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Reply by Authors to R. Prabhakaran

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EACH comment by Professor Prabhakaran will be addressed in the order presented.

1) We acknowledge that interlaminar stresses are an important three-dimensional localized effect at the hole boundary. However, solutions require addressing the complete three-dimensional elasticity boundary value problem. No analytic solution to this extremely complex problem currently exists for general loadings surrounding an open hole in an arbitrary orthotropic laminate. Tang[2] explains the complexity of this problem relative to open holes, and also provides an extensive reference list. The authors recognized that modeling all observed phenomenon would have required a three-dimensional, nonlinear, inelastic stress analysis. We chose a phenomenological approach[3] to permit use of available and general two-dimensional, linear-elastic, closed-form analysis in conjunction with known material failure criteria. The wisdom of our analytic approach and associated approximations was evaluated by correlating predictions with test data which we reported in our paper.[1]

2) Our paper demonstrates that the analytic procedure used, within acceptable engineering accuracy, predicts the effect of hole size on laminate tensile strength. Specimen width to diameter ratios were maintained constant. We question the general validity of Prabhakaran's comment concerning "inherent size effect . . . of unnotched tensile strength with width." Prabhakaran[4] arrives at this conclusion based on data obtained from specimens fabricated from E-glass fabric/epoxy. Nonlinear and inelastic mechanical behavior[5] are present in glass-epoxy and initiate at low strains (.004 mm/mm) relative to final failure (.029 mm/mm). Glass-epoxy mechanical behavior is *not* similar to graphite-epoxy behavior which exhibits relatively linear-elastic behavior to tensile failure.

All *laminate* strength data were obtained from specimens loaded to failure in tension, *lamina* unnotched strength data were obtained from sandwich beam and rail-shear specimens.

3) The important differences between our analytic procedure and the "two-parameter models" are not those which Prabhakaran discusses. Our objective was to predict tensile strength for *arbitrary* laminate constructions, under *general* loadings, with *minimal* test data requirements. The ability to do this was realized when we extended the characteristic dimension failure hypothesis to a ply-by-ply analysis. This permitted a single body of unidirectional (lamina) mechanical property data to be used for prediction of arbitrary laminate strengths, regardless of failure location on the hole boundary. Previous methods required unnotched *laminate* strength test data at the failure location of each new laminate. The utility of our method rests on its ability to predict strengths, within acceptable engineering accuracies, while maintaining a constant characteristic dimension, and *not* requiring a new test to be performed for each laminate analyzed.

Reasons for selecting the Tsai-Hill material failure criteria were not discussed in the authors' paper. Without dwelling on this point, we could have used "maximum strain," "Tsai-Wu," or other well-known material failure criteria with equal success. No recommendation of the Tsai-Hill criterion over others was intended. No statistical evaluations of data bases were performed.

4) We reported an analytic procedure which we feel has engineering utility, minimizes test requirements, and permits use of available elastic, closed-form analysis. Prabhakaran's comment on the possibility of the characteristic dimension being "anisotropic" was not pursued because the degree of correlation between predicted strengths and test data was considered acceptable. For these predictions, the characteristic dimension was maintained constant. Resultant errors caused by assuming a constant (characteristic) dimension should be weighed by each user against his personal requirements for predictive accuracy and generality. The primary issue being raised again by Prabhakaran is whether the use of a constant "characteristic" dimension is valid. This can only be assessed by comparison of test data with prediction. The authors feel that their presented correlations justify the use of a constant value.

5) The authors are not convinced that analysis or physical phenomena associated with *failure* of homogeneous isotropic metals should necessarily be applicable to failures of heterogeneous, anisotropic composite laminates.

References

[1] Garbo, S. P. and Ogonowski, J. M., "Strength Predictions of Composite Laminates with Unloaded Fastener Holes," *AIAA Journal*, Vol. 18, May 1980, pp. 585-589.

[2] Tang, S., "Interlaminar Stresses Around Circular Cutout of Composite Plates Under Tension," AIAA Paper 77-409, 1977.

[3] Wu, E. M., "Strength and Fracture of Composites," *Composite Materials*, Vol. 5, Academic Press, N. Y., 1974.

[4] Prabhakaran, R., "Tensile Fracture of Composites with Circular Holes," *Materials and Science Engineering*, Vol. 41, Nov. 1979, pp. 121-125.

[5] *Plastics For Aerospace Vehicles*, Pt. 1, U. S. Government Printing Office, MIL-HDBK-17A, Jan. 1971.

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