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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The objective of this research was a systematic fatigue fracture analysis and development of fundamentals of predictive nondestructive evaluation of adhesive composite joints for aerospace structural applications. Fatigue fracture of joints was studied using fracture mechanics methods. A mixed mode fracture model was developed and validated. Feasibility of prediction of fatigue life of joints was demonstrated. Several methods of nondestructive evaluation of cracks in joints were significantly enhanced based on wave propagation modeling. Ultrasonic through thickness and longitudinal (acousto-ultrasonic) methods were explored and sensor configurations were optimized based on modeling. The accuracy of crack location evaluation was enhanced by modal analysis. A pioneering method of nondestructive evaluation of loading mode mixity at the crack tip was developed based on the pattern recognition acoustic emission (AE) analysis. The method was validated experimentally and confirmed by modeling. The feasibility of real-time monitoring of adhesive joints using built-in sensors was demonstrated. A new method and specimen for experimental evaluation of transverse fracture resistance of anisotropic composites was developed. The results provide better understanding of fatigue behavior of adhesive composite joints. The demonstrated combined modeling-based QNDE and advanced fracture mechanics approach for life prediction constitutes a fundamental basis for the next generation Smart NDE (SNDE) systems with mechanics-based predictive capabilities. The research was performed in close collaboration with AFRL/MLBC.

15. SUBJECT TERMS

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EXECUTIVE SUMMARY

Adhesive joining technology has been recognized as critical for the development of automated low-cost fabrication processes for large, integrated aerospace structures. This technology is also critical for the repair of damaged metallic and composite structures and maintenance of the ageing aircraft fleet. Lightweight polymer composite patches are capable of minimizing balance and clearance problems on control surfaces, can be readily formed to complex contours, and can minimize undesirable stiffness increases by tailoring reinforcement to suit the loading configuration. Two major problems impeding wider use of adhesive composite joints in aerospace structures are poor understanding of their fatigue behavior and lack of methods of their nondestructive evaluation (NDE) and life prediction.

The objective of this research was a systematic fatigue fracture analysis and development of fundamentals of predictive nondestructive evaluation of adhesive composite joints. Our previous studies of adhesive lap joints of several configurations showed that most joints failed via slow bond crack propagation under fatigue. In this project, the fatigue crack propagation in joints was studied systematically using fracture mechanics approach. The base experimental information was collected from the mode I, II, and mixed mode tests. Fracture mechanisms were analyzed using fractography and advanced acoustic emission (AE) analysis. A mixed mode fracture criterion was developed and validated experimentally. This criterion and the improved nonlinear models of lap joints were used to predict fatigue fracture and life of joints. The approach was validated on joints with deliberately introduced cracks. Good correlation was obtained between the predicted and experimentally observed lives of adhesive joints.

The newly developed predictive method above required, among other things, two input parameters, i.e. crack tip location and loading mode mixity at the crack tip. Several methods were explored and developed for nondestructive evaluation of these parameters. A host of ultrasonic NDE methods for crack location evaluation were significantly enhanced based on wave propagation modeling. Through thickness and longitudinal (acousto-ultrasonic) methods were explored and multiple sensor configurations were optimized based on modeling. The accuracy of crack location evaluation was enhanced by modal analysis. A pioneering new method of nondestructive evaluation of loading mode mixity at the crack tip was developed based on the pattern recognition analysis of the AE signals from fracture. The method was validated experimentally and further enhanced by modeling transient AE waves from bond cracks under various loading conditions. The feasibility of real-time monitoring of adhesive joints using built-in sensors was demonstrated. Finally, a new method and specimen for experimental evaluation of transverse fracture resistance of anisotropic composites was developed. Application of the method to carbon-epoxy composite produced the world's highest fracture anisotropy recorded for a structural material. The method will be critical for evaluation and prediction of bond crack kinking and branching into the composite adherends.

The results provide better understanding of fatigue behavior of adhesive composite joints. The demonstrated feasibility to combine quantitative, modeling-based QNDE and advanced fracture mechanics for life prediction constitutes a fundamental basis for the third generation Smart NDE (SNDE) devices with mechanics-based predictive capabilities. The research was performed in close collaboration with the composites group at AFRL/MLBC.

1. Statement of the Problem Studied

This project addressed durability and damage and fracture development in adhesive composite joints for aerospace structural applications. Defense applications of advanced polymer matrix composites span aerospace structures, weapons systems, ammunition, ground vehicles, transportation infrastructure, electronics, and many other systems. An interest in the use of adhesive joints in these structures has increased significantly over the last several years for several reasons. The key advantage of adhesive joint technology is that it enables the development of large, low-cost, highly integrated structures. This manufacturing technique significantly reduces the high-cost hand-assembly labor steps in fabricating composite structures. Adhesive joints are ideal for joining parts in highly contoured, low observable composite structures. This technology is also critical to the repair of damaged metallic and composite structures. However, there are several problems associated with adhesive joints that impede their wider use in military and civilian applications. The first problem concerns a general lack of understanding of their fatigue behavior and durability performance. The second problem concerns the inspectability and in-service monitoring of joints. These two interrelated problems were addressed in this project. The objective of this research was comprehensive experimental and theoretical analysis of adhesive composite joints of several configurations under static and fatigue loadings and development of fundamentals of their predictive nondestructive evaluation.

2. Summary of the Most Significant Results

The research was organized in several technical tasks described below. The progress was documented in interim technical reports, annual progress reports, publications, and dissertations (see next section). The research was performed in close collaboration with AFRL/MLBC (Dr. Greg Schoepner, Dr. Steven Donaldson, Dr. Ajit Roy, and Dr. Nick Pagano). Composite material of interest to the Air Force was provided by AFRL/MLBC and studied at UNL. The PI has made several visits to AFRL to report the progress and to discuss the plans. The significant research results are summarized briefly below. More detailed technical presentation and examples are given in the Appendix.

Mixed Mode Fatigue Fracture Analysis of Adhesive Composite Joints and Development of Methods of Life Prediction

Fatigue behavior of joints made from aerospace-grade carbon-epoxy adherends and an adhesive used in the Air Force was analyzed. Initial work was performed on specimens manufactured from high-temperature Boeing-certified carbon-epoxy prepreg T2G-190-12F263 obtained from Hexcel. The results were later successfully verified on joints made from IM7/5250-4 prepreg provided by AFRL/MLBC. Cytec FM 300-2M film adhesive used in the Air Force was utilized in this study. Adhesive joints of various configurations were manufactured by secondary curing following manufacturer-recommended curing cycles.

Fatigue fracture under Mode I, II, and mixed mode loadings was characterized by the double cantilever beam, end notch flexure, and cracked lap shear tests, respectively. Extensive systematic experimental data on fatigue fracture of joints was generated. Several methods of data reduction were applied and compared including the nonlinear FE analysis. A mixed mode fracture criterion was developed and validated. This criterion and the improved nonlinear models of lap joints were used to predict fatigue fracture and life of joints. The approach was validated by experimental analysis of lap joints with cracks of various initial lengths. Good correlation was obtained between the predicted and experimentally observed lives of adhesive joints.

Analysis of Damage and Fracture Micromechanisms

AE analysis of fatigue fracture mechanisms in joints was performed under Mode I, II, and mixed mode loadings. A hybrid transient-parametric method of analysis of histories of damage and fracture micromechanisms developed earlier was further generalized and applied for the analysis of damage evolution in a laminates subjected to mechanical, thermal, and combined thermomechanical fatigue (TMF) loading. Thermomechanical testing was performed with a specially designed and built TMF testing apparatus. Characteristic AE waveforms were identified based on the transient analysis and the multiparametric filters for different waveforms were built in the parametric AE spaces. Transferability of the multiparametric filters between different environmental and loading conditions was validated for the first time. Composite damage modes for the characteristic waveforms were identified based on independent observations. Cumulative histories of different damage micromechanisms were extracted and analyzed for each loading condition. Micromechanics models of composite stiffness degradation due to various damage modes were used to predict modulus degradation under fatigue based on the classified acoustic emission histories of fatigue damage. It was shown for the first time that the classified AE histories can be used to predict the stiffness degradation of the composite adherends subjected to quasi-static and fatigue loading at different temperatures as well as composites subjected to thermomechanical fatigue loadings.

Development of NDE Methods of Bond Crack Detection

Several methods of quantitative nondestructive evaluation of cracks in adhesive composite joints were explored and developed in this study. 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 generally 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 dynamic numerical simulations 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 hybrid method of through-thickness interrogation was developed. The method was found promising for robust active crack location evaluation. Improved data reduction methods for the increased evaluation accuracy were developed based on modal analysis. Capabilities of the methods were illustrated on carbon-epoxy single-lap joints with embedded cracks of various lengths. The developed methods can be used with either external or built-in sensors and transducers.

Evaluation of Loading Mode Mixity at Crack Tip

Systematic analysis of AE signals from joints subjected to pure and mixed mode loadings was performed for the first time by a pattern recognition and classification method. It was discovered that the ratio of the classified AE signals from mixed mode fatigue fracture correlated with the mode mixity of loading. The mechanism of the observed phenomenon was investigated with help from dynamic numerical modeling of wave propagation from various fracture sources in joints under pure and mixed mode loading conditions. Random AE signals from the crack extension events under various types of loads were simulated for the first time using specially developed dynamic FEM models. The simulated signals were subjected to pattern recognition analysis and the results were compared with experimental data. It was shown that the simulated AE signals could be classified by the pattern recognition system, similarly to the experimental AE signals. These results verified that the discovered correlation can be used for robust nondestructive evaluation of the load mixity at the crack tip under fatigue. The latter parameter is crucial for the new, mechanism-based life prediction methodology for joints described above.

Development and Evaluation of Built-In Sensing Capability for Real-Time Monitoring of Joints

Feasibility of use of low profile surface mounted and embedded film sensors for crack detection and AE analysis of joints was evaluated for the first time. Specimens with embedded film sensors were manufactured and tested. It was shown that PVDF film sensors could survive the composite manufacturing temperatures and were sensitive enough to detect dynamic AE signals with reasonable frequency content. The latter is critically important for the potential use of these sensors with our developed hybrid transient-parametric method of analysis of fracture and damage micromechanisms in composites and joints. Feasibility of such an analysis with PVDF film sensors was demonstrated. Characteristic AE waveforms were identified based on the transient AE data from PVDF sensors and cumulative histories of different damage micromechanisms were extracted for various loading conditions.

Development of Method of Anisotropic Fracture Analysis

In collaboration with Dr. N. Pagano of AFRL, a new method of experimental evaluation of transverse fracture toughness of advanced composites was proposed and developed. The method was experimentally evaluated on carbon-epoxy composites. The highest fracture anisotropy for a structural material was measured and reported for the first time. The results can be used for analysis of crack kinking and branching into the composite adherends during fracture of adhesive composite joints.

Fracture Mechanics Modeling of Cracks in Composites and Joints

New analytic models were developed for advanced fracture analysis of laminated composites and joints. Several new closed-form SIF solutions for laminates were derived based on fracture mechanics. 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 solutions enhance the available library of elementary solutions suitable for delaminated composite analysis. The results can be used to analyze and further improve the delamination resistance of advanced composites and joints.

3. List of Publications and Other Outcomes

Graduated Students

[1] K. Myers, M.S., "Acoustic Emission Analysis of Micromechanisms of Fracture in Composites and Joints", Institute of Composite Materials, University of Kaiserslautern / Department of Engineering Mechanics, University of Nebraska-Lincoln, 2001 (Advisor: Y.A. Dzenis)

[2] M. Qin, PhD, "Theoretical and Experimental Analysis of Adhesive Composite Joints", Department of Engineering Mechanics, University of Nebraska-Lincoln, 2003 (Advisor: Y.A. Dzenis)

[3] X. Wu, PhD, "Fracture of Advanced Laminated Composites", Department of Engineering Mechanics, University of Nebraska-Lincoln, 2003 (Advisor: Y.A. Dzenis)

Continuing students: Y. Chen (Ph.D.) and K. Nistala (M.S.)

Patent Applications

[1] Dzenis, Y., "Transient-Parametric Method to Discriminate Histories of Sources of Acoustic Emission", U.S. Patent Application Serial No. 60/174,215, 2000 (pending)

[2] Dzenis, Y. and Qin, M., "Method for Nondestructive Evaluation of Mode Mixity of Loading in Mixed Mode Fracture", UNL Patent Disclosure, 2001

[3] Y. Dzenis, M. Qin (both UNL), N. Pagano (AFRL), "A Method for Evaluation of Anisotropic Critical Energy Release Rate in Advanced Composites", UNL Patent Disclosure, 2002

Books Edited

[1] "Progress in Non-Destructive Evaluation", C. Cetinkaya, Y. Dzenis, and S. Joshi, Eds., Proceedings of the NDE Symposium, 2002 ASME International Engineering Congress and Exposition (IMECE2002), American Society of Mechanical Engineering, 2002 (the volume contains 6 chapters and 19 full-length papers)

[2] "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

Journal Papers

[1] Dzenis, Y.A. and Qian, J., "Analysis of Microdamage Evolution Histories in Composites", International Journal of Solids and Structures, Vol. 38, 2001, pp. 1831-1854

[2] Kayupov, M. and Dzenis, Y.A., "Stress Concentrations Caused by Bond Cracks in Single-Lap Adhesive Composite Joints", Composite Structures, Vol. 54, 2001, pp. 215-220

[3] Wu, X.-F. and Dzenis, Y.A., "Rate Effects on Mode-I Delamination Toughness of a Graphite/ Epoxy Laminated Composite", International Journal of Fracture, 2001, Vol. 112, pp. 19-112

[4] 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

[5] 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

[6] 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

[7] 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

[8] 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

[9] 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

[10] 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

[11] 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

[12] 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

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

[14] 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

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

[16] 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

[17] 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

[18] 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

[19] Wu, X.-F., Dzenis, Y., :Determination of dynamic delamination toughness of a graphite-fiber/ epoxy composite using Hopkinson pressure bar", Polymer Composites (in press)

[20] Wu, X.-F., Dzenis, Y., Experimental determination of probabilistic edge-delamination strength of a graphite-fiber/epoxy composite", Composite Structures (in press)

[21] Wu, X.-F., Dzenis, Y., E. Gokdag. "Edge-cracked orthotropic bimaterial butt joint under anti-plane singularity", International Journal of Nonlinear Sciences and Numerical Simulation (in press)

[22] Wu, X.-F., Dzenis, Y., B. D. Rinschen. "Screw dislocation interacting with interfacial edge-cracks in piezoelectric bimaterial strips", International Journal of Nonlinear Sciences and Numerical Simulation (in press)

[23] Wu, X.-F., Dzenis, Y., "Polarized surface acoustic wave (SAW) propagation in elastic half-space coated with an anisotropic laminate", Composites Science and Technology (accepted)

Conference Papers

[1] Dzenis, Y., "Analysis of Histories of Damage Micromechanisms in Laminates Under Fatigue", DURACOSYS'01, Tokyo, Japan, 6-9 November 2001

[2] Qin, M. and Dzenis, Y., "Nonlinear Numerical and Experimental Analysis of Single Lap Adhesive Composite Joints with Delaminated Adherends", 13th International Conference on Composite Materials ICCM-13, Beijing, China, 25-29 June 2001, Paper 1688

[3] 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, Washington D.C., October 2001, 14 p.

[4] Dzenis Y. and Qian, J., "Microdamage Evolution Histories in Advanced Composites", 7th ASME NDE Topical Conference, San Antonio, Texas, April 23-25, 2001

[5] Dzenis Y. and Qian, J., "Hybrid Transient-Parametric AE Analysis of Histories of Damage Micromechanisms in Composites", SPIE 6th International Symposium "NDE for Health Monitoring and Diagnostic", Newport Beach, CA, 4-8 March 2001, Paper 4335-53

[6] Saunders, I. and Dzenis, Y.A., "Fatigue Behavior of Single Lap Adhesive Composite Joints", In: Resent Developments in Durability Analysis of Composite Systems", A.H. Cardon, H. Fukuda, K.L. Reifsnider, G. Verchery, Eds., Proc. of the Fourth Int Conf on Durability Analysis of Composite, A.A. Balkema: Rotterdam, 2001, pp. 127-131

[7] 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.

[8] 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.

[9] 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

[10] 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.

[11] 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

[12] 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

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

[14] 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, Virginia, Aug 2004

Interim Progress Reports

[1] Dzenis, Y.A., "FATIGUE FRACTURE ANALYSIS AND DEVELOPMENT OF FUNDAMENTALS OF PREDICTIVE NDE OF ADHESIVE COMPOSITE JOINTS", AFOSR GRANT NO. F49620-01-1-0124 Interim Report No. 1, 2001

[2] Dzenis, Y.A., "FATIGUE FRACTURE ANALYSIS AND DEVELOPMENT OF FUNDAMENTALS OF PREDICTIVE NDE OF ADHESIVE COMPOSITE JOINTS", AFOSR GRANT NO. F49620-01-1-0124 Interim Report No. 2, 2002

[3] Dzenis, Y.A., "FATIGUE FRACTURE ANALYSIS AND DEVELOPMENT OF FUNDAMENTALS OF PREDICTIVE NDE OF ADHESIVE COMPOSITE JOINTS", AFOSR GRANT NO. F49620-01-1-0124 Interim Report No. 3, 2003

Awards, Honors

Principal Investigator (Y. Dzenis):

UNL Department of Engineering Mechanics Faculty Research Award (2001)

Visiting Professorship, Universite Pierre et Marie Curie - Paris VI, France (2002)

Adjunct Associate Professorship, Department of Civil Engineering, Texas A&M University (2002)

Robert C. McBroom Endowed Chair UNL (2003)

Promoted to Full Professor (2003)

UNL College of Engineering Faculty Service Award (2003)

UNL Department of Engineering Mechanics Faculty Research Award (2003)

Visiting Professorship, Universite Pierre et Marie Curie - Paris VI, France (2004)

UNL College of Engineering Faculty Research Award (2004)

Laboratory Development

With partial support from this grant, development of a comprehensive experimental laboratory on advanced composites and NDE was continued by the PI at UNL. The laboratory consists of composite manufacturing, characterization, and testing equipment and includes such unique experimental devices as a complete thermal analysis system with two dynamic mechanical thermal analyzers, a unique set of devices for thermomechanical fatigue testing of polymer composites (a novel cyclic heating device and a TMF test control and data acquisition system were designed and built at UNL with support from this grant), a state-of-the-art acoustic emission system (augmented with an advanced pulser for acousto-ultrasonic studies with support from this grant), and a unique set of four ultrasonic nondestructive evaluation devices with overlapping resolutions and fields of view in the range from centimeters to nanometers. The latter include C-SCAN, scanning acoustic tomograph, 'true' scanning acoustic microscope, and scanning probe microscope.

4. List of Participating Scientific Personnel

Principal Investigator:		Y. Dzenis
Graduate Students:		
	Fully supported	M. Qin (Ph.D.)
	Partially supported	K. Nistala (M.S.)
		X. Wu (Ph.D.)
		Y. Chen (Ph.D.)
Visiting Professor:		O.-Y. Kwon, Inha University, Korea (2001-02; partially supported)

Advisors and Contributors at AFRL/MLBC:

G. Schoeppner, A. Roy, S. Donaldson, N. Pagano, M. Forte

5. Report of Inventions

The new hybrid transient-parametric method of acoustic emission analysis of histories of damage micromechanisms described in section 2 is being patented by UNL (U.S. patent pending).

APPENDIX: METHODS AND TECHNICAL DATA SUMMARY

Project: F49620-01-1-0124

Title: **Fatigue Fracture Analysis and Development of Fundamentals of Predictive NDE of Adhesive Composite Joints**

PI: Y. Dzenis, Department of Engineering Mechanics, University of Nebraska-Lincoln

Objectives

- Development of intelligent nondestructive evaluation methods with mechanics-based predictive capabilities (Smart NDE)
- Development of joints with integrated (built-in) nondestructive capabilities for real-time monitoring of quality and life expectancy

State-of-the-art

- Static models and design methods for bonded joints
- Limited experimental fatigue data
- Attempts to directly correlate NDE parameters with strength
- No reliable methods for NDE for life

Approach

- Combination of modeling-based quantitative NDE with fatigue damage and fracture mechanics to provide predictive capabilities

Benefits

- Improved reliability of bonded joints in repairs, large integrated composite structures in air and space systems, weapons, etc
- Increased confidence in adhesive bonding technology for aerospace applications

Rationale

History of Nondestructive Evaluation Systems

- Qualitative
- Quantitative (QNDE)
  - Inspection
  - Monitoring

Next Generation Smart Predictive NDE (SNDE): Proposed Novel Concept

- Combination of QNDE with advanced damage and fracture mechanics
- Predictive: Predicts residual properties and life of structures
- Smart: Enables intelligent decisions on part replacement/repair or allowable flight scenarios

Suitability for Composite

- Damage tolerant
- Enable built-in sensors

Adhesive Composite Joints

- Important for repair and integrated manufacturing of large composite structures
- Lack methods of NDE and life prediction

Background Information and Partnerships

Background

- Adhesive composite joints behave non-linearly under loading
- Most adhesive joints fail with bond crack propagation under fatigue
- Slow bond crack propagation constitutes substantial portion of fatigue life
- Damage in adherends can be important and should be accounted for

Recent studies

- Non-linear analysis of crack propagation in joints
- Analysis of joints with delaminated adherends
- Extraction of histories of damage micromechanisms
- Preliminary analysis of mixed mode fatigue fracture

Partnerships

- AFRL/MLBC: G. Schoeppner, S. Donaldson, A. Roy, N. Pagano, M. Forte
- UDRI: B. Rice

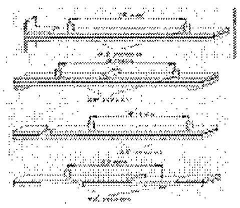
Outline

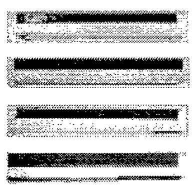
1. Fatigue analysis of joints and life prediction
2. Evaluation of damage and fracture micromechanisms
3. Modeling-based QNDE of crack tip location
4. Evaluation of loading mode mixity at the crack tip
5. Demonstration of feasibility of on-line monitoring of joints with embedded sensors
6. Anisotropic fracture analysis of composites

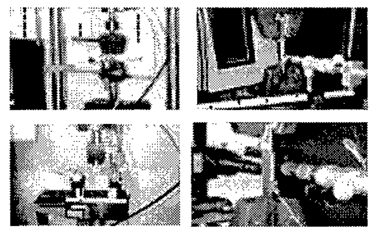
1. Fatigue Fracture Analysis of Joints

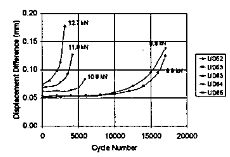
Summary: Comprehensive analysis of fatigue behavior of joints was conducted under pure mode and mixed mode loadings with continuous crack propagation and NDE monitoring

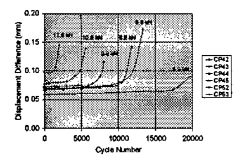
Example: Fatigue crack propagation in joints with unidirectional and cross-ply adherends









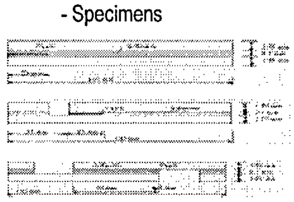


Development of Mixed Mode Fatigue Fracture Model

Summary: Mixed mode fatigue fracture is being predicted based on experimental pure mode data and nonlinear analysis

Example: Fatigue crack propagation data and life prediction for joints with initial cracks

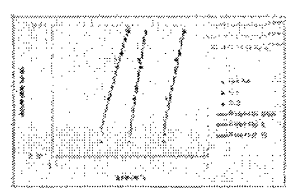
- Specimens



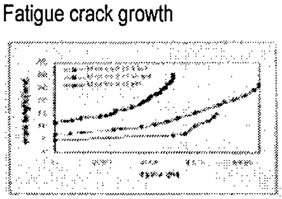
DCB and ENF

CLS

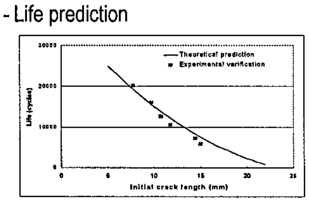
Lap Joint



- Fatigue crack growth



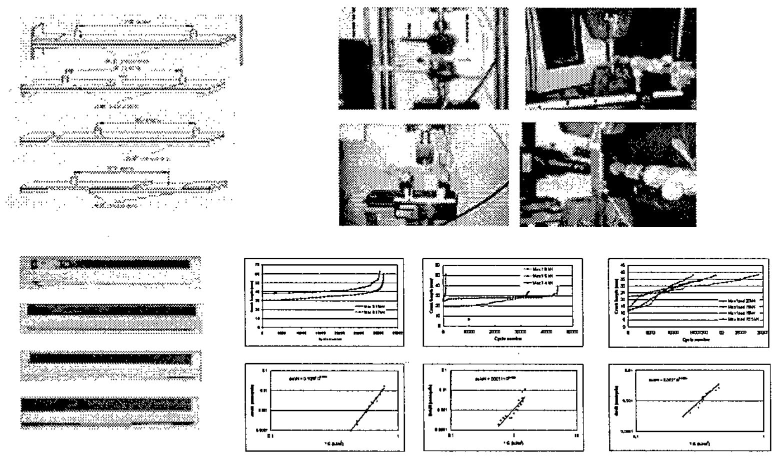
- Life prediction



Fatigue Characterization of IM7/5250-4 Joints

Summary: Fatigue behavior of joints was studied under pure mode and mixed mode loadings with crack observation and NDE monitoring

Example: Fatigue crack propagation in joints under pure mode and mixed mode loads

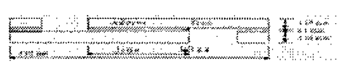


Validation of Fatigue Fracture Model and Life Prediction for IM7/5250-4

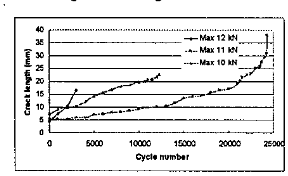
Summary: Mixed mode fatigue fracture and life were predicted based on experimental pure mode data and nonlinear analysis

Example: Fatigue crack propagation data and life prediction for lap joints with initial cracks

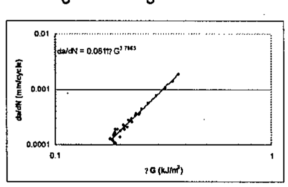
- Lap joints



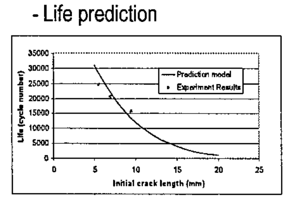
- Fatigue crack growth



- Fatigue crack growth



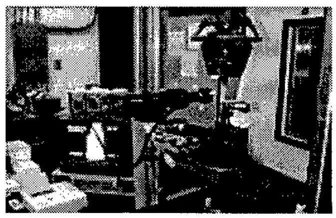
- Life prediction

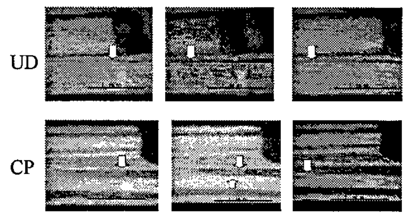


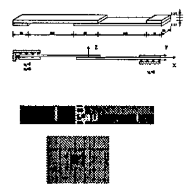
Non-Linear Analysis of Crack Propagation in Joints

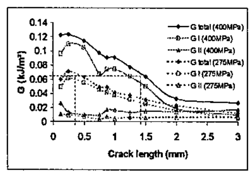
Summary: Non-linear models of joints with arbitrary laminated adherends and cracks were developed and experimentally validated

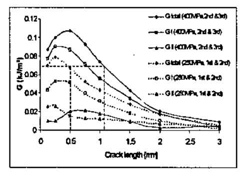
Example: Prediction of crack propagation in joints with unidirectional and cross-ply adherends







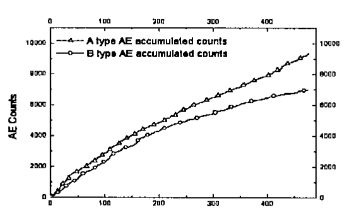


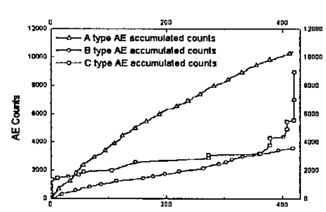


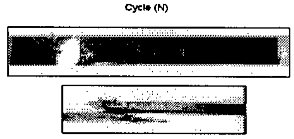
2. Identification and Extraction of Histories of Damage and Fracture Micromechanisms

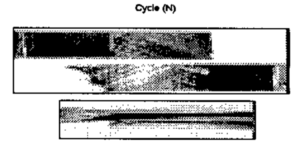
Summary: New transient-parametric method of AE signal analysis was developed and successfully applied to extract histories of damage and fracture micromechanisms in adherends and joints. The method can be used for on-line damage monitoring and will produce input data for life prediction

Example: Histories of fatigue damage in quasi-isotropic [0/+-45/90] and [90/+-30] laminates







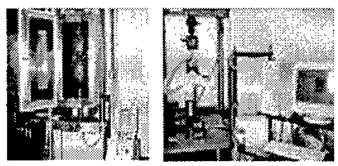


Mechanism-Based Modeling of Fatigue Degradation

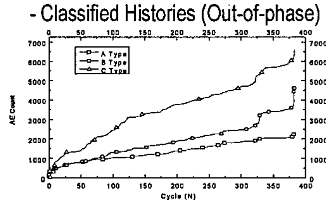
Summary: Micromechanics modeling of cracks was used to predict properties degradation in conjunction with extracted AE histories of damage and fracture micromechanisms under fatigue

Example: Analysis of damage micromechanisms and prediction of degradation of graphite-epoxy laminate under in-phase and out-of-phase thermomechanical fatigue loading

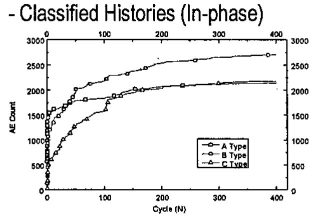
- TMF Testing



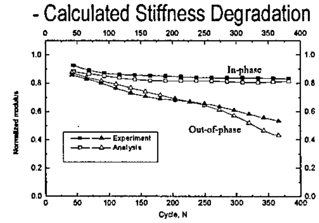
- Classified Histories (Out-of-phase)



- Classified Histories (In-phase)



- Calculated Stiffness Degradation



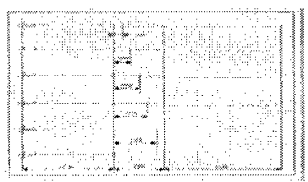
3. QNDE of Bond Cracks

- ✍Vibrational spectroscopy
- ✍Acoustic emission
- ✍Modeling-based AU

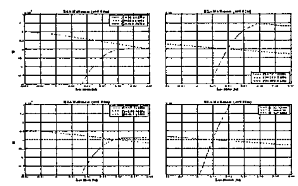
Crack Tip Location: Vibrational Spectroscopy

Summary: Vibrational analysis of cracked joints was performed both analytically and numerically
Example: Comparison of crack location in lap joint by analytical and numerical techniques

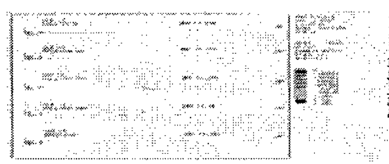
- FE Model of cracked lap joints



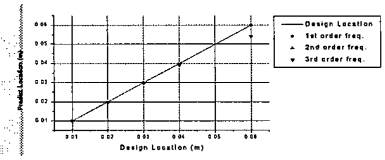
- Characteristic equation



- Vibrational modes



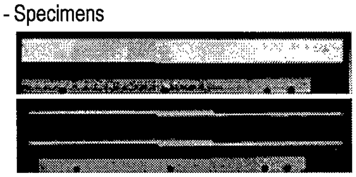
- Predicted locations



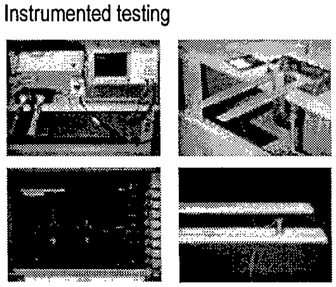
Experimental Validation

Summary: Experimental vibrational analysis was performed on joints with deliberately introduced cracks
Example: Verification of variation of frequencies with crack location

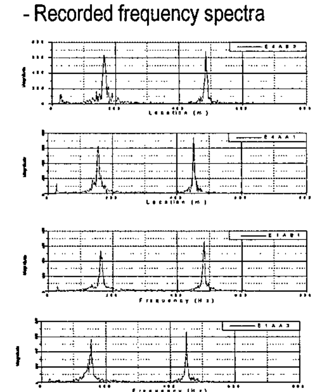
- Specimens



- Instrumented testing



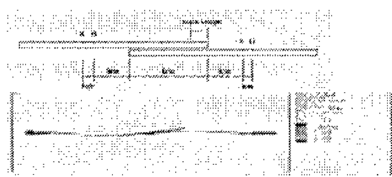
- Recorded frequency spectra



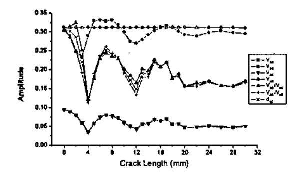
Acousto-Ultrasonic Analysis

Summary: Analytical and numerical models were developed for quantitative acousto-ultrasonic analysis
Example: Acousto-ultrasonic analysis of cracked lap joint

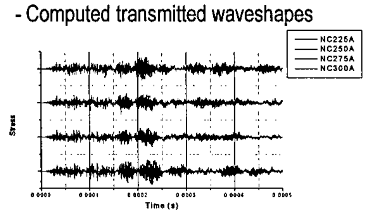
- Model: A,D – transducers, B,C - sensors



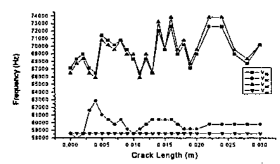
- Amplitude transfer through cracked joint



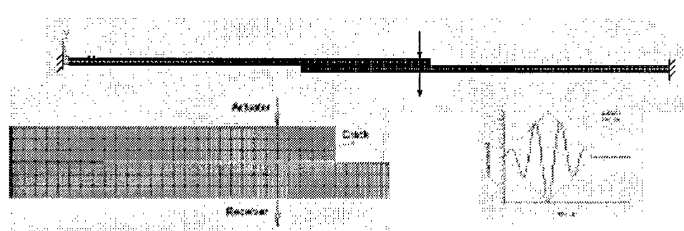
- Computed transmitted waveshapes



- Frequency response

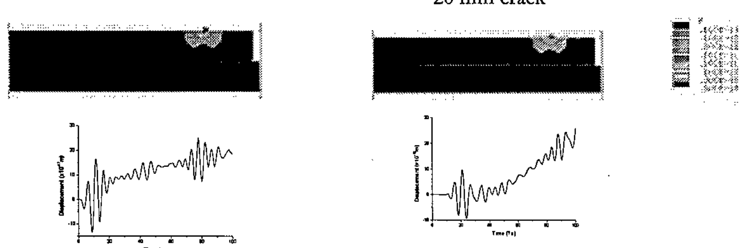


Through Thickness Interrogation: Point Load / Sensor

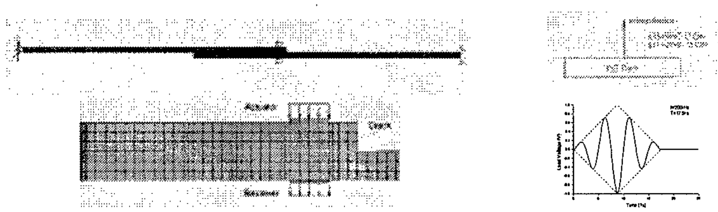


5 mm crack

20 mm crack

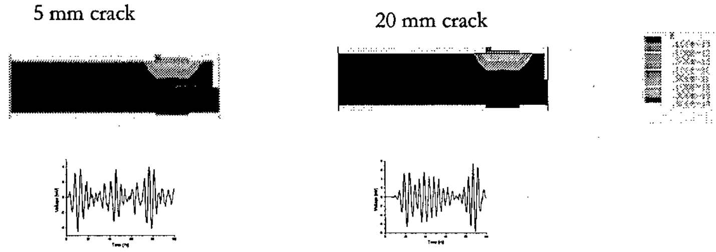


Through Thickness Interrogation: Patch Sensor / Transducer



5 mm crack

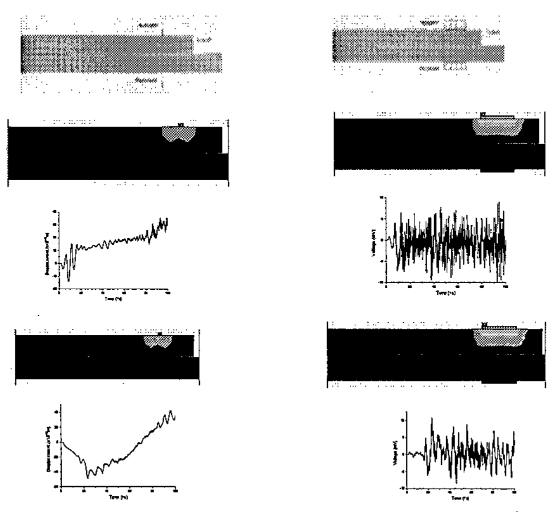
20 mm crack



Effect of Contact Between Crack Faces

5 mm crack

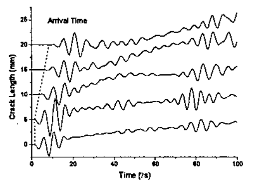
20 mm crack



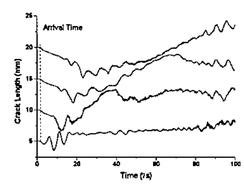
Crack Size Detection

Point Load / Sensor

? No Contact:

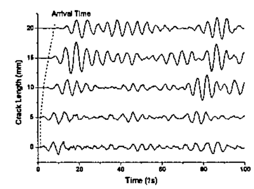


? Contact:

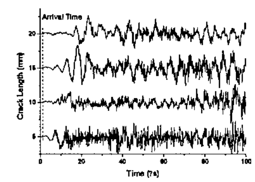


Patch Load / Sensor

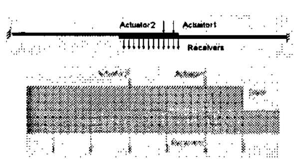
? No Contact:

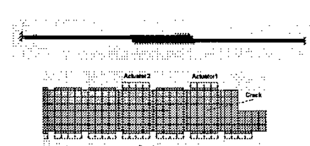


? Contact:

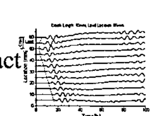


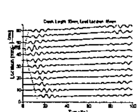
Multiple Actuators / Sensors

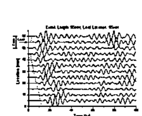


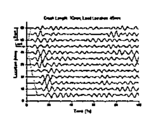


No Contact

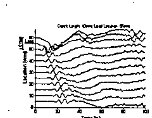


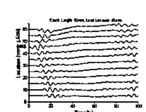


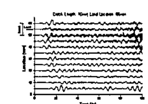


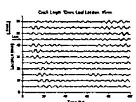


Contact

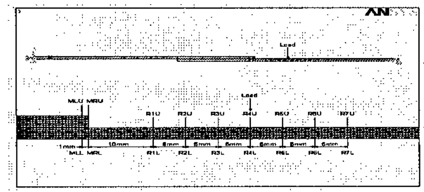




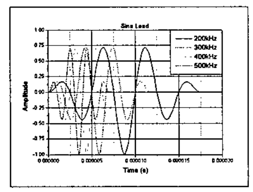




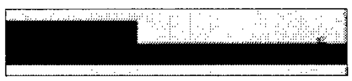
Hybrid Acousto-Ultrasonic Method



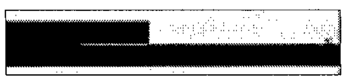
- Input signals



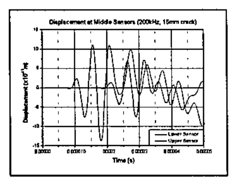
- No Crack



- Crack length 10 mm



- Detected signals at sensor locations

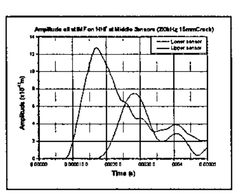


Improved Evaluation of Crack Length by HHT Method

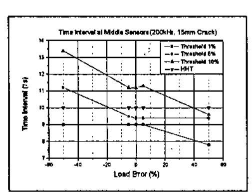
- ToA evaluation by threshold method

Load Error (%)	T1 (s)	T2 (s)	dT (s)
50	1.00E-05	1.96E-05	9.60E-06
5	1.01E-05	2.14E-05	1.13E-05
0	1.02E-05	2.14E-05	1.12E-05
-5	1.02E-05	2.14E-05	1.12E-05
-50	1.06E-05	2.40E-05	1.34E-05

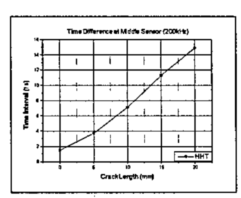
- HHT Method



- Comparison



- HHT master curve

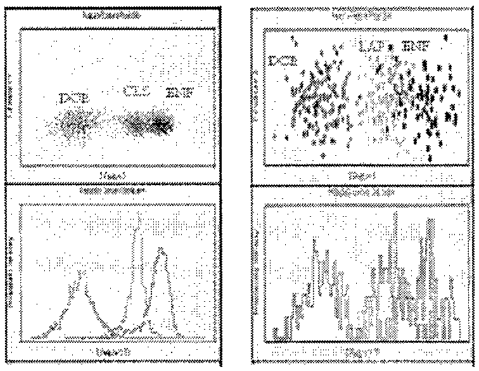


4. Nondestructive Evaluation of Loading Mode Mixity

Summary: AE waveforms pattern recognition analysis was performed on pure and mixed mode data
Example: Comparative analysis of pure mode (DCB and ENF) and mixed mode (CLS and lap joint) AE signals under fatigue

- AE waveform classification

CLS LAP



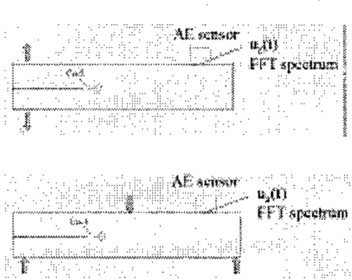
- Mode II signal content

Test	Filtered AE	G_{II}/G (FEA)
CLS	70.7%	71.4%
Lap	63.5%	60.4%

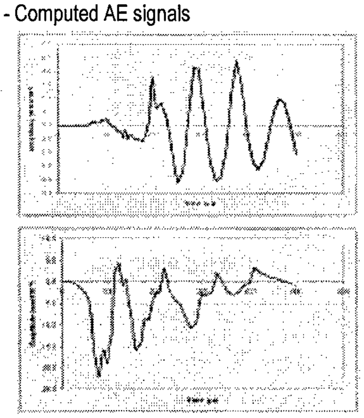
Dynamic FE Modeling of AE Signals

Summary: Modeling of stress wave propagation from fracture events under different loads was performed
Example: Dynamic FE models and computed AE signals

- Dynamic FE Models



- Computed AE signals



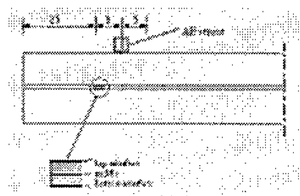
Mode I

Mode II

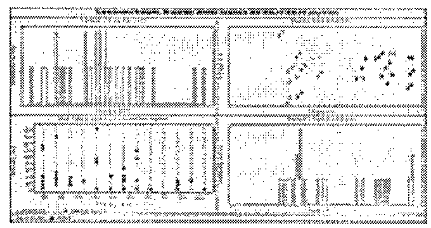
Statistical Analysis of Simulated AE Signals

Summary: FEM stress waves from variable fracture sources were computed for the first time and analyzed by pattern recognition with experimentally obtained classifier
Example: Dynamic FE modeling and signal classification

- Variable source location



- Use of experimental AE classifier on pure mode AE

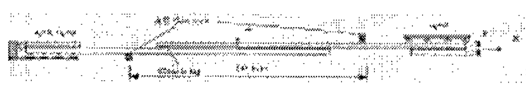


-Mode II signal content in lap joint AE

Experimental AE	Numerical AE	G_{II}/G (FEA)
63.5%	62.4%	60.4%

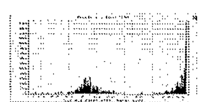
Evaluation of IM7/5250-4 Joints

Summary: Acoustic emission analysis was used to evaluate crack location and mode mixity
Example: Removal of fretting noise and acoustic emission crack location analysis under fatigue

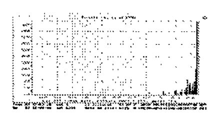


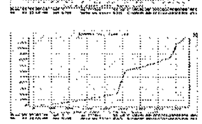
- Unfiltered Data

- Filtered Data

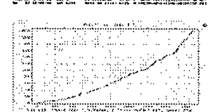


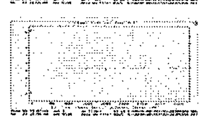
Counts vs. load



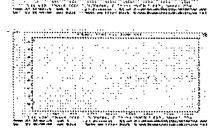


AE event history





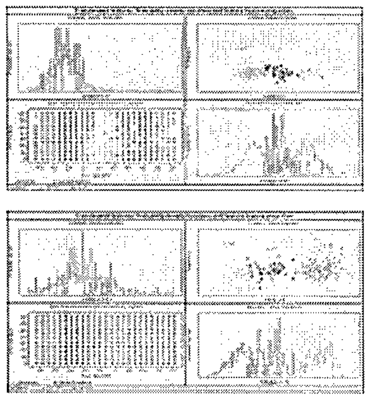
AE location history



AE Signal Classification for IM7/5250-4 Joints

Summary: AE waveform pattern recognition was performed on pure mode and mixed mode data
Example: Comparative analysis of pure mode (DCB and ENF) and mixed mode (CLS and lap joint) AE signals from IM7/5250-4 joints under fatigue

- AE Waveform Classification



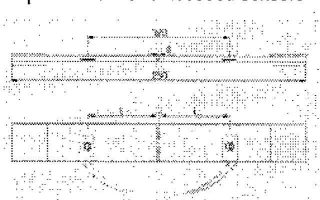
- Mode II Signal Content

CLS	AE Mode II / AE total	LAP Joint	AE Mode II / AE total
Fatigue tests	66.50%	Fatigue tests	63.80%
Static tests	65.70%	Static tests	62.50%
Nonlinear FEM	67.30%	Nonlinear FEM	60.60%

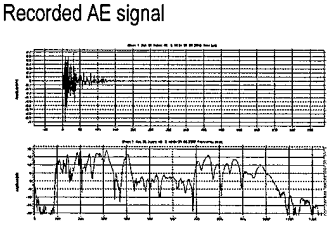
5. Embedded Film Sensors for Real-Time Integrated NDE

Summary: Development of laminates with built-in sensors/transducers for real-time (in-service) detection and quantification of damage and fracture to be used in conjunction with predictive models
Example: Embedded PVDF film sensors in laminated composite adherends

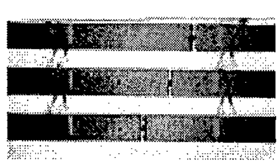
- Specimens with embedded sensors



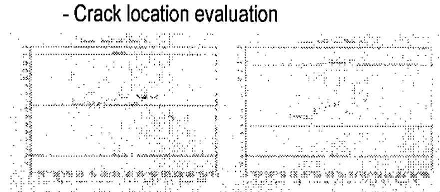
- Recorded AE signal



- Manufactured specimens



- Crack location evaluation



Classification of AE Signals from Embedded PVDF Sensors

Summary: Previously developed hybrid transient-parametric method of AE analysis was applied on AE signals from embedded sensors for the first time

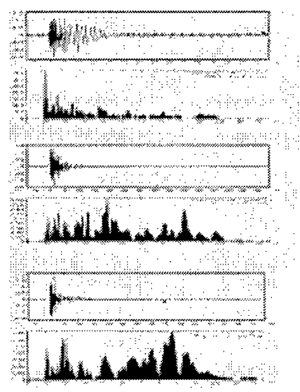
Example: Characteristic AE waveforms and parametric regions

- Characteristic AE waveforms

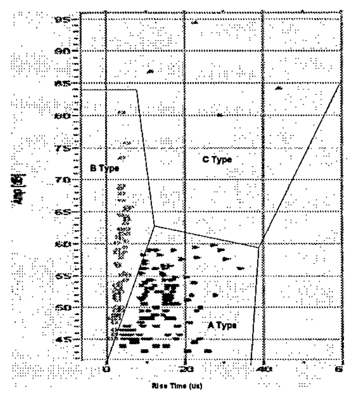
A type

B type

C type



- Parametric regions

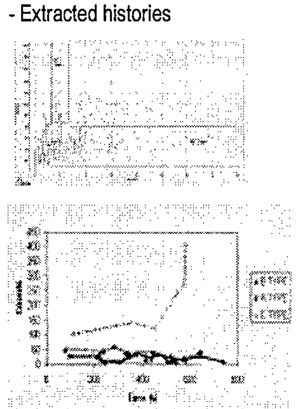


Extracted Histories of Micromechanisms

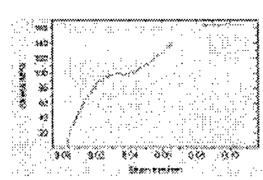
Summary: Previously developed hybrid transient-parametric method of AE analysis was applied on AE signals from embedded sensors for the first time

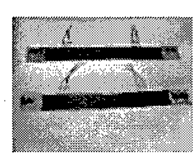
Example: Extracted histories of damage micromechanisms

- Extracted histories



- Correlation with mechanical behavior



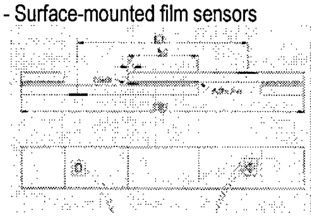


Surface-Mounted Film Sensors for Real-Time Monitoring of Joints

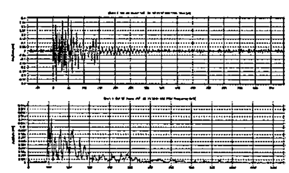
Summary: Development of joints with low-profile surface-mounted film sensors/transducers for real-time detection and quantification of damage and fracture to be used in conjunction with models of life prediction

Example: Novel surface-mounted PVDF film sensors with dynamic wave detection capability

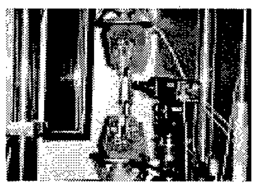
- Surface-mounted film sensors



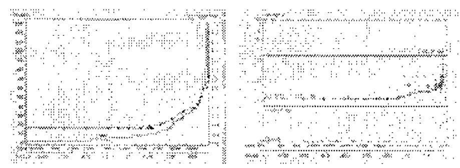
- Feasibility of dynamic AE recording



- Fatigue test set-up



- On-line AE monitoring of fatigue crack

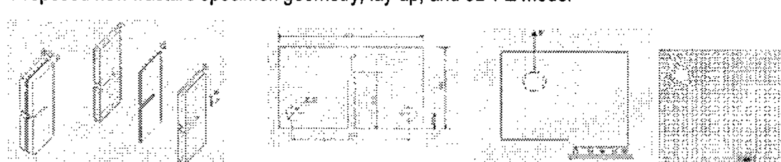


6. Evaluation of Anisotropic Fracture Toughness of Composites

Summary: Pioneering test method was developed in collaboration with AFRL for evaluation of anisotropic fracture toughness of advanced composites

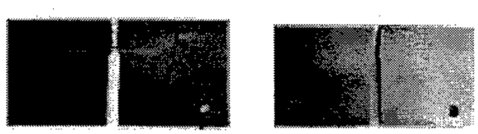
Example: World's highest fracture anisotropy (1,011) measured with the newly developed method

- Proposed new fracture specimen geometry, lay-up, and 3D FE model



$[90_{20}/0/90_{20}]$

- Tested specimens

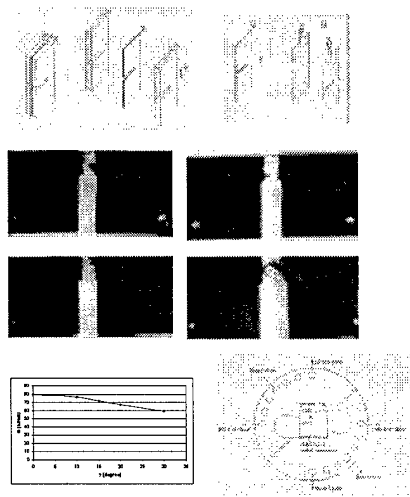


- Results

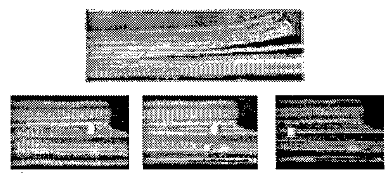
Fracture Direction	G_I kJ/m²
Parallel	0.079
Transverse	79.9

Potential Applications

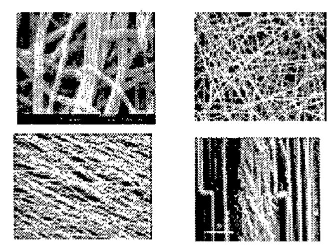
- Fracture at an angle to the fiber direction



- Bond crack kinking / branching into composite adherends



- Novel nanofibers and nanocomposites



Summary

Accomplishments

- Fatigue behavior of joints for aerospace structural applications has been studied in-depth
- Feasibility of linking advanced damage and fracture mechanics and modeling-based QNDE to provide predictive capabilities has been demonstrated for the first time

Smart Predictive NDE (SNDE) of Aerospace Structures: Proposed Novel Concept

- Classify damage
- Develop and validate predictive models
- Develop QNDE methods to extract *relevant* damage parameters
- Integrate in a system

Need Systems Approach and Collaborative Research and Engineering (Big Task)

Potential

- Real-time SNDE-based analysis of projected structural integrity and allowable flight scenarios
- SNDE-based decisions to restrict activity and activate self-healing (pain-restricted motion-healing in biosystems)
- Autonomous SNDE evaluation of efficiency of self-healing and quantitative prediction of extended life