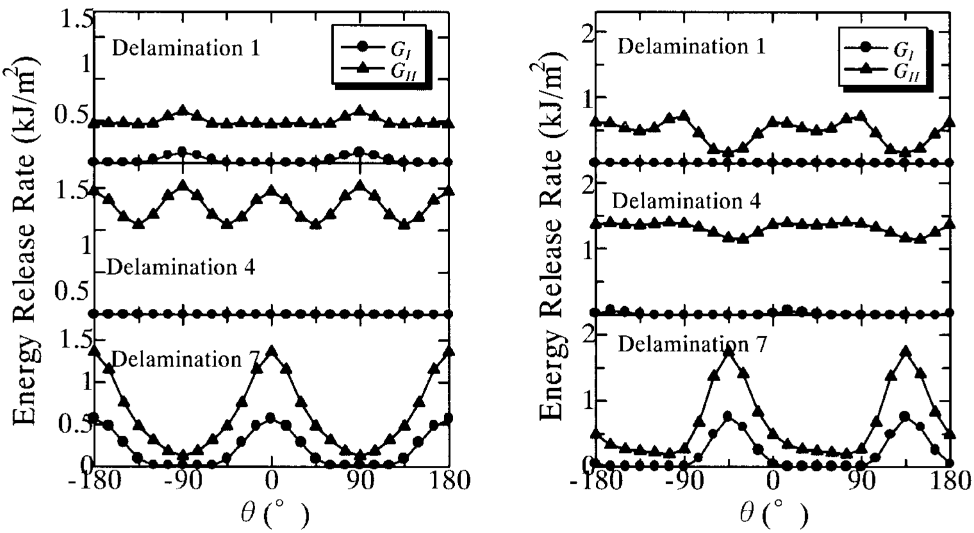
Figure 8. Changes of energy release rate distribution with the increase of the load for quasi-isotropic laminate.

becomes more evident with the increase of the load. The energy release rate distributions at the other delaminations have the same tendency as the delaminations 1, 2, 6 and 7. From the results, we can say that the delaminations tend to propagate in the fiber direction of the layer below the delamination at each interface. This coincides with the experimentally obtained delamination shape (often referred to as peanut shape) at each interface.

The components of the energy release rate for the cross-ply and quasi-isotropic laminates are plotted in Figs 9a and 9b, respectively. Both results are basically similar to that of the isotropic plate. The mode III component is negligibly small for both cases at any load level. The mode II component is still dominant at the delamination fronts above middle surface. But a mode I component existing at the delaminations near the bottom surface is not very small compared to the mode II component and must be considered to discuss the instability of the delaminations.

3.2. The case of Model B

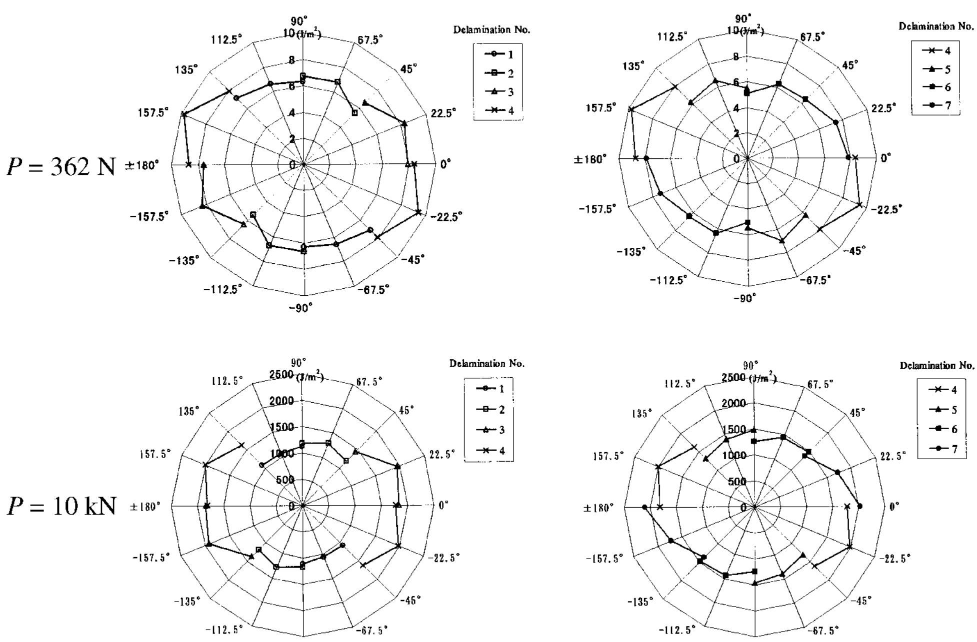
The total energy release rates at the delamination fronts at $P = 362$ N and $P = 10$ kN for model B are plotted in Fig. 10. The plots of Fig. 10a show the energy release rates at the delaminations above the middle surface and Fig. 10b shows those below the middle surface. At the low load of $P = 362$ N, the energy release



(a) Cross-ply laminate

(b) Quasi-isotropic laminate

Figure 9. The distribution of mode I and mode II components for cross-ply laminate and quasi-isotropic laminate.



(a) above the middle surface

(b) below the middle surface

Figure 10. Change of energy release rate distribution for Model B.

rate is maximum at the delamination 4 which locates at the middle surface. The gap of the energy release rate is not large between the neighboring delaminations, which are connected via a transverse crack. At large load of $P = 10$ kN, the energy release rate below the middle surface tends to be larger than that above the middle surface similar to the case of the circular delaminations. At this load, the geometrical nonlinearity is not so significant for this model as for Model A, because the delaminated area of Model B is about 1/4 of that of the Model A. As the number of plies is eight and only one round of spiral is considered, the projected shape of the energy release rate distribution is elliptic, i.e. the predicted projected damage is thought to be a little elliptic. But the shape is not strongly elongated. The difference of the energy release rate is not significant as shown in both Fig. 10a and 10b, because all the delamination edges are almost aligned to the fiber direction of the layer outside the delamination. If a greater number of plies are considered, the projected shape is thought to be more nearly rounded. More important is that even the present model with the transverse cracks and delaminations does not explain the experimentally observed damage shape, in which the largest delamination always locates near the bottom surface. Some dynamic effect may contribute to the formation of typical impact damage.

4. CONCLUSION

Two types of damage models are numerically analyzed by using the finite element method and energy release rate distributions are obtained. From the analysis, we may reach the following conclusions.

- The effect of geometrical nonlinearlity must be considered to discuss the instability of delaminations in the laminate.
- The energy release rate distribution is almost circular for square isotropic laminates.
- Though the energy release rate tends to be large at the middle surface at low load level, the position of the maximum value moves to the back surface with increase of the load.
- The energy release rate, being large in the fiber direction of the lamina just outside the delamination at low load level, rapidly increases in the fiber direction of the lamina just below the delamination with increase of the load.
- The energy release rate distribution for the model B is a little elliptic but the expected delamination shape may not be significantly elongated.

The large delamination near the back surface often observed in impact damage cannot be clearly shown from the numerical result of the present models. More factors must exist during the damage accumulation process.

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