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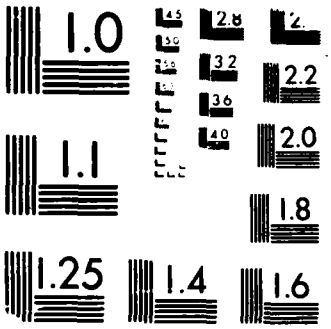

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This final report presents the major findings of research for the investigation of some basic properties of hybrid composite materials. The topics covered in this study were:

1. Statistical strength theory of continuous fiber composites
2. Non-linear stress strain behavior of hybrid composites
3. Two-dimensional fabric composites
   - 3.1 woven hybrid composites
   - 3.2 notched strength of woven fabric composites with molded-in holes
   - 3.3 friction and wear of advanced thermoplastic composites
   - 3.4 impact behavior and damage tolerance of woven carbon fiber reinforced advance thermoplastic composites.
4. Flexural and axial compressive failures of three-dimensionally braided composite I-beams.
5. Three-dimensional analysis of transient interlaminar thermal stress of cross-ply composites.

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thermosetting composites, thermoplastic composites, flexural failure, compressive failure, three-dimensional braided composites, transient thermal stress, interlaminar stress.

No. 19 Continued
The research results are reported in 17 technical papers: 8 journal published articles, 5 conference proceeding articles, 1 encyclopedia article, 2 ASTM-STP articles in press, and 1 journal article submitted for publication.

Besides the principal investigator, 2 post doctoral fellows, 2 Ph.D. students, 3 M.S. students and 2 B.S. students participated in this research program.

AN INVESTIGATION OF SOME BASIC PROPERTIES OF HYBRID COMPOSITE MATERIALS

TSU-WEI CHOU

MARCH 25, 1988

U. S. ARMY RESEARCH OFFICE

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UNIVERSITY OF DELAWARE

Summary of the Most Important Results

1. Statistical Strength Theory of Continuous Fiber Composites.

   A probabilistic ultimate failure strength theory has been developed to assess the effects due to the scattering of lamina strength, relative fiber volume fraction, composite size and laminate stacking sequence.

   The statistical variation of fiber strength makes it necessary to understand the change of stress concentration factor along the length of a fiber next to a broken fiber. Solutions of the dynamic stress concentration factor along the fiber length have been obtained.

2. Nonlinear Stress-Strain Behavior of Hybrid Composites.

   An analytical procedure for predicting the nonlinear stress-strain relations of laminate composites has been developed. The case of fibre reinforced plastic - filament wound (FRP-FW) pipes is considered as an example. In the analysis, the elastic moduli of the laminate are calculated by the laminate theory; the anisotropy of carbon fibre, the elastic interaction among the fibres and the nonlinear shear stress-strain relations of the constitutive laminae are considered. Nonlinear stress increments corresponding to small increments in the uniaxial tensile strain are obtained by the laminate theory. The failure of each lamina is predicted by Tsai-Wu's failure criterion.

   In the experiments, high toughness FW pipes have been fabricated and tested under uniaxial tensile loading. The comparison between analytical and experimental results indicates that Tsai-Wu's criterion predicts the local failures of matrix or fibre/matrix interface, which do not cause the fatal damage of FW pipes. The analytical calculation provides a close estimation for the nonlinear stress-strain response of the carbon/glass hybrid FRP-FW pipe.

3. Two-Dimensional Fabric Composites

   3.1 Woven Hybrid Composites

   Having developed the methodology for analyzing orthogonal biaxial woven composites, the technique has been carried further to investigate thermo-mechanical properties of composites composed of non-orthogonal woven fabrics. The model system studied is the Doweave or triaxial fabric. The analytical method developed can be readily applied to examine the effects of fabrication induced distortion in biaxial woven composites.

3.2 Notched Strength of Woven Fabric Composites with Molded-In Holes.

The feasibility of enhancing damage tolerance and durability of fiber composites through the design of microstructure has been examined using three woven fabric reinforced composite systems (carbon, Kevlar, and carbon/Kevlar in epoxy matrix). Enhancement in notch strength is demonstrated by comparing the performance of composites with drilled and molded-in circular holes. For specimens with molded-in holes, the failure strengths were mostly higher than those of drilled cases. Strength enhancement in the range of 2.7-38.3% was observed. Furthermore, for certain lay-ups of Kevlar and carbon/Kevlar hybrid laminates, the presence of molded-in holes does not reduce the unnotched laminate strength. Strength enhancement of 0.4-22.1% was observed in this comparison. Comparisons of experimental data with existing notched strength theories are made. The advantages of molded-in holes in the joining of fiber composites also have been demonstrated for carbon and Kevlar composites. The effects of hole size and hole-edge-distance on joint strength have been determined.

3.3 Friction and Wear of Advanced Thermoplastic Composites.

In view of the increased tribological applications of polymers and their composites, and to aid better understanding and utilization of materials, an effort was made to investigate the fundamental aspects of the friction and wear mechanisms of three categories of materials: neat poly-ether-ether-ketone (PEEK) matrix, its unidirectional and its 2-D woven graphite-fiber composites.

Wear mechanisms may be classified as adhesive, non-adhesive (abrasive, corrosive, fretting, etc.), or a combination of both. A given material can exhibit any of these mechanisms depending on the sliding counterpart and the environment, all of which comprise a unique tribological system. Friction and wear are hence system properties, rather than material properties. This effort examines the materials under two types of testing conditions: abrasive-dominant (sliding against SiC abrasive paper) and adhesive-dominant (sliding against a smooth steel surface).

A modified rule-of-mixtures approach is found to be very successful in predicting the friction and wear behavior of the woven composite from that of the unidirectional continuous fiber composite. The influences of the test parameters: contact pressure and sliding velocity (p.v-factors), fiber orientation and temperature are incorporated into a theoretical model for the prediction of wear rate.

3.4 Impact Behavior and Damage Tolerance of Woven Carbon Fiber Reinforced Advanced Thermoplastic Composites.

The objective of this research effort is to study the impact behavior and damage tolerance of 2-D woven carbon fiber reinforced advanced thermoplastic composites using instrumented falling weight impact and compression-after-impact tests. The matrices, polyetheretherketone (PEEK) and polyphenylene sulfide (PPS), and the carbon fiber based 5-harness satin weave, were film stacked to manufacture the laminates. Ultrasonic C-scan was employed both before impact, for quality checking, and after impact, to determine the damage zone area. The behavior of the two material systems at different impact energies and velocities has been examined. A measurement of the residual compression strength, using Boeing compression after impact test fixture quantifies the damage tolerance.

4. Flexural and Axial Compressive Failures of Three-Dimensionally Braided Composite I-Beams.

Four-point flexure tests showed linear stress-strain behavior of the three-dimensionally braided I-beams up to the point of initial failure. Flexural and axial compressive tests provided consistent data for compressive moduli as well as a good resolution for the characterization of initiation and propagation of damage. Under four-point flexural and compressive loadings, the failure mode of three-dimensionally braided composite I-beams is different from that of conventional laminated composites. The absence of delamination observed in the three material/geometry combinations for the composite I-beams demonstrated the inherent through-the-thickness reinforcement of the three-dimensionally braided composites.

5. Three-Dimensional Analysis of Transient Interlaminar Thermal Stress of Cross-Ply Composites

The problem of thermal-mechanical behavior of monolithic materials has received considerable attention. With the increasing application of advanced fiber composites under severe environment, there is the obvious need of researches on such behavior, especially for metal and ceramic matrix composites. This is because the temperature ranges in which MMC and CMC are utilized are much higher than that for polymer based composites. The interlaminar stress plays an important role in the initiation of failure in composite laminates. It has been well established that there exists a boundary layer effect when a finite-width, symmetric laminate is subjected to a uniaxial extension (mechanical load).

The thermal transient effect in unidirectional fiber composites has been reported by Chou and co-workers. The present research analyzes an elastic, bidirectional and symmetric composite laminate subjected to an edge temperature change. The transient

interlaminar stresses due to the temperature field have been obtained by a zero-order perturbation analysis of the governing equations. The laminate was considered to be composed of two regions, i.e. interior region and boundary layer region. The classical plate theory was supposed to hold, and terms related to higher order of the thickness-to-width ratio in the dimensionless elastic equations were dropped in the analysis of the interior region. A stretching parameter was introduced into the governing equations, and the Prandtl's primitive matching principle for singular perturbation was used in the study of the boundary layer region. Results for a four-layer and bidirectional graphite/metal laminate show a strong edge effect of interlaminar stress, and the transient stress is much greater than that generated in a steady-state temperature field.

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17. "Probabilistic Strength Analysis of Interlaminated Hybrid Composites," submitted for publication.

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