

## REPORT DOCUMENTATION PAGE

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14. ABSTRACT The objectives of this project are to study durability and damage and fracture development in adhesive composite joints for aerospace structural applications and to develop methods of their intelligent nondestructive evaluations and life prediction. In the third reporting period, the focus was on the development of robust methods of quantitative nondestructive evaluation of crack length and loading mode mixity needed for life prediction in conjunction with the previously developed models of fatigue fracture in joints. Methods of vibrational spectroscopy, acousto-ultrasonics, and acoustic emission location analysis were evaluated experimentally. Dynamic models of wave propagation were developed and used for improved data reduction. A new method of through-thickness interrogation was developed and studied. Specimens with embedded sensors were manufactured and tested. Work has continued on the evaluation of the new composite provided by AFRL. New analytic models were developed for advanced fracture analysis of advanced laminated composites and joints.					
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**Progress Report 09/01/2002 – 08/31/2003**

**Grant Data**

AFOSR Grant No. F49620-01-1-0124

“Fatigue Fracture Analysis and Development of Fundamentals of Predictive NDE of Adhesive Composite Joints”

Principal Investigator: Yuris Dzenis, Department of Engineering Mechanics,  
University of Nebraska-Lincoln

**Objectives**

The main objectives of this project are to study durability and damage and fracture development in adhesive composite joints for aerospace structural applications and to develop methods of their intelligent nondestructive evaluations and life prediction.

**Status of Effort**

In the third reporting period, the focus was on the development of robust methods of quantitative nondestructive evaluation of crack length and loading mode mixity needed for life prediction in conjunction with the previously developed models of fatigue fracture in joints. Methods of vibrational spectroscopy, acousto-ultrasonics, and acoustic emission location analysis were evaluated experimentally. Dynamic models of wave propagation were developed and used for improved data reduction. A new method of through-thickness interrogation was developed and studied. Specimens with embedded sensors were manufactured and tested. Work has continued on the evaluation of the new composite provided by AFRL. New analytic models were developed for advanced fracture analysis of advanced laminated composites and joints.

## **Accomplishments / New Findings**

Several methods of quantitative nondestructive evaluation of crack tip location in adhesive composite joints were explored. Experimental analysis of vibrational spectroscopy, acousto-ultrasonics (AU), and acoustic emission (AE) methods showed that models were needed for robust quantitative data reduction. Such dynamic models of vibration and wave propagation were developed and used to analyze the experimental data. The vibrational spectroscopy method showed poor resolution for the systems studied. The AE method was found adequate with the disadvantage of being a passive method. The AU method was found to be the best for active interrogation, however the resolution of the conventional longitudinal method of crack detection was poor. Extensive numerical studies were conducted to find optimal sensor-transducer configuration. Multiple sensors and transducers located in different places on and within a joint were modeled. As a result, a new method of through-thickness interrogation was developed. The method was found promising for robust active crack location evaluation. Data reduction methods for the best resolution are currently being investigated. The method can be applied with both external and built-in sensors and transducers.

Specimens with embedded film sensors were manufactured and tested. It was shown that low profile surface mounted and embedded PVDF film sensors can be used for crack detection and AE analysis. PVDF film sensors were able to survive the composite manufacturing temperatures and were sensitive enough to detect dynamic AE signals with broad frequency content. The latter is critically important for the applicability of these sensors for use with our previously developed hybrid transient-parametric method of analysis of fracture and damage micromechanisms in composites and joints. Such analysis with PVDF film sensors is now in progress.

Development of non-destructive methods of evaluation of loading mode mixity continued. AE pattern recognition method discovered previously in our experiments was critically tested based on pioneering statistical numerical modeling of AE signals. Random AE signals from the crack extension events under various types of loads were simulated for the first time using variations of dynamic FEM models developed before. The simulated signals were subjected to pattern recognition analysis and the results were compared with experimental data. It was shown, for the first time that numerical simulation data could be recognized by the pattern recognition system and classified, similar to the experimental AE signals. These results substantially improved the confidence and quality of our previously formulated new nondestructive method of evaluation of the load mixity at the crack tip under. The latter is crucial for the new mechanism-based life prediction of joints.

Work has continued on evaluation of new composite of interest to the Air Force (provided by AFRL – Dr. G. Schoepner). The new method of experimental evaluation of transverse fracture toughness of advanced composites developed in collaboration with Dr. N. Pagano of AFRL was successfully applied to evaluate an advanced carbon-epoxy

composite. The highest fracture anisotropy for a structural material was measured and reported for the first time. The results can be used in analysis of crack kinking into the composite adherends during fracture of adhesive composite joints.

Finally, several new closed-form SIF solutions for laminates were derived based on fracture mechanics. These solutions enhance the available library of elementary solutions suitable for delaminated composite analysis. Stress singularity indices at free-edges and interfacial crack tips in advanced laminated composites were obtained by means of Stroh's formalism and a general solution procedure was developed for interfacial cracks in multi-layered anisotropic laminates. These results can be used to analyze and further improve the delamination resistance of the novel advanced composites and joints.

### **Personnel Supported**

Principal Investigator: Y. Dzenis

#### Graduate Students:

M. Qin (Ph.D., in progress, will graduate in December of 2003)

X. Wu (Ph.D., graduated in August, 2003)

Y. Chen (Ph.D., in progress)

K. Nistala (M.S., in progress)

### **Publications and Other Outcomes**

#### Books Edited

"Progress in Non-Destructive Evaluation", Y. Dzenis and C. Cetinkaya, Eds., Proceedings of the NDE Symposium, 2003 ASME International Engineering Congress and Exposition (IMECE2003), American Society of Mechanical Engineering, 2003

## Papers

Dzenis, Y.A., "Cycle-based Analysis of Damage and Failure in Advanced Composites Under Fatigue. 1 - Experimental Observation of Damage Development Within Loading Cycles", *International Journal of Fatigue*, 2003, Vol. 25, No. 6, pp. 499-510

Dzenis, Y.A., "Cycle-based Analysis of Damage and Failure in Advanced Composites Under Fatigue. 2 - Stochastic Mesomechanics Modeling", *International Journal of Fatigue*, 2003, Vol. 25, No. 6, pp. 511-520

Dzenis, Y., Qin, M., and Pagano, N., "A Method of Evaluation of Transverse Critical Energy Release Rate (Fiber Failure Mode) in Advanced Composites", *International Journal of Fracture*, 2003, Vol. 118, No. 1, pp. 11-16

Wu, X.-F., Dzenis, Y., and Zou, W.-S., "Moving screw dislocation in piezoelectric bimetals", *Physica Status Solidi B: Basic Research*, 2003, Vol. 238, No. 1, pp. 120-126

Wu, X.-F., Dzenis, Y., and Zou, W.-S., "Interfacial Edge Crack between two Bonded Dissimilar Orthotropic Strips under Antiplane Point Loading", *ZAMM*, 2003, Vol. 83, No. 6, pp. 419-422

Wu, X.-F., Cohn, S., Dzenis, Y., "Screw Dislocation Interacting with Interface and Interfacial Cracks in Piezoelectric Bimetals", *International Journal of Engineering Science*, 2003, Vol. 41, No. 7, pp. 667-682

Qin, M. and Dzenis, Y.A., "Analysis of Single Lap Adhesive Composite Joints with Delaminated Adherends", *Composites B: Engineering*, 2003, Vol. 34, No. 2, pp. 167-173

Wu, X.-F., Dzenis, Y., and Fan, T.-Y., "Two Semi-Infinite Interfacial Cracks Between Two Bonded Dissimilar Elastic Strips", *International Journal of Engineering Science*, 2003, Vol. 41, No. 15, pp. 1699-1710

Wu, X.-F., Dzenis, Y., and Fan, T.-Y., "Screw dislocation interacting with twin interfacial edge cracks between two bonded dissimilar piezoelectric strips", *Mechanics Research Communications*, 2003, 30: 547-555

Dzenis, Y.A. and Qian, J., "Analysis and Identification of Acoustic Emission from Damage and Internal Friction in Advanced Composites Under Fatigue", *Journal of Acoustic Emission*, 2002, Vol. 20, pp. 99-107

Dzenis, Y. and Saunders, I., "On the Possibility of Discrimination of Mixed Mode Fatigue Fracture Mechanisms in Adhesive Composite Joints by Advanced Acoustic Emission Analysis", International Journal of Fracture, 2002, Vol. 117, No. 4, pp. 123-128

Wu, X.-F., Dzenis, Y., and Zou, W.-S., "Screw Dislocation Interacting With an Interfacial Edge Crack Between Two Bonded Dissimilar Piezoelectric Wedges", International Journal of Fracture, 2002, Vol. 117, No. 3, pp. 19-114

Qian, J. and Dzenis, Y.A., "Extraction of Histories of Damage Micromechanisms in Unidirectional Composites by Transient-Parametric Analysis", Journal of Acoustic Emission, Dec 2002, Vol. 20, pp. 16-24

Wu, X.-F., Dzenis, Y., "Closed-Form Solution For the Size of Plastic Zone in an Edge-Cracked Strip", International Journal of Engineering Science, 2002, Vol. 40, pp. 1751-1759

Wu, X.-F., Dzenis, Y., "Closed-Form Solution For a Mode-III Interfacial Edge Crack Between Two Bonded Dissimilar Anisotropic Strips", Mechanics Research Communications, 2002, Vol. 29, No. 5, pp. 407-412

#### Graduated Students

X. Wu, "Fracture of Advanced Laminated Composites", Ph.D. Dissertation, Department of Engineering Mechanics, University of Nebraska-Lincoln, 2003 (Advisor: Y.A. Dzenis)

#### **Interactions/Transitions**

#### Conference Presentations

Dzenis, Y. and Qian, J., "Identification of AE from Internal Fretting in Composites under Fatigue", ASME Paper IMECE2003-43931, 2003 ASME IMECE Procs, 2003, 6 p.

Dzenis, Y., Qin, M., and Pagano, N., "Evaluation of Transverse Critical Energy Release Rate (Fiber Failure Mode) in Advanced Composites", 9th International Conference on The Mechanical Behavior of Materials, Geneva, Switzerland, May 2003

Petersen, B. and Dzenis, Y., "Novel Composites with Nanoparticle Reinforced Interfaces", SES 40th Tech Meeting, Ann Arbor, 2003

Dzenis, Y.A., "Advanced Nanofiber Composites", COMP'03, International Conference on Composite Materials, Corfu, Greece, 2003 (Invited Keynote)

Kwon, O.-Y., Brosig, D., Nistala, K., Dzenis, Y., "A Disposable PVDF Sensor Applied to the Detection of Fatigue Crack Growth in Bonded Composite Joints", ASME Paper IMECE2002-33489, 2002 ASME IMECE Procs (CD-Rom), Vol. 3, 2002, 6 p.

Kwon, O.-Y., Jun, J., Dzenis, Y., "Nondestructive Methods for the Damage Assessment of Cylindrically Curved Composite Laminates Subjected to Low-Velocity Impact", ASME Paper IMECE2002-33430, 2002 ASME IMECE Procs (CD-Rom), Vol. 3, 2002, 6 p.

Dzenis, Y.A., "High-Performance Nanofibers and Nanocomposites", NSF-EC Workshop on Nanomanufacturing and Processing, 2002, San Juan, Puerto Rico (Invited Expert Presentation), 18 p. (Procs. to be published electronically by NSF)

#### Interactions with AFRL and Private Sector

Dzenis, Y.A., "Fatigue Fracture Analysis and Development of Fundamentals of Predictive NDE of Adhesive Composite Joints", Presentation at AFOSR Mechanics and Materials Program Review, Santa Fe, Sept 2003

Dzenis, Y.A., "Evaluation and Prediction of Fatigue Life of Adhesive Composite Joints", Presentation at AFOSR Mechanics and Materials Program Review, Washington D.C., October 2002

Collaboration with G. Schoeppner and S. Donaldson of AFRL continued. New carbon-epoxy composite prepreg provided by AFRL was successfully tested in adhesive joints by UNL. Feasibility of life prediction by the developed methods was demonstrated on a material of the Air Force interest.

New method of experimental evaluation of transverse fracture toughness of advanced composites developed in collaboration with Dr. N. Pagano of AFRL was successfully applied to evaluate an advanced carbon-epoxy composite. The highest fracture anisotropy for a structural material was measured and reported for the first time. The results can be used in analysis of crack kinking into the composite adherends during fracture of adhesive composite joints.

## Honors / Awards

### *Principal Investigator:*

- 2003 Robert C. McBroom Endowed Professorship
- 2003 Promoted to Full Professor
- 2003 UNL College of Engineering Faculty Service Award (one per College)
- 2003 Faculty Research Award, Department of Engineering Mechanics, UNL
- 2002 Visiting Professorship, Universite Pierre et Marie Curie - Paris VI, France
- 2002 Adjunct Associate Professorship, Department of Civil Engineering, Texas A&M University (in conjunction with joint Engineering Study Abroad Program in France)