Postbuckling Analysis and Optimization of Composite Stiffened Panel Considering Skin-Stiffener Debonding

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Abstract

The postbuckling analysis for composite stiffened structures is a representative nonlinear analysis that is difficult to get analysis results and requires a lot of computational time. A stable, accurate, and efficient postbuckling analysis module for the structures was studied.

In order to predict the realistic behavior in postbuckling region, cohesive elements were introduced to analysis model for a consideration of skin-stiffener debonding. The analysis results were compared and verified with those of experiment and previous analysis without cohesive elements. Global behaviors and failure loads of analysis results were very similar with experimental results. Based on this analysis model, optimal design for a stacking angle of composite stiffened panel was performed, and it was confirmed that the optimized result show higher maximum failure load in postbuckling region.

1 Introduction

Composites consist of two or more materials and have mechanical, thermal and physical anisotropy which is the main characteristic and advantage from perspective of structural design. Furthermore, composites have higher stiffness and strength to weight ratio than isotropic material, so it makes possible to design and manufacture more efficient and safe structures. So far, many researches on the optimization of composite using those characteristics are being studied, but the analysis and prediction of postbuckling behavior in complex structure has remained elusive for the structural engineer.

The postbuckling analysis for composite stiffened structures has so nonlinear properties that it is difficult to get a correct analysis results and a lot of computational time is needed.

Also, it has difficulties in the prediction of failure load by the effects of the skin delamination or skin-stiffener debonding. Especially, the skin-stiffener debonding makes the structure to have a buckling prior to the designed critical buckling load, so that is a key factor to affect postbuckling strength of whole structure. Some researcher [1,2] investigated about skin-stiffener debonding to understand and estimate the failure patterns in specific cases, but an enough explanation has not been given in previous studies for the whole postbuckling analysis process of composite stiffened shell structures with the simulation of debonding failure. Therefore a stable and accurate postbuckling analysis module simulating the beginning and evolution of debonding failure is needed to analyze and optimize the composite stiffened structures. So, to simulate exact postbuckling behavior to predict exact final failure load, skin-stiffener debonding was considered to analysis model using cohesive elements [3,4].

In this study, finite element model of composite stiffened panel applied cohesive elements for skin-stiffener debonding was setup. The nonlinear postbuckling analysis was performed with consideration of progressive damage failure. The analysis results were compared and verified with those of experiment and previous analysis without cohesive elements. Based on this analysis model, optimal design for a stacking angle of composite stiffened panel was performed.

2 Postbuckling Behavior of Composite Stiffened Panel

2.1 Characteristics of Postbuckling Behavior

Based on the previous research [5] that investigated the postbuckling characteristics of the composite stiffened shell structure, finite element analysis module was build up. Test specimen was a part of the fuselage structure of a launch vehicle (KSLV-1) which is under development at KARI (Korea Aerospace Research Institute), and the tests were conducted on composite hat-stiffened curved panels under compressive loading [6].

Fig. 1, 2 show the experimental apparatus and the lay-up sequence of the test specimen, respectively. Moire fringe technique was used to observe the buckling mode, like Fig. 3, and then it is possible to find local deformations at the free edges and the local buckling at the skin between the stiffeners. From the load-end shortening curve in Fig. 4, the final failure load was 198.5 kN.

Fig. 1. Compressive load apparatus for buckling test

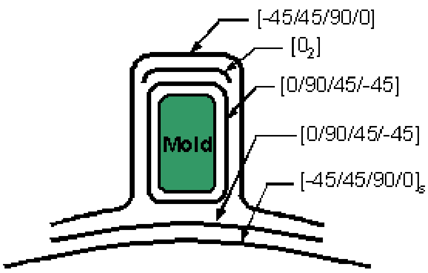
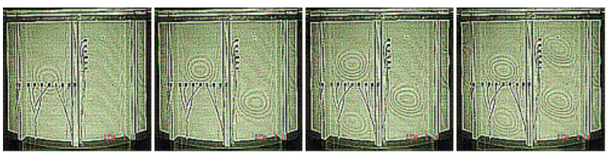


Fig. 2. Stacking angle sequence



(a)1st:62kN (b)2nd:64kN (c)3rd:73kN (d)4th:81kN
Fig. 3. Buckling mode results in experiment

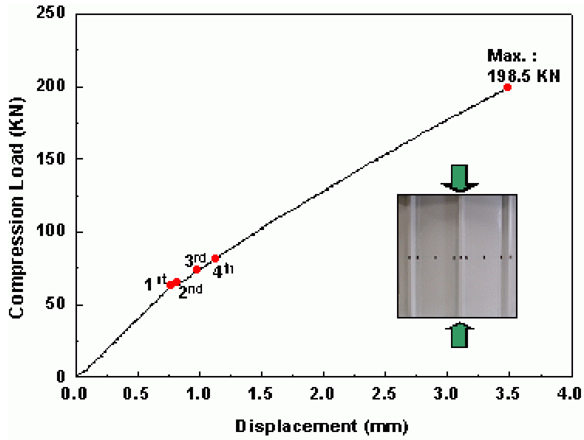


Fig. 4. Load-end shortening curve for experiment

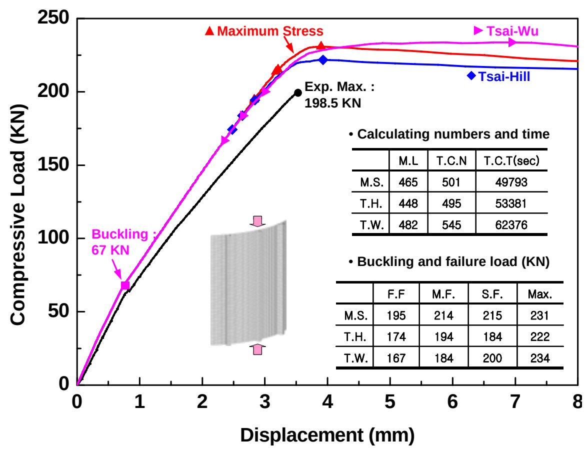


Fig. 5. Load-end shortening curve for FE analysis

2.2 Postbuckling Analysis

To analyze the characteristics by analytical method, ABAQUS was adopted. FE model of composite stiffened panel was constructed and STABILIZE method was used for a stable nonlinear postbuckling analysis. This curved shell structure was made of carbon/epoxy unidirectional prepreg (HT145/RS1222). And also, the progressive damage of composite material was applied using USDFLD (USer Defined FieLD) for accurate prediction of the ultimate failure load [5].

In the load-end shortening curves for the analysis and experiment (Fig. 5), the initial slope of analysis result was similar with that of the experiment, but there is much difference in the postbuckling region. The ultimate failure load of analyses was higher than the experimental result, also. These differences can result from the neglect of skin-stiffener debonding in analyses.

From the above results, the necessary of application of debonding to FE model is confirmed.

3 Analysis of Skin-Stiffener Debonding

3.1 Cohesive Elements

The cohesive elements is a interface element which can simulate the behavior of bonded interface, like an adhesive joints or interlaminate in composites. It models the initiation and the propagation of damage leading to eventual failure at the bonded interface, and generally be considered to be of zero thickness

Cohesive behavior defined directly in terms of a traction-separation law [4]. Eq. 1 shows a linear elastic traction-separation law prior to damage, and after damage initiation, cohesive element simulate the delamination at interfaces of composites in terms of traction versus separation.

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{Bmatrix} = K_P \delta \qquad (1)$$

The nominal traction stress vector, t, consists of three components of t_n , t_s and t_t which represent the normal and the two shear tractions, respectively. The corresponding separations are denoted by δ_n, δ_s, and δ_t. Fig. 6 shows a Fracture mode I and II behavior of the constitutive law of cohesive element [7]. The first part of that is a linear relation with a high value of penalty stiffness, K_P which can be estimated by Eq. 2 [8].

$$K_P \cong \frac{E}{T_0} \qquad (2)$$

To predict a damage initiation, the maximum nominal stress/strain ratio or quadratic functional nominal stress/strain criterion (Eq. 3) was used. Also, damage evolution can be defined based on the fracture energy that is equal to the area under the traction-separation curve. The mixed-mode formulations were used such as the power law form, or Benzeggagh-Kenane (BK) form in Eq. 4.

Recently, ABAQUS, a commercial FE analysis tool, imbedded the cohesive element which is used in the FE model of this research.

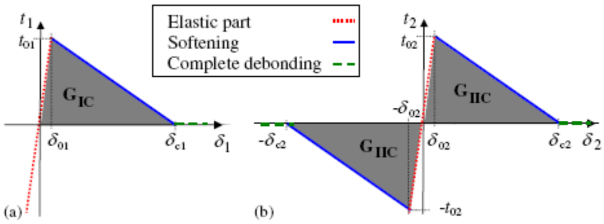


Fig. 6. (a) Fracture mode I and (b) mode II behavior in cohesive element [7]

$$\left\{\frac{t_n}{t^o{}_n}\right\}^2 + \left\{\frac{t_s}{t^o{}_s}\right\}^2 + \left\{\frac{t_t}{t^o{}_t}\right\}^2 = 1 \qquad (3)$$

$$G_n^C + (G_s^C - G_n^C)\left\{\frac{G_S}{G_T}\right\} = G^C \qquad (4)$$

$$G_S = G_s + G_t, G_T = G_n + G_S$$

3.2 Analysis of Composite Stiffened Panel using Cohesive Elements

From the basis of former analysis model, FE model of composite stiffened panel applied cohesive elements was constructed. FE model and the boundary conditions are shown in Fig. 7. The model was consisted with 2-dimensional shell elements (S4R) and 3-dimensional cohesive elements (COH3D8) with 16411 nodes and 21240 elements, and has a relatively fine mesh in the stiffener adhesive area. The structure is made of carbon/epoxy unidirectional prepreg, and the stacking sequence is $[-45/45/90/0]_S$.

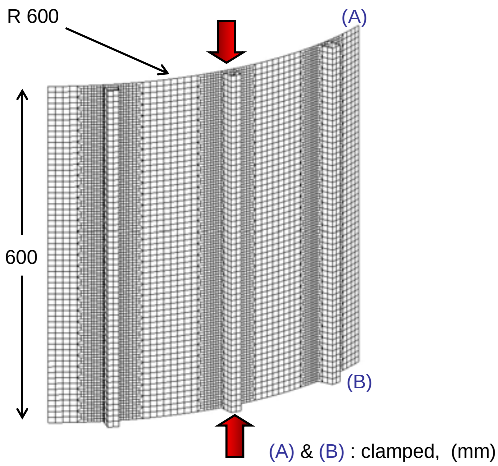


Fig. 7. The geometry of analysis model and the boundary conditions

Fig. 8 shows the load-end shortening curve for the postbuckling analysis considering skin-stiffener debonding(3), comparing with those of the previous experiment(1) and the analysis without cohesive element(2). The initial slopes of all cases are almost same before the first buckling load, though the analysis result(3) agree with experiment one more than that(2) in the postbuckling region. This is due to that debonding behavior was applied to the analysis model, therefore maximum failure load decreased. From above results, the need of cohesive element was confirmed.

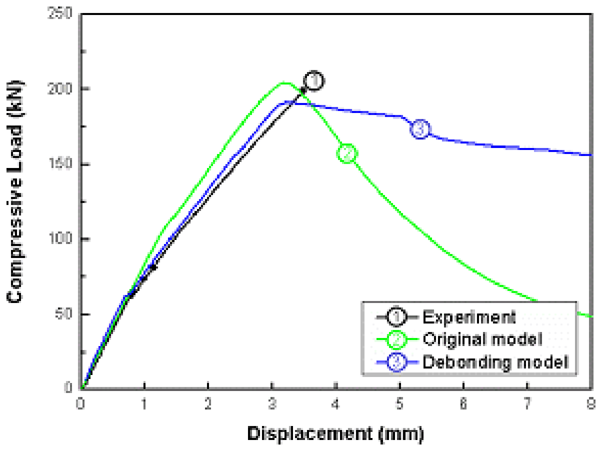


Fig. 8. Load-end shortening curve for the experiment and analyses results

4 Micro Genetic Algorithm

In the optimal design of composite structures, genetic algorithm has been used widely. Genetic algorithm (GA) is powerful and easily adopted to many different optimization problems cause of these advantages; GA uses a nondeterministic and probabilistic scheme for a calculation process, so it can avoid a premature convergence. Moreover, by the use of discrete design variables, it is simple and suitable to use the discrete ply angles of composites as design variables.

However GA has been known that it needs huge calculation costs. In order to reduce the calculation cost of classical single GA (SGA), micro genetic algorithm (micro-GA) was introduced. Micro-GA is more effective than a conventional GA, because the diversities from the nominal convergence and the re-initialization process, the specific characters of micro-GA, make it to search the optimums with a small population size.

In the Fig. 9, the optimal procedure using micro-GA is shown.

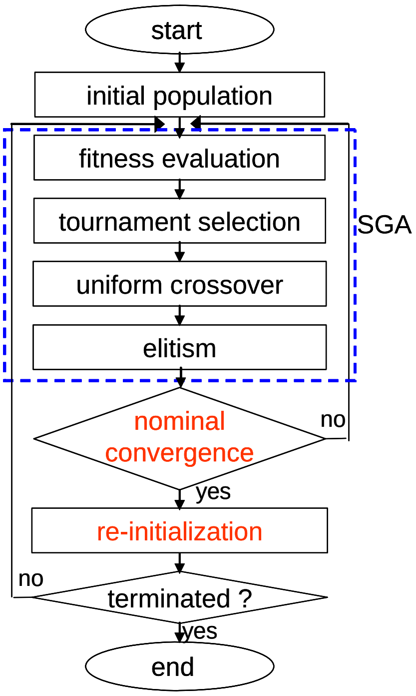


Fig. 9. Flow chart of micro-GA procedure

5 Optimal Design of Composite Stiffened Panel

5.1 Linear Buckling Load Optimization

For the verification of optimizing performance using micro-GA, optimal design for a stacking angle of composite stiffened panel was performed. A linear (eigenvalue) bucking analysis was applied for investigation because it is simpler and need less calculation costs than nonlinear postbuckling analysis. Optimization objective was to maximize linear buckling load of composite stiffened panel of launch vehicle, which was the same model with a previous chapter in this study.

$$-90^\circ \le x_1, x_2, x_3, x_4 \le 90^\circ \qquad (5)$$
$$\Delta x_i = 15^\circ$$

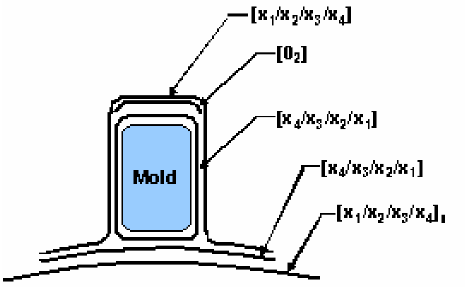


Fig. 10. Stacking sequence for design variables

The stacking angle of skin and stiffeners composite plies were used for the design variable, and assumed as symmetric. The four variables were selected to maintain symmetry for full structure, and their variation range and level are shown in Eq. 5 and Fig. 10. All calculation points were examined in order to verify the performance of optimum search. The global optimum was located on the two points as shown below with the critical buckling load, P_{cr_opt} is 89.775 kN

$$[x_1 / x_2 / x_3 / x_4] = [-15/45/-90/-75],\ [15/-45/-90/75]$$

The optimization result of micro-GA was compared with that of general single GA (SGA) during 20 times of repeated tries. Table 1 summaries the parameters and results of SGA and micro-GA. Both algorithms had similar success number and same result near the global optimum.

Table 1. Genetic algorithm variables and optimum results of linear buckling load

variables	**SGA**	**Micro-GA**
Population size	30	5
Maximum generation	200	400
Pc	0.7	0.5
Success number	10/20	12/20
Near optimums	87.191 kN 89.265 kN	87.191 kN 89.265 kN
Calculation points	2610	687

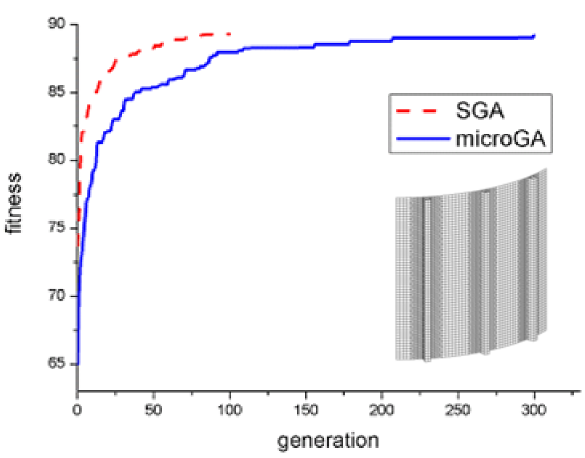


Fig. 11. History of elite fitness in optimization

The evolution of elite fitness in optimization process is illustrated from Fig. 11. At the early stage, micro-GA had slower growth rate than SGA, but it found the same optimum finally. However, micro-GA used only 30% of calculation points of SGA, and that proves its own effectiveness.

5.2 Nonlinear Postbuckling Failure Load Optimization

Optimization for a stacking angle of composite stiffened panel was performed with the nonlinear postbuckling analysis model. The same loading condition and analysis model considering skin-stiffener debonding in chapter 3.3 was used. Also, micro-GA was adopted for optimization with equal design variable of Eq. 5. Objective function was to maximize postbuckling failure load, and symmetric stacking sequence was assumed.

Table 2 shows the parameters and results of optimization, and the evolution of elite fitness in optimization process is illustrated from Fig. 11. d the postbuckling failure load of optimized and unoptimized analysis results are compared in Fig. 13. The final optimum is occurred at the points of $[15/-45/15/0]_S$ with a maximum failure load of 222.7 kN, after 3 times of repeated optimization process.

As shown in Fig. 13, the optimized maximum failure load is 21.3% and 12.2% higher than those of the unoptimized analysis result and experiment result, respectively. In addition, it is confirm that the slope of curve, means structural stiffness, increase very much.

Table 2. Genetic algorithm variables and optimum results of nonlinear postbuckling failure load

variables	**Micro-GA**
Population size	5
Maximum generation	200
Pc	0.5
Success number	1/3
Optimums	222.7 kN
Calculation points	453

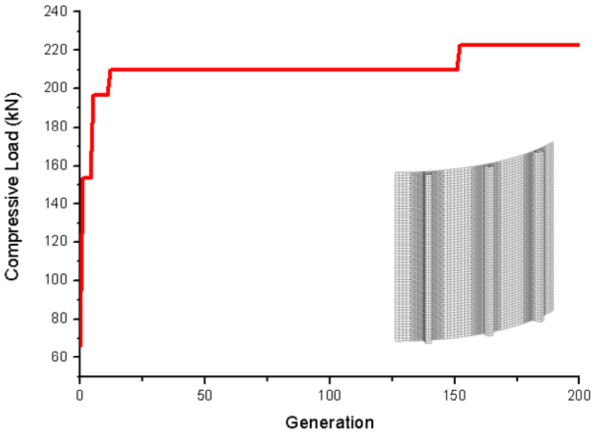


Fig. 12. History of elite fitness in optimization

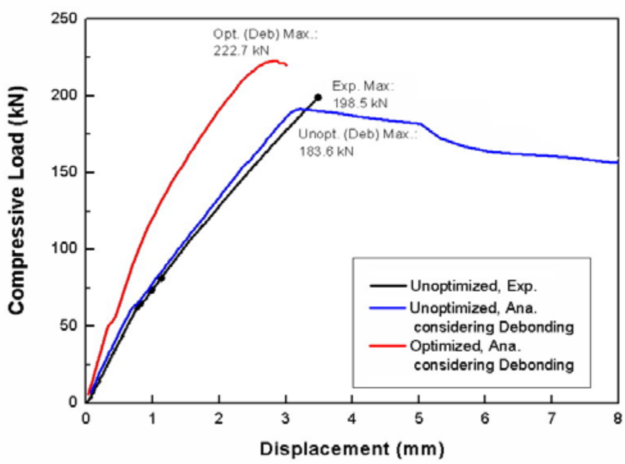


Fig. 13. Optimized and unoptimized analysis results

5 Conclusion

In order to predict the realistic behavior in postbuckling region, cohesive elements were introduced to analysis model for a consideration of skin-stiffener debonding. The nonlinear postbuckling analysis result was compared with those of experiment and previous analysis without cohesive elements. Global behaviors and failure loads of analysis results were very similar with experimental results. Therefore, the need of cohesive element for the postbuckling analysis of composite stiffened panel was confirmed.

Based on this analysis model, optimal design for a stacking angle of composite stiffened panel was performed. For effective optimal process, the application of micro-GA was suggested and verified by the optimization of linear buckling load. It was confirmed that the optimized result show a higher maximum failure load in postbuckling region.

References

[1] J. W. H. Yap, M. L. Scott, R. S. Thomson and D. Hachenberg, “The analysis of skin-to-stiffener debonding in composite aerospace structures,” *Composite Structures*, 57, pp. 425-435, 2002

[2] R. Krueger, M. K. Cvitkovich, T. K. O’Brien and P. J. Minguet, “Testing and Analysis of Composite Skin/Stringer Debonding Under Multi-Axial Loading,” *Journal of Composite Materials*, 34, 15, pp. 1263-1300, 2000

[3] P. P. Camanho, C. G. Dávila and S. T. Pinho, “Fracture analysis of composite co-cured structural joints using decohesive elements,” *Fatigue Fract. Engng. Mater. Struct.*, 27, 2004

[4] ABAQUS/Standard User's Manual V.6.5.

[5] S. H. Oh, K. S. Kim and C. G. Kim, “An efficient postbuckling analysis technique for composite stiffened curved panels”, *Composite Structures*, 74, 3, pp. 361-369, 2006.

[6] K. S. Kim, J. S. Yoo, J. M. An, Y. S. Jang, Y. M. Yi and G. R. Cho, “Postbuckling Failure Behaviors of Hat-Stiffened Composite Panels with Different Bonding Methods,” *Key Engineering Materials*, pp. 181-184, 2007.

[7] P. Robinson, U. Galvanetto, D. Tumino, G. Bellucci and D. Violeau, “Numerical simulation of fatigue-driven delamination using interface elements,” *Int. J. Numer. Meth. Engng*, 63, pp. 1824–1848, 2005.

[8] L. Daudeville, O. Allix and P. Ladevèze, “Delamination analysis by damage mechanics: some applications,” *Composites Engineering*, 5, pp. 17–24, 1995.