Out of Plane Gradients in Laminated Composites

Final Report - NASA Grant: NAG-1-841
Period: Dec. 17, 1987 to Dec. 31, 1993

Principal Investigator: Carl T. Herakovich
University of Virginia

Summary

The research under this grant focused on three different, but related, research projects. All three projects were concerned with predicting the interlaminar stresses that develop in laminated composites in the presence of free edges. The first project was dedicated to the development of a new semi-analytical approximate solution for predicting interlaminar stresses. The second project was devoted to a study of the influence of boundary conditions, geometric parameters and material modelling on interlaminar stresses in stiffened composite panels. The third project was dedicated to the development of a new finite element for efficient analysis of interlaminar stresses in curved, stiffened panels. A summary of each of the projects follows.

One Ph.D. and one M.S. were awarded to students supported by this grant. It is anticipated that a second M.S. will be awarded in May, 1994.

Semi-Analytical Approximate Solution

The solution method is based upon statically admissible stress states that are arrived at through consideration of local material mismatch effects and global equilibrium requirments.The stresses in individual layers are approximated by products of polynomial and exponential functions. Unknown parameters in the functions are determined by imposing the stationary condition of the principle of minimum complementary energy. Newton's method is implemented to solve a system of fourteen non-linear algebraic equations, thus making the

solution technique semi-analytical. The effectiveness of the method was demonstrated through application to a variety of laminates and loading conditions. The demonstrated accuracy and efficiency of the method makes it ideally suited for parametric studies.

Interlaminar Stresses in Flat Stiffened Panels

This project was a finite element analysis of various parameters that influence the prediction of interlaminar stresses in flat stiffened composite panels subjected to inplane tensile loading. A study of five different boundary conditions ranging from free to constrained edges, fifteen different laminate stacking sequences of skin and stiffener and seven different stiffener sizes showed that boundary conditions are the most dominant factor in establishing the magnitude of interlaminar stresses. A study of smeared laminate properties as compared with predictions using individual layer properties showed that the smeared properties approach underestimate the interlaminar stresses significantly. This project was complemented with funding through NASA Grant NGT-70230.

Interlaminar Stresses in Curved Stiffened Panels

This project has concentrated on the development of an efficient method for analyzing interlaminar stresses in stiffened curved panels. The method of solution has been formulated as a two-dimensional finite element problem providing results for three-dimensional states of stress and strain for a curvilinear model in a state of generalized plain strain. A new finite element has been formulated and is now being incorporated as a user-defined element in the ABAQUS finite element code. This project was initiated with funding from the NASA grant, but support had to be switched to the Academic Enhancement Program at the University of Virginia when the NASA funding ceased.

Publications:

1. Rose, C.A., and Herakovich, C.T.,"An Approximate Analytical Solution for Interlaminar Stresses in Angle-Ply Laminates", ***Composites: Design, Manufacture, and Application***, (S.W. Tsai and G.S. Springer, eds), ICCM VIII, SAMPE, 1991.
2. Rose, C. A. & Herakovich, C. T., "An Approximate Solution for Interlaminar Stresses in Laminated Composites Subjected to Bending and Extension", Pro-

ceedings Am. Society Composites Seventh Technical Conference, Technomic Publishing Co. Inc., 1992, pp. 1125-1135, (also under review by request for J. Reinforced Plastics & Composites).

3. Rose, C. A. & Herakovich, C. T., "An Approximate Solution for Interlaminar Stresses in Composite Laminates", **Composites Engineering**, Vol. 3, No. 3, 1993, pp. 271-285.
4. D. C. Fenton, C. T. Herakovich, J.H Starnes, Jr., "On Interlaminar Stresses in Composite Stiffened Panels"(in preparation).

Presentations:

1. Rose, C. A and ***Herakovich, C. T.***, "Approximate Solution for Interlaminar Stresses including Mismatch", 27th Annual Meeting of the Society of Engineering Science, Santa Fe, NM Oct., 1990.
2. **Rose, C. A.** & Herakovich, C. T., "An Approximate Solution for Interlaminar Stresses in Laminated Composites Subjected to Bending and Extension", Am. Society Composites Seventh Technical Conference, Penn. State Univ., Oct., 1992.

Reports:

1. Cheryl A. Rose, & Herakovich, Carl T., "An Approximate Solution for Interlaminar Stresses in Laminated Composites", AM-92-02, University of Virginia, May, 1992,
2. David C. Fenton, Starnes, James, H., Jr., & Herakovich, Carl T., "Interlaminar Stresses in Stiffened Composite Panels", AM-93-01, University of Virginia, January, 1993.

Student Participation:

1. Cheryl A. Rose, Ph.D. in Civil Engineering & Applied Mechanics, May, 1992, Dissertation: "An Approximate Solution for Interlaminar Stresses in Laminated Composites"
2. David C. Fenton, M.S. in Applied Mechanics, December, 1992, Thesis: "Interlaminar Stresses in Stiffened Composite Panels", (with additional support from NASA Grant NGT-70230)
3. Cheryl L. Hersh, M.S. in Civil Engineering & Applied Mechanics (expected May, 1994)