LA-UR-97-⁷-3151

Approved for public release;
distribution is unlimited

Title: **A Thermodynamically Consistent, Damage-Dependent, Interface Debonding Model for Composites**

Author(s): J. N. Johnson, T-1
B. E. Clements, T-1
F. L. Addessio, T-3
T. O. Williams, T-3

Submitted to: DOE Office of Scientific and Technical Information (OSTI)

RECEIVED
DEC 01 1997
OSTI

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

A Thermodynamically Consistent, Damage-Dependent, Interface Debonding Model for Composites

James N. Johnson,* Bradford E. Clements, Frank L. Addessio, and Todd O. Williams

Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The ability to design composite materials and analyze processing procedures relies on the availability of constitutive models that describe their dynamic response accurately. The strength, damage evolution, and failure of interfaces within composites often dominate their macroscopic performance but are not well characterized. The design of such composites for particular applications requires adequate knowledge of interfacial characteristics. Given the large number of potential loading scenarios that an engineering composite can be subjected to, it is obviously beneficial to have reliable and accurate theoretical methods for their quantitative treatment in numerical calculation. This project addresses the fundamental aspects of interfacial debonding in composites, and examines the basic behavior in practical situations.

Background and Research Objectives

Advanced materials such as composites (metal, ceramic, or polymer-matrix) are receiving increased attention due to their higher specific strengths, stiffnesses, and high-temperature properties. Increased utilization of these materials under dynamic loading conditions requires an understanding of the relationship between high-rate/shock-wave response as a function of microstructure if predictive material behavior capabilities are to be attained. In contrast to single-phase materials, composites feature (i) heterogeneous mixtures (either a layered, woven, or laminated, etc., structure); (ii) anisotropic elasticity and plasticity; and (iii) interfacial effects that influence the plastic flow and fracture behavior. These three attributes cause distinct and unusual material response when composites are subjected to dynamic loading. Because these advanced materials are significantly more complex structurally than single-phase, pure materials, it is necessary that specific research thrusts be developed and pursued that address those aspects of material behavior specifically related to such things as interfacial damage.

The objective of this project has been to facilitate the development of predictive computational models of the mechanical response of composite materials based on a

* Principal Investigator, e-mail: jnj@lanl.gov

fundamental understanding of interfacial delamination. Physically based and thermodynamically consistent theoretical models improve our ability to predict the manner in which the dynamic response of composites may depend on the loading rates, unloading paths, orientation and temperature. This capability enables us to better select and design materials for large-strain, high-strain-rate loading conditions.

Importance to LANL's Science and Technology Base and National R&D Needs

The scientific impact of this research is to increase our fundamental understanding and predictive modeling capability of the deformational response of composite materials. Previous thrusts have been primarily the modeling of single-phase materials and composites with perfectly bonded interfaces. The successful development of more sophisticated models of composite material behavior, which include rational models of interfacial debonding, advances the state-of-the-art in constitutive descriptions of high-rate material behavior. This advance includes the multidisciplinary fields of shock-wave physics, materials science, continuum mechanics, and numerical methods. Advanced material classes, particularly composites, will be increasingly important in the future to a variety of DOE, DoD, and advanced manufacturing initiatives. This is driven by performance optimization of fewer systems due to financial considerations, political pressures, and national competitiveness. The DOE and DoD weapons programs must investigate the use of high-technology and high-leverage technologies to address safety and durability of current weapons systems in the stockpile.

This project has served as a basis for establishing a long-term, coordinated capability at Los Alamos to investigate the response of composite materials to interfacial debonding under a variety of tensile and shear loading conditions. Such a capability is necessary for many conventional and nuclear weapons-related projects at Los Alamos, and is also crucial if these material classes are to be utilized under dynamic conditions in non-defense applications such as those experienced during civilian transportation vehicle crash-worthiness and foreign-object damage assessments. Spin-off utilization of the fundamental deformation and modeling tools developed in this program is directly applicable to technology transfer, particularly engine-turbine-blade containment concerns in aerospace, in addition to the other nondefense applications described above. Los Alamos possesses the research breadth to investigate deformational properties of these advanced materials in a combined program which includes material modeling, quasi-static and dynamic experimentation, and numerical methods.

Scientific Approach and Accomplishments

The thermodynamical properties of an interface separating the constituents of a composite are important for their role in governing the net response of the composite to an applied stress load. By tailoring the interfacial properties one can design a composite with desired mechanical attributes, and thus turn complications related to interfacial strengths into potential advantage. This can be done by choosing materials with interfacial strengths to be either above or below the material strengths of the composite constituents. A weak interface, for example, can debond under a specified load and thus preserve the integrity of the constituents even when the applied load exceeds the failure stress of the constituents. On the other hand, perfect interfacial bonding is advantageous when it is desirable to have complete stress or heat transmission throughout the composite. Designing a composite suited for a given application requires adequate knowledge of the interfacial characteristics and, in turn, this requires extensive experimental investigation. Given the large number of loading scenarios to which a composite can be subjected, it is obviously beneficial to have a reliable and accurate theoretical model for treating the interface. The scientific approach for investigating and describing interfacial behavior in composites is based on the highly successful Method of Cells (MOC) homogenization technique developed by Jacob Aboudi.¹

When perfect interfacial bonding occurs, displacement and traction continuity are conditions enforced by the MOC analysis. On the other hand, for imperfect interfacial bonding, the displacement becomes discontinuous at the interface as described by an Interfacial Constitutive Equation (ICE).

Specific accomplishments over the course of this project have included the following results:

- Adoption of procedures for generating equivalent homogeneous models of the macroscopic, dynamic, mechanical response of engineered composites for use directly in continuum mechanics simulations. This includes the establishment of the independence of the ICE from the homogenization procedure and a proper treatment of material rotations within the homogenization procedure itself.
- The MOC homogenization technique has been used to simulate the average response of a Ti/Al laminate to hydrostatic loading; each layer of laminate being a homogeneous, isotropic metal. Consideration of a rigorous treatment of elastic nonlinearity was

included to provide improved understanding of the requirements for a physically consistent approach.

- Specific accomplishments in the most recent years of this project include the combination of an interface model with previous results (anisotropy, plastic deformation, and nonlinear elasticity) for the homogenization of composite material behavior in the presence of a generalized ICE. The traction (force) across a pre-existing interface is given as a function of the jump in displacement. The jump in the displacement field increases as the interface fails. The response of both the fiber-matrix interface (debonding) and the interface between laminae (delamination) is provided by the interface model. Also accomplished most recently is a three-dimensional model for composite material behavior, including delamination, for application to plastic bonded explosives.

Publications

1. Aidun, J. B. and Addessio, F. L., "An Enhanced Cell Model with Nonlinear Elasticity," *J. Composite Materials*, **30**, pp. 248-258 (1996).
2. Clements, B. E., Johnson, J. N., and Hixson, R. S., "Stress Waves in Composite Materials," *Physical Review*, accepted for publication (1996).
3. Addessio, F. L. and Aidun, J. B., "Analysis of Shock-Induced Damage in Fiber-Reinforced Composites," *High-Pressure Shock Compression of Solids, III*, in press (1996).

Reference

- [1] Aboudi, J., Mechanics of Composite Materials, Volume 29, Studies of Applied Mechanics Series, Elsevier Science Publishers B.V., New York, 328 pages (1991).