Optimal Design of Laminate Composites with Gradient Structure for Weight Reduction

Sung Ki Back*, Tae Jin Kang and Kyung Woo Lee*****

Keywords: laminate composites, gradient structure, weight reduction

ABSTRACT

In an effort to construct a structure under the design principle of minimal use of materials for maximum performances, a discrete gradient structure has been introduced in laminate composite systems. Using a sequential linear programming method, the gradient structure of composites to maximize the buckling load was optimized in terms of fiber volume fraction and thickness of each layer. Theoretical optimization results were then verified with experimental ones. The buckling load of laminate composite showed maximum value with the outmost [0°] layer concentrated by almost all the fibers when the ratio of length to width(aspect ratio) was less than 1.0. But when the aspect ratio was 2.0, the optimum was determined in a structure where the thickness and fiber volume fraction were well balanced in each layer. From the optimization of gradient structure, the optimal fiber volume fraction and thickness of each layer were proposed. Experimental results agreed well with the theoretical ones. Gradient structures have also shown an advantage in the weight reduction of composites compared with the conventional homogeneous structures.

1. INTRODUCTION

The desire to make new materials and/or structures with better performance than current ones has continued from man's earliest days. Engineering design is a process for structuralization of required functions. There are two approaches to embodiment of new functions starting from a certain material. One is the direction of affording new intrinsic

---

* Department of Fiber and Polymer Science, Seoul National University

** Department of Fiber and Polymer Science, Seoul National University

*** Division of Fashion and Textiles, Dong-A University

properties to the material itself, and the other is the direction of achieving new functions by way of new structuralization process and/or new method of structure control starting from common materials.

With increasing use of fiber-reinforced composites in various fields, especially in the weight sensitive fields such as aerospace industries, the concern about new structuralization of composites have been rapidly increased in recent years. This has not only accelerated the development of new material systems but also advanced the optimal design of composite materials. Recently many researches have been reported on the subject of structural optimization.

Schmit and Farshi[1,2] reported a method for the optimum design of laminated composite plates for minimum weight, subjected to multiple in-plane loading conditions.

A cracked fiber reinforced angle-ply laminate composites were analyzed using fracture mechanics by Wang and Karihaloo[3,4]. The solution of the formulated min{max} optimization problem was obtained by the bound-formulation method and mathematical programming[5].

Riche et al.[6-7] used discrete ply angles as a design variable in the optimum design of composite laminates with respect to buckling load.

Todoroki et al.[8] proposed an object-oriented approach to optimize composite laminated plate stiffness with discrete ply angles.

Hu and Lin[9] investigated the buckling resistance of symmetrically laminated plates with a given material system and subjected them to uniaxial compression with respect to the fiber orientations by using a sequential linear programming method[10] together with a simple move-limit strategy.

Okamoto[11,12] put forward new concepts of engineering design. He proposed many promising designs, for example, inhomogeneous composites in cylindrical tube structures, functionally graded materials/structures, multi-functional composites, and intelligent composites which changed their own properties and/or grew and changed their shapes, adapting to their environment.

In the present investigation, the buckling optimization of laminate composites with different fiber volume fractions and thicknesses of each layer was performed using a sequential linear programming method, together with a simple move-limit strategy. The critical buckling loads of composites were calculated using the bifurcation buckling analysis, implemented in the ABAQUS[13] finite element program. And post-buckling analysis was followed on the basis of results of buckling optimization. Firstly, the calculation of the fiber volume fraction of each layer in given composite systems and optimization procedures are briefly reviewed. Then the associate optimal results are presented, together with the most useful conclusions obtained from this study.

2. ANALYSIS

2.1 Finite Element Analysis

In the finite element analysis, the laminate plates were modeled using nine-node isoparametric laminate shell elements with six degrees of freedom for a node(three displacements and three rotations).

2-2. Model Geometry and Boundary Conditions

The buckling loads and post buckling strengths of the laminate composites subjected to a uniaxial compressive load N_x in the x direction per unit length applied at the top edge of the laminate composite in the x direction were analyzed. The aspect ratio had the values of 0.5 and 2.0, respectively. The total thickness of the composite was 2.4 mm. The fiber volume fraction of each layer was between 0% and 70%. We considered the boundary conditions that prevented out movements in the y and z directions, v and w, but allowed in-plane movement, u with no rotations on the top of the model. At the bottom, all displacements and rotations were prevented.

2-3. Determination of Buckling Load

A system of non-linear algebraic equations in the incremental form of finite element analysis is expressed as

$$[K_t]d\{u\} = d\{p\}$$

where $[K_t]$ is the tangent stiffness matrix, d{u} is the incremental nodal displacement vector and d{p} is the incremental nodal force vector.

Within the range of elastic behavior, it is well known that when the deformation of a structure is small, the non-linear theory leads to the same critical load as the linear one. Consequently, if only the buckling load is to be determined, the calculation can be greatly simplified by assuming that the deformation is small. The linearized formulation gives a tangent stiffness matrix in the following expression:

$$[K_t] = [K_L] + [K_\sigma]$$

where $[K_L]$ is a linear stiffness matrix and $[K_\sigma]$ is a stress stiffness matrix. If a stress stiffness matrix $[K_\sigma]_{ref}$ is generated according to a reference load $\{p\}_{ref}$, for another load level {p},

we have $$\{p\} = \lambda\{p\}_{ref} \quad ; \quad [K_\sigma] = \lambda[K_\sigma]_{ref}$$

When buckling occurs, the external loads do not change, i.e. d{p}=0. Then the bifurcation solution for the linearized buckling problem may be determined from the following eigenvalue equation:

$$([K_L] + \lambda_{cr}[K_\sigma]_{ref})d\{u\} = 0$$

where λ_{cr} is an eigenvalue and d{u} becomes the eigenvector defining the buckling mode. The critical load $\{p\}_{cr}$ can be obtained from $\{p\}_{cr} = \lambda_{cr}\{p\}_{ref}$.

3. EXPERIMENTS

A basic materials characterization of unidirectional laminae aims to establish their intrinsic elastic and strength properties to predict the buckling load and post buckling strength of laminated composites. Comparisons of theoretical buckling optimization results with experimental results were performed.

4. CONCLUSIONS

Buckling optimization for laminate composites with gradient structure was performed under a uniaxial compressive loading condition with respect to the thickness and fiber volume fraction of each layer. Post-buckling analysis was also performed for the laminate composites. For verification purpose, experiments were performed and compared with predicted optimal structures. From this study, the following conclusions were made.

1. Analyses showed that the buckling load and post-buckling strength increase as the gross fiber volume fraction increases for both the gradient-structured and homogeneous composites.
2. Experiments were in good agreement with the optimization results obtained using the sequential linear programming method.
3 Optimization results of laminate composites were affected by the aspect ratio. For the aspect ratio of 0.5, the optimum was obtained when the volume of fiber was maximized in the out-most layer. However, for the aspect ratio of 2.0, the optimum needs balanced values between the thickness and fiber volume fraction in each layer. Especially, in cases of $[0/90]_s$ and $[90/0]_s$ composites, in spite of the increase of the gross fiber volume fraction, the thickness ratio of the outer layer did not increase significantly and the fiber volume fraction of the inner layer increased as the gross fiber volume fraction increased.

4 Gradient structures also had an advantage over conventional homogeneous structures by saving fiber volumes in the composite systems. For the laminate composite with gradient structure, the fiber volume was reduced by 15-30% and the weight of composite by 6-12% as compared to the conventional homogeneous composites.

REFERENCES

1. L. A. Schmit Jr. and B. Farshi, “Optimum Laminate Design for Strength and Stiffness”, Int. J. Num. Meth. Engng., Vol. 7, pp. 519-536, 1973
2. L. A. Schmit Jr. and B. Farshi, “Optimum Design or Laminated Fiber Composite Plates”, Int. J. Num. Meth. Engng., Vol. 11, pp. 623-630, 1977
3. J. Wang and B. L. Karihaloo, “Optimum in situ Strength Design of Composite Laminates. Part I: In situ Strength Parameters”, J. Compos. Meter., Vol. 30, No. 12, pp.1314-1337, 1996
4. J. Wang and B. L. Karihaloo, “Optimum in situ Strength Design of Composite Laminates. Part II: Optimum Design”, J. Compos. Meter., Vol. 30, No. 12, pp. 1338-1357, 1996
5. N. Olhoff, “Multicriterion Structural Optimization via Bound formulation and Mathematical Programming”, Struct. Optimiz., Vol.1, pp. 11-17, 1989
6. R. L. Riche and R. T. Haftka, “ Optimization of Laminate Stacking Sequence for Buckling Load Maximization by Genetic Algorithm”, AIAA J., Vol. 31, No. 5, pp. 951-957, 1993
7. R. T. Haftka and J. L. Walsh, “Stacking Sequence Optimization for Buckling of laminated Plate by Integer Programming”, AIAA J., Vol. 30, No. 3. Pp. 814-819, 1992
8. A. Todoroki et al., "Object-Oriented Approach to Optimize Composite Laminated Plate Stiffness with Discrete Ply Angles", J. Compos. Mater., Vol. 30, No. 9, pp.1020-1041, 1996
9. H. T. Hu and B. H. Lin, “Buckling Optimization of Symmetrically Laminated Plate with Various Geometris and End Conditions, Composites Science and Technology, Vol. 55, pp. 277-285, 1995
10. O. C. Zienkiewicz and J. S. Champbell, “Shape Optimization and Sequential Linear Programming, in Opimum Structural Design, Theory and Application”, ed. R. H. Gallagher and O. C. Zienkiewicz, John Wiley, New York, pp. 109-126, 1973
11. H. Okamoto, “A Dialogue on Biomimetic Design for Natural Technology”, Biomimetics, vol. 2, No. 1, pp. 1-13, 1994
12. H. Okamoto, “Biomimetic Fiber Reinforced Composites”, Proc. 4th Japan International SAMPE Symposium, Sep. 25-28, pp. 627-632, 1995
13. ABAQUS, Hibbit, Karlsson & Sorenson Inc. 1080 Main Street, Providence, Rhode Island, USA