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FINAL REPORT

A COMPARATIVE EVALUATION OF IN-PLANE SHEAR TEST METHODS FOR LAMINATED GRAPHITE-EPOXY COMPOSITES

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PERIOD OF PERFORMANCE

September, 1989 through December, 1991.

OBJECTIVES

To evaluate popular shear test methods for various forms of graphite-epoxy composite materials.

To determine the shear response of graphite-epoxy composites with various forms of fiber architecture.

APPROACH AND PROGRAM DEVELOPMENT

Numerical and full-field experimental stress analyses were performed on four shear test configurations for unidirectional and bidirectional graphite-epoxy laminates to assess the uniformity and purity of the shear stress (strain) fields produced in the specimen test section, and to determine the material in-plane shear modulus and shear response. The test methods were the 10° off-axis, the ±45° tension, the Iosipescu V-notch and a compact U-notch specimen. Specimens were prepared from AS4/3501-6 graphite-epoxy panels, instrumented with conventional strain gage rosettes and with a cross-line moire grating, and loaded in a convenient testing machine. The shear responses obtained for each test method and the two methods of specimen instrumentation were compared.

In a second phase of the program the shear responses obtained from Iosipescu V-notch beam specimens were determined for woven fabric geometries of different weave and fiber architectures. Again the responses of specimens obtained from strain gage rosettes and moire interferometry were compared.

Additional experiments were performed on a bidirectional cruciform specimen which was also instrumented with strain gages and a moire grating.

KEY RESULTS AND OBSERVATIONS

A comparison of the shear responses obtained for the 10° off-axis, the ±45° tension and the Iosipescu specimen is reported in papers B2 and E1. It was found that, for consistent values of the in-plane shear modulus, the 10° off-axis specimen needed a correction factor to be applied to account for the nonuniform strain field produced in the specimen as a result of the gripping constraint and the shear-extension coupling which is a property of this specimen. The moire interferometry experiments provided clear evidence of the global nonuniformity of the strain fields. The ±45° specimen suffered from nonuniformity of the strain fields as a result of nonuniform fiber distribution in the laminates, apparently associated with the fiber tows used in the production of the prepreg.

The experiments on the Iosipescu specimens uncovered several aspects of the specimen and specimen-fixture interactions which led to important improvements in the test procedure and the production of reliable material property data - see papers A1, A2 and B1. It was found that the uniformity of the shear strain fields produced in the specimen test section depended upon the orthotropic ratio of the material (E_1/E_2) and that for highly orthotropic materials such as unidirectional graphite-epoxy, the shear strain in the center of the specimen test section could be more than 20% greater than the average shear strain across the specimen, for the specimen with the fibers in the 90° (fibers parallel to the direction of the applied load), and more than 13% lower than the average shear strain for specimens tested with the fibers in the 0° orientation (fibers parallel to the specimen longitudinal axis). A consistent finite element model of the Iosipescu specimen tested in the modified Wyoming test fixture was developed to provide numerical estimates of the degree of uniformity, or lack thereof, in the specimen test section for a wide range of material systems - see paper B1. It was demonstrated by means of numerical analysis that the specimen fixture interactions depended upon the material orthotropic ratio, and approximate expression for the nonuniform shear field correction factor, in terms of the orthotropic ratio, was developed.

It was shown that specimen twisting can, in cases where the stiffness in the loading direction is large enough, lead to erroneous shear responses. It was shown that the effects of twisting upon the measurement of the in-plane shear moodulus can be eliminated by using pairs of strain gages on the front and back surfaces of the specimen. The twisting phenomenon was demonstrated using a range of material systems - see papers B3 and C1 - and shown to be greatly reduced by applying a compliant layer between the specimen and the fixture. Graphite-epoxy specimens tested with 90° and 0°/90° fiber configurations were shown to be susceptible to twisting. Tests on the compact U-notch specimen showed that this specimen configuration was extremely sensitive to twisting with all fiber orientations. Significant stress concentrations were found at two opposite corners of the notches close to the fixture. Variations on the Iosipescu specimen with U and semi-circular notches were, however, proposed and evaluated - see paper D1 (in draft form).

Iosipescu specimens tested with the fibers in the 0° direction were shown to be sensitive to the local specimen-fixture interactions so that nominally identical specimens could produce different shear strain fields in the specimen test section. This sensitivity of the 0° specimens to the load introduction regions was shown to be responsible for relatively large scatter in data reported in the literature.

At the time of the performance of the program of research the ASTM was developing a draft standard for the test protocol for the composite Iosipescu V-notch specimen. The results of the present program have been presented periodically to the ASTM D30-04 Committee drafting the standard and the findings of the research introduced into the standard which is in the final stages of passage. One of the papers -A1- is cited as a reference in the draft standard.

The experimental techniques were applied to graphite-epoxy composites with the fibers in the form of various weaves - uniweave, plain weave (with 3 and 12K tows) and satin weave (5- and 8-harness). It was found that the fiber architecture defined unit cell sizes which were of the same order or larger than the strain gages used in the conventional test procedure. The moire experiments provided full-field displacement data which could be related to the local nonuniform deformations associated with the fiber architectures and tow sizes - see paper D2 (in draft form).

Moire interferometric and strain gage measurements performed on bidirectional graphite-epoxy cruciform specimens showed that ideal equal and opposite (tensile and compressive) loads were not introduced into the arms of the specimen and that the strain fields developed in the specimen test section were not uniform. A paper has been presented in which the experimental data were used to illustrate the application of recently developed local hybrid methods of moire data reduction. A paper covering the experimental and numerical analyses and the performance of the cruciform specimen will be prepared.

PAPERS, REPORTS AND PRESENTATIONS

A. PAPERS PUBLISHED IN MAJOR JOURNALS

1. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L., "An Experimental Investigation of Iosipescu Specimen for Composite Materials," Experimental Mechanics, 31 (4), 1991, pp. 328-336.

2. Morton, J., Ho, H., Tsai, M. Y. and Farley, G. L., "An Evaluation of the Iosipescu Specimen for Composite Materials Shear Property Measurement," J. Composite Materials, 26 (5), 1992, pp. 708-750.

B. PAPERS ACCEPTED FOR PUBLICATION

1. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L., "Numerical Analysis of the Iosipescu Specimen for Composite Materials," Accepted for publication in Composites Science and Technology, Sept., 1991.

2. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L., "A Comparison of Three Popular Test Methods for Determining the Shear Modulus of Composite Materials," Accepted for publication in Composites Engineering, Jan., 1992.

3. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L., "An Experimental Procedure for the Iosipescu Composite Specimen Tested in the Modified Wyoming Fixtures," Accepted for publicationn J. Composites Technology & Research, Oct., 1991.

C. PAPERS SUBMITTED FOR PUBLICATION

1. Ho, H., Budiman, H. T., Tsai, M. Y., Morton, J. and Farley, G. L., "Composite Material Shear Property Measurement using the Iosipescu Specimen," ASTM Eleventh Symposium on Composite Materials: Testing and Design, ASTM STP, Pittsburg, May, 1992.

D. PAPERS IN PREPARATION

1. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L. "Evaluation of Notched Specimen Designs for Shear Testing of Composite Materials."

2. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L., "In-Plane Shear Properties of Graphite Woven Fabric Composites."

E. CONFERENCE PRESENTATIONS

1. Ho, H., Tsai, M. Y., Morton, J. and Farley, G. L., "A Comparison of Three Shear Test Methods for Composite Materials." Composites: Analysis, Manufacture, and Design, Proceedings of ICCM VIII, July 15-19, SAMPE, 36-L, 1991.

2. Ho, H., Tsai, M. Y. and Morton, J., "Experimental and Numerical Analysis of the Iosipescu V-Notch Shear Specimen for Composite Materials," CCMS Technical Review, VPI&SU, Blacksburg, September 23-26, 1990.

F. Ph.D. DISSERTATIONS

1. Application of Localized Hybrid Methods of Stress Analysis to Some Problems in the Mechanics of Composites.
   M. Y. Tsai,
   November, 1990.

2. An Evaluation of the Iosipescu Specimen for Composite Materials Shear Property Measurement.
   H. Ho,
   July, 1991.
   NOTE: Recipient of the College of Engineering Award for Research Excellence.

G. SEMINARS and PRESENTATIONS

Evaluation of the Iosipescu specimen for composite shear property measurement:
ASTM D30.04 Committee, Spring Meeting, San Francisco, April, 1990.

Evaluation of the Iosipescu specimen for composite shear property measurement:
ICI Fiberite Advanced Materials, Tempe, Arizona, April, 1990.

Evaluation of the Iosipescu specimen for composite shear property measurement:
FMC Defense Systems, San Jose, April, 1990.

Evaluation of test methods for composite shear property measurement:
NASA Langley Research Center, May, 1990.

Evaluation of test methods for composite shear property measurement:
Imperial College of Science, Technology and Medicine, London, August, 1990.

Evaluation of test methods for composite shear property measurement:
Oxford University, August, 1990.

An evaluation of the Iosipescu specimen for composite shear property measurement:
Center for Composite Materials and Structures, VPI&SU, September, 1990.

Evaluation of test methods for composite shear property measurement:
Boeing Aerospace and Electronics Division, Seattle, October, 1990.

Evaluation of test methods for composite shear property measurement:
Dow, Tagerwilen, Switzerland, March, 1991.

Evaluation of test methods for composite shear property measurement:
BASF, Charlotte, North Carolina, April, 1991.

Evaluation of test methods for composite shear property measurement:
BP Research Center, Cleveland, Ohio, June, 1991.

Evaluation of test methods for composite shear property measurement:
EMPA, Dubendorf, Switzerland, July, 1991.

Evaluation of test methods for composite shear property measurement:
Shell Billiton research Center, Arnhem, The Netherlands, July, 1991.

Evaluation of test methods for composite shear property measurement:
DSM, Geleen, The Netherlands, July, 1991.

Evaluation of test methods for composite shear property measurement:
Rolls-Royce plc, Derby, England, August, 1991.

Shear property measurement in composite materials: Mechanics and materials.
ETH Zurich, Switzerland, December, 1991.

Shear modulus measurement in composite materials.
ULB/VUB, Brussels, Belgium, February, 1992.

Shear modulus measurement in composite materials.
KU, Leuven, Belgium, March, 1992.