COMPRESSIVE BEHAVIOR OF IMPACT DAMAGED COMPOSITE LAMINATES

Hiroshi Suemasu*, Wataru Sasaki**, Yuuichiro Aoki***, Takashi Ishikawa****

*Department of Mechanical Engineering, Sophia University, **Graduate School, Sophia University
*** **Advanced Composites Center,** JAXA, ****APG, JAXA

Keywords: Compression, Impact Damage, Buckling,Composite Laminate,CAI, FEM

Abstract

Mechanism of Compressive property degradation of the composite laminated plates due to transverse impact is numerically studied. The damage in quasi isotropic laminates ($[45°/90°/-45°/0°]_n$) caused by the transverse impact is called a characteristic damage state (CDS), which consists of a spiral array of inter-connected transverse cracks and delaminations. The results were compared with those of laminated plates having circular delaminations of an equivalent number and size. The compressive property degradation due to the spiral array damage was found to be insignificant compared to the circular delaminations even if the damage growth was considered. It was because the portion around the center axis connected each other through the thickness constrained relative movements of the separated ligaments. It can be said that some other factors of the impact damage neglected in the present model must contribute to the property degradation.

1 Introduction

Composite laminates are used particularly for aerospace structures due to their high specific strength and stiffness. As the toughness is not sufficient particularly in thickness direction, it is important to evaluate the over-all performance of the composite laminates by appropriate methods considering various damage tolerant properties. Compression after impact (CAI) test provides us a design data for compression strength of the composite laminates for aerospace structure[1)]. However, the mechanical meaning of CAI strength is not clear yet. Since delaminations due to the impact are thought to be the main reason for a significant reduction in the compressive strength of composite laminates, the effect of the delamination(s) on the compressive behavior has been studied by many researchers [for example 2-8]. However, the impact damage does not consist of simple circular or elliptical delaminations, but is said to take a double spiral array of inter-connected transverse cracks and delaminations shown in Fig. 1. The compressive behavior of the spiral damage model may be different from those of model with multiple circular delaminations. Suemasu[8)] have numerically studied the effect of the characteristic impact damage on buckling and postbuckling problems.

In the present paper, the buckling behavior of the buckling and post buckling behaviors of the plates with characteristic impact damage are

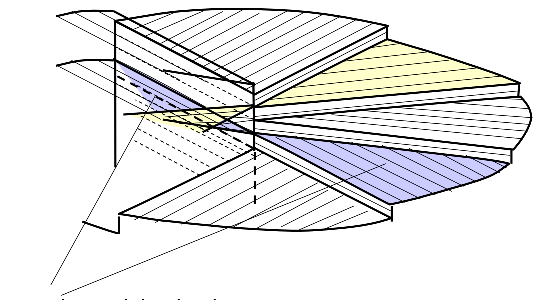
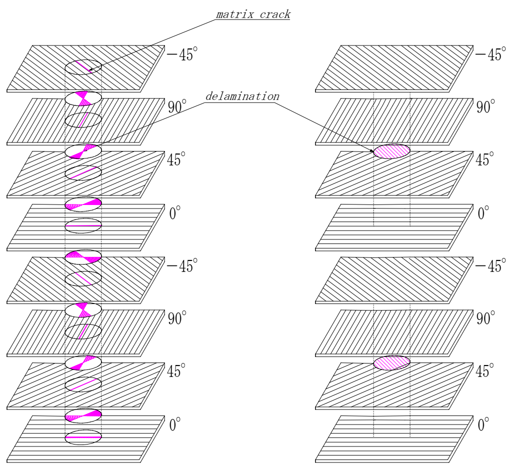


Fig. 1 A characteristic impact damage model

numerically studied to understand the effect of impact damage on the buckling and failure properties of composite pates considering damage growth.

2. Finite Element Analysis on compression instability

The compressive behaviors of the plates with characteristic damage were numerically solved by using a finite element program (ABAQUS /standard 5.8). Two models A, B as shown in Fig. 2 were considered to see the effect of the characteristic damage on compressive instability. Model A had a spiral shape damage, while model B had two circular delaminations whose total size was almost same as that of model A. The dimensions of the plate were 150mm×100mm and the thickness of 4 mm. The side edges were simply supported and free in the inplane direction. Unsymmetric laminates $[0/-45°/90°/45°]_2$ were considered instead of symmetric laminate to make the problem simple. The elastic properties of the individual lamina were E_L=56.5 GPa, E_T=E_z= 9.15 GPa, G_{Lz}= G_{Tz}= 4.18 GPa, ν_{LT}=ν_{Lz}=0.262, ν_{Tz}=0.316. The indexes *L, T, z* denote the directions of fiber, transverse to fiber and thickness, respectively. The finite element discretization was shown in Fig. 3. The loading edges were fixed and a uniform inplane displacement was applied. Three cases of damage sizes 30mm, 40mm and 50mm were analyzed. A 20 node three-dimensional solid element was used and each lamina was modeled by one layer of the solid element. To consider the contact condition at the damage surface a nonlinear spring element was set between all the corresponding nodes on the damaged surface as shown in Fig. 4, which had large spring constant only in compressive direction and zero in tensile direction. This is an approximation of the contact problem. We applied small forces in the normal direction to the plate to have small deflection and small initial opening of damage before applying compression displacement.



(a) (b)

Fig. 2 Analytical models
(a) model A: Spiral mode damage
(b) model B: Circular delamination model

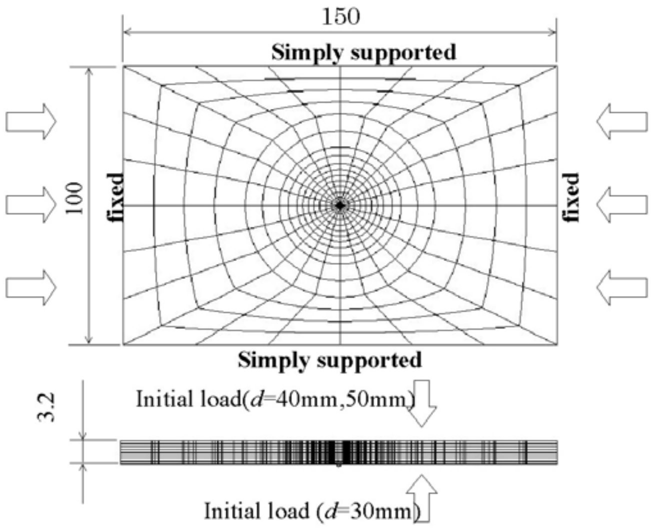


Fig. 2 A finite element discretization of a rectangular laminate with a characteristic damage.

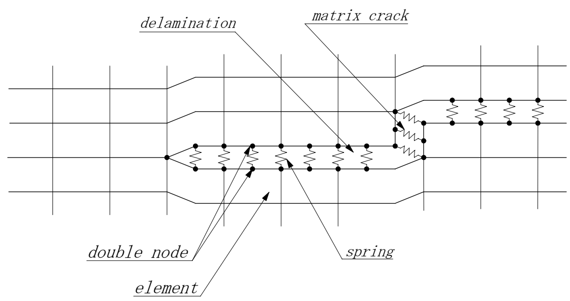


Fig. 4 Contact condition for the analysis. A spring elements was set between the damaged interface.

3. Results and Discussions of the compression instability

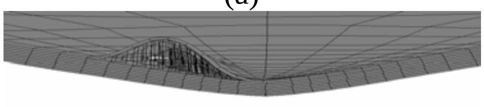
Small concentrated forces were applied on two points on its center line so that the plate had both symmetric and antisymmetric components. The deformations of model B and model A are shown in Figs 6 and 7, respectively. The diameter of the damages was 40 mm. The figures (a) were the results when the plate was in local instability and figures (b) were in global instability. The deformed portion was limited only to a delaminated portion of the compression side when plate was in the local buckling. The deformed shape of the damaged portion was similar to that of the delaminated plate fixed at the boundary. In the global instability, the model (B) with two circular delaminations showed a globally antisymmetric shape, while the spiral model remained globally symmetric shape. This was because large relative sliding of the delaminated surface was allowed for model (A) and not allowed for model (B) due to the connected at the center of the damage.

(a)

(b)

Fig. 6 Deformation of the model A
(a) P=25kN, (b) P=40kN

(a)



(b)

Fig. 7Deformation of model A (d=40mm)
(a) P=25kN, (b) P=40kN

The relationships between the applied load and deflection of the plate were plotted in Figs. 7, 8 and 9. For model B, the deflection of the center of the circular delamination is plotted. For model A, the deflection of the center of the quarter sector is plotted to clearly see the effect of the local buckling. In Fig. 7 the result of the small damage of d=30 mm. At the load of 20 kN, the local buckling occurred for both case. The buckling load of the thin surface quarter sector happened to have similar buckling strain to the circular delamination which was four times thicker than the quarter sector of model A. In this case both models did not show the change of buckling shape from symmetric shape to antisymmetric one. Global buckling regions of both models were similar to that of the intact plate.

When the diameters of the damage were larger (d=40 mm and 50 mm), the deflection of the model B became almost zero in the global buckling, while that of model A changed from negative to positive and increased with the load. As the effect of the spiral shape damage on the local bending stiffness reduction was small, the plate remained in symmetric shape in postbuckling.

The applied load is plotted against the loading edge displacement for the model A and B in Figs. 10 and 11, respectively. The compressive stiffness reduction was very small in postbuckling path in the case of model A compared to the model B. From the above results the spiral damage caused little reduction of global stiffness compared with the model B of same size damage.

The deformation shape is shown in Fig. 12 when the opening load was applied at the damaged portion of the model A. This figure shows that the center of the damage was connected from the back to the front, which constrained the relative displacement. It means that the local instability was only that of the surface delaminated portion and the rest was stable. Some other mechanism must contributed to reduce the compressive performance degradation of real laminates.

From the above results, we cannot expect that the characteristic damage itself causes significant reduction of the compression strength. There must be something such as damage growth before or just after the local buckling if the characteristic damage cause significant strength reduction.

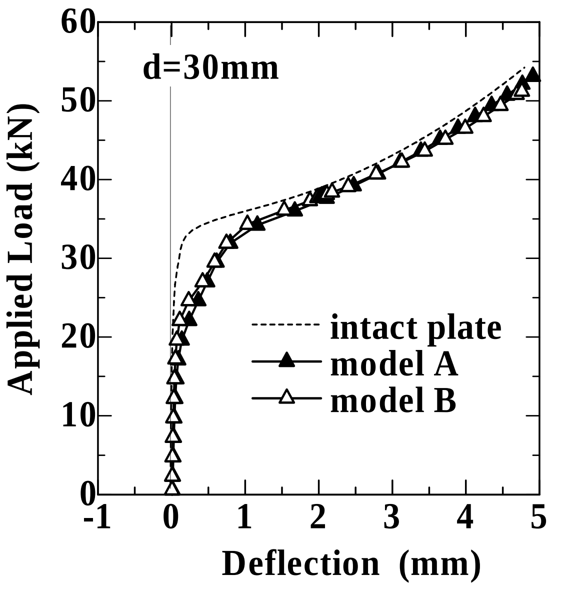


Fig. 8 The relationships between the load and the displacements of plate center (*d*=30 mm)

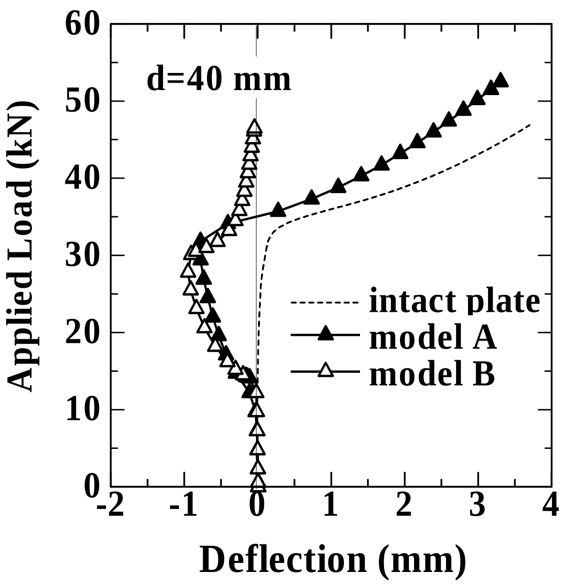


Fig. 9 The relationships between the load and the deflections of plate center for model B and center of the delaminated portion just at the surface. (d=40 mm)

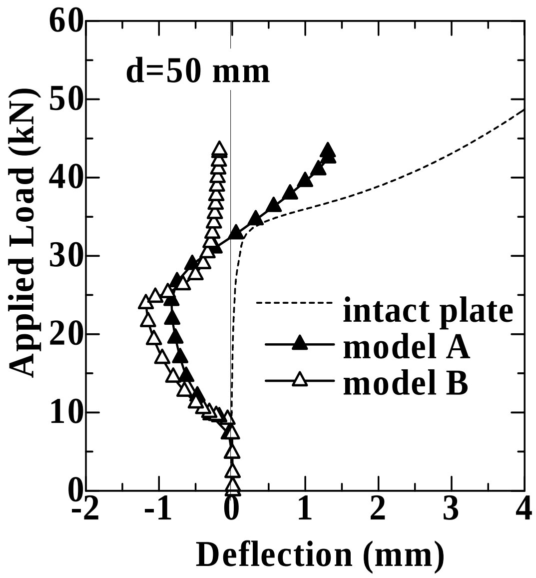


Fig. 10 The relationships between the load and the deflections of plate center for model B and center of the delaminated portion just at the surface. (d=50 mm)

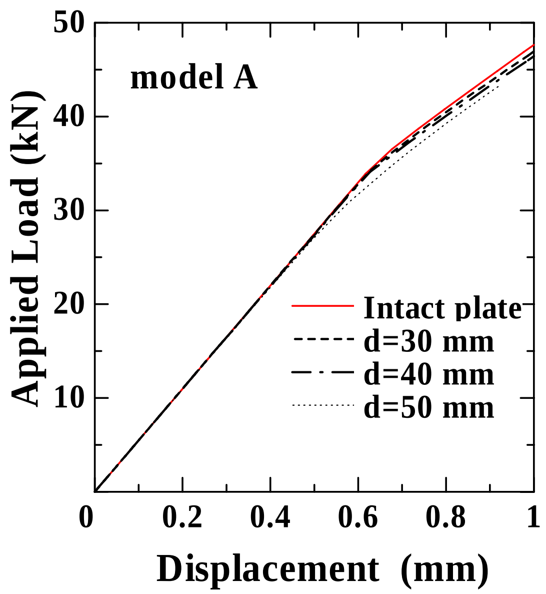


Fig. 11 The relationship between the load and the loading edge displacement of plate center for model A.

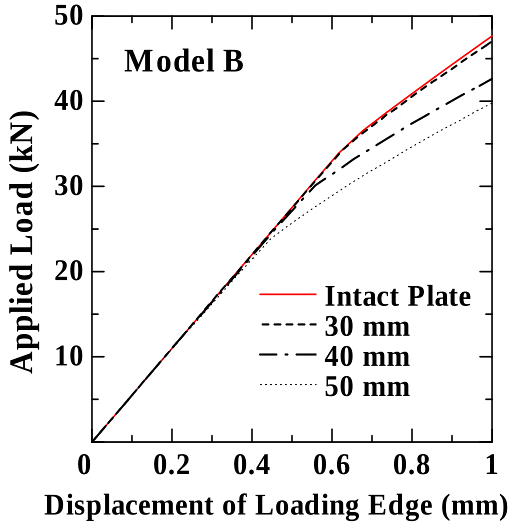


Fig. 12 The relationship between the load and the displacements of plate center for model B and (d=50 mm)

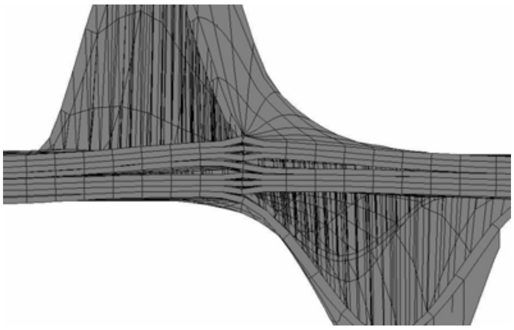


Fig. 13 The deformation at the damaged portion when the opening force was applied at the damaged portion.

4. Finite Element Analysis of Damage growth of impact damaged laminates

A cohesive element with 16 nodes, 8 nodes each on top and bottom surfaces illustrated in Fig. 14 was used to simulate delamination growth. The element had no thickness at unloaded condition. Since the crack tip area deforms strongly, the elements should be sufficiently small compared to the process zone size. A bi-linear load-displacement model was adopted. The area below the curve was equal to the critical energy release rate of the laminate. The cohesive element was implemented in the finite element code using 'user subroutine'.

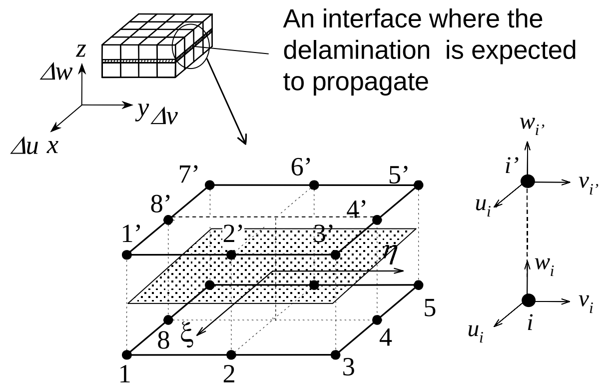


Fig. 14 Configuration of the cohesive element

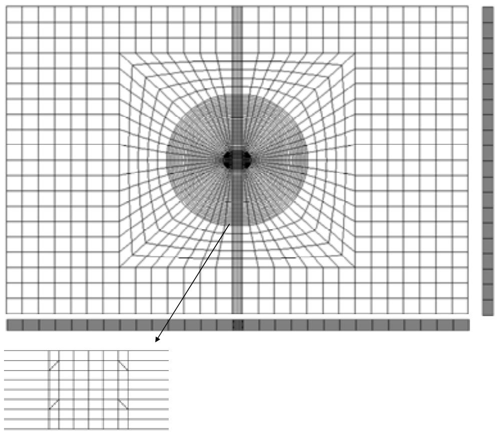
5. Results and Discussions of the compressive behavior considering Damage growth

The finite element discretisation of the delaminated models A and B are shown in Fig. 15. Fine finite element mesh was necessary to obtain smooth convergence of the solution. The initial delaminated areas of model A can be inferred from Fig.19. In the Figure the initial delaminated area of an interface consisted of two sectored ring of center angle 45°. In the 90° layer, a pair of transverse cracks inclined by 45° from the section were introduced and two transverse cracks normal to the surface were assumed each in the other layers in order to study the damage growth before or just after the local buckling due to the relative movement of the crack surface. The elastic properties of each lamina and critical energy release rate were E_x=E_y=57.5 GPa, E_z=8.87 GPa, ν_{xy}=0.32, ν_{xz}= ν_{yz}=0.34, G_{xz}=G_{yz} =4.605 GPa and G_{cr}=400 Jm^{-2}.

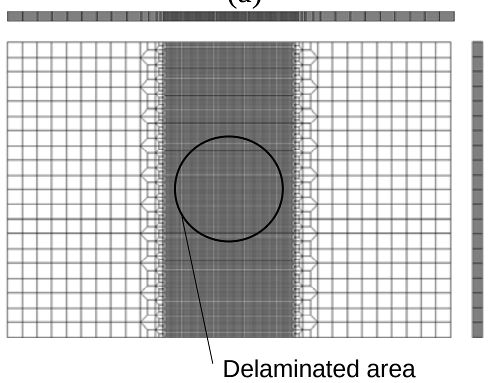
5. Results and discussions of the numerical analysis with delamination growth

. The models A and B were analyzed considering damage growth. The relationships between the load and the center deflection of each delaminated portion of the plate of models A and B are plotted in Figs.17 and 18. In the case of model B the laminate deformed with the load after the local buckling without damage growth before it became unstable at the load

P≈63kN. From Fig 19, it was thought to be caused by unstable damage growth. The unstable damage growth caused loss of load carrying capability of the plate and unstable move of system. In the case of model A the damage slightly grew with the load increase as shown in Fig. 20. The calculation became impossible because unstable growth of damage occurred at the load about 63 kN. The damage growth may not cause the global plate rapture, because the numerical analysis in case of model A was stopped at the instance that two counterpart delaminations had just attached each other as shown in the last figure of Fig. 20. In the present analysis the plate was in the region of global buckling when the damage growth was initiated.



(a)



(b)

Fig. 15 A finite element model of a delaminated composite plate (a) model A, (b) model B.

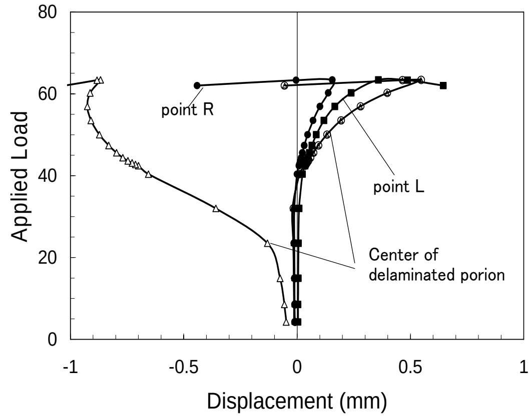


Fig.17 Relationships between the load and the center deflections of the delaminated portions of model B

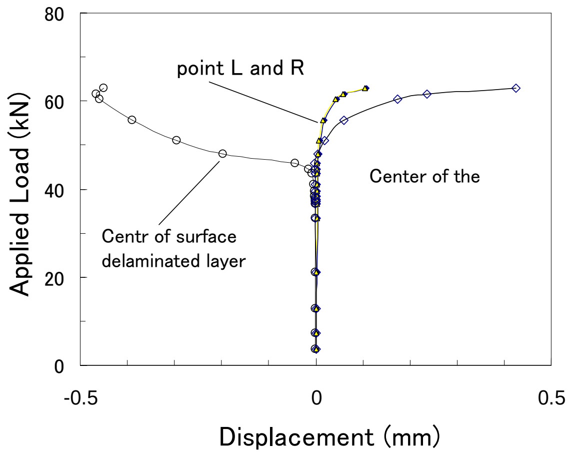


Fig.18 Relationships between the load and the deflections of three point of delaminated portions of model A

.

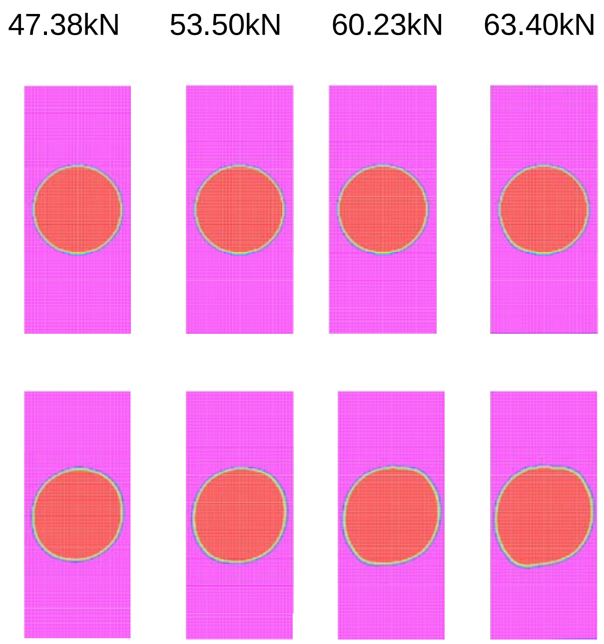


Fig. 19 Delamination growth history of the delaminated plate with three different size delaminations

6. Conclusions

Numerical analysis of the models considering impact damage was done to see the CAI strength and availability of the circular damage model. The damage growth was considered there was no significant damage growth in characteristic damage model of the impact damage before final rapture.

The present research was supported by Japan Aerospace eXploration Agency(JAXA)..

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, Composite Science and Technology, 55, pp.349-363, 1995.
2) Dost E.F., Ilcewicz L.B. and Gosse J.H., Sublaminate Stability Based Modeling of Impact-Damaged Composite Laminates, Proc. 3rd Technical Conference of American Society of Composites, pp.354-363, 1988.
3) Soutis C., and Curtis P.T., Prediction of the Post –Impact Compressive Strength of CFRP Laminated Composites, Composite Science and Technology, 56, pp.677-684, 1996.
4) Lee S.M., "Compression-After-Impact of Composites with Toughened Matrices" SAMPE Journal, pp.64-68, 1986.
5) Prichard J.C. and Hogg P.J., "The Role of Impact Damage in Post-Impact Compression Testing", Composites, Vol.21, No.6, pp.503-511, 1990.
6) Suemasu H., Kumagai T. and Gozu K. : Compressive Behavior of Rectangular Composite Laminates with Multiple Circular Delaminations I. Experiment and Analytical Development, AIAA Journal, Vol.36, No.7, pp.1279-1285, 1998.
7) Suemasu H. and Kumagai T.: Compressive Behavior of Rectangular Composite Laminates with Multiple Circular Delaminations II. Finite Element Analysis, AIAA Journal, Vol.36, No.7, pp.1286-1290, 1998.
8) Suemasu H., Nakamura K., Ishikawa T., Degradation of Compressive Properties of Composite Laminates due to Spiral Shape Damage, Journal of Japan Society for Aeronautics and Space Sciences, pp.457-458, 2003

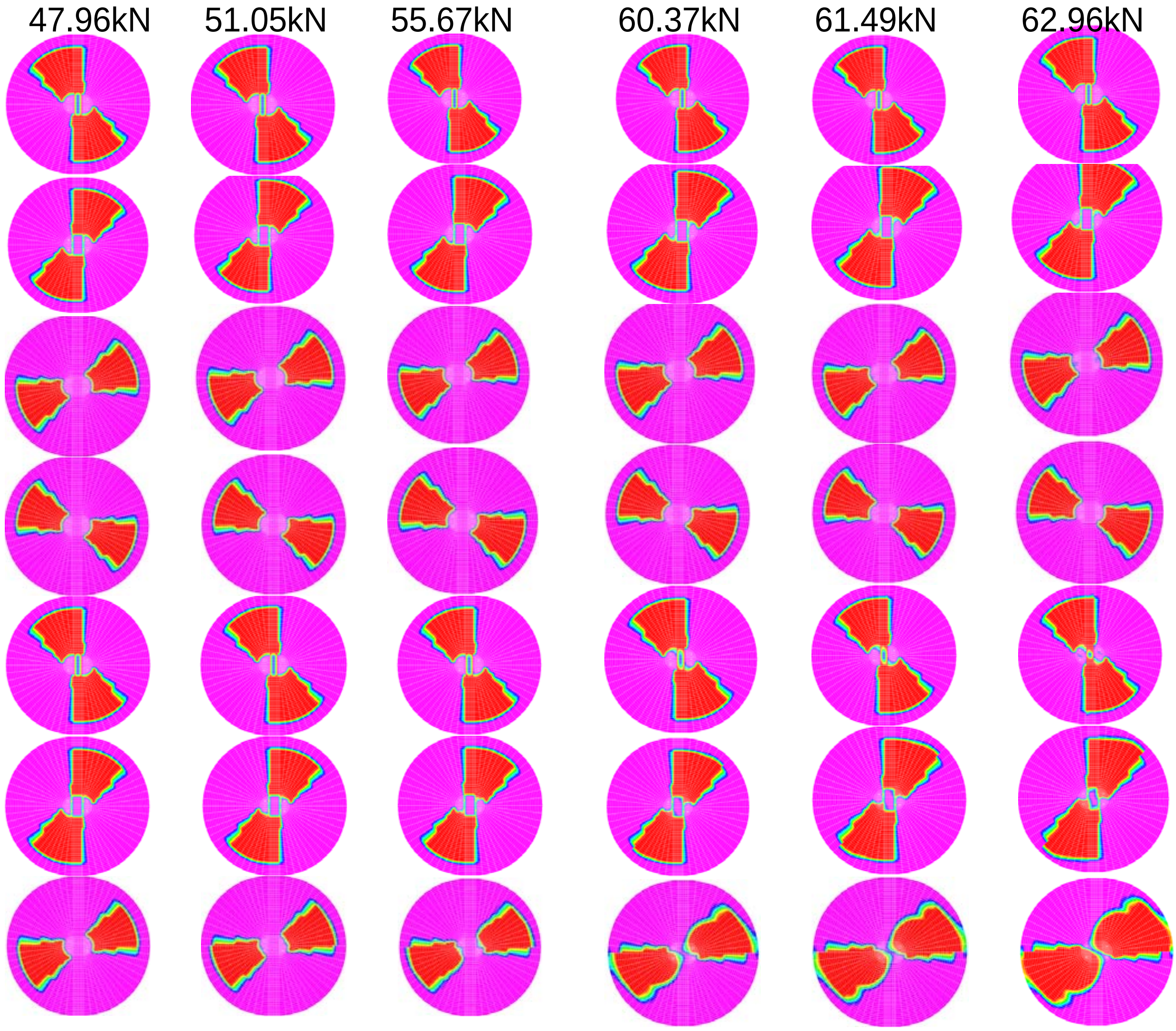


Fig.20 Damage growth at each interlaminar interface with load increase. The growth started from the locally buckled lower interface.