



GEORGIA INSTITUTE OF TECHNOLOGY  
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/27/92

Project No. E-20-678 \_\_\_\_\_ Center No. R6555-0A0 \_\_\_\_\_  
Project Director ATLURI S N \_\_\_\_\_ School/Lab CIVIL ENGR \_\_\_\_\_  
Sponsor NAVY/OFC OF NAVAL RESEARCH \_\_\_\_\_  
Contract/Grant No. N00014-88-K-0496 \_\_\_\_\_ Contract Entity GTRC  
Prime Contract No. \_\_\_\_\_  
Title FUNDAMENTAL INVESTIG. OF FRACTURE & DEFORMATION IN BRITTLE MATERIALS..MET  
Effective Completion Date 910630 (Performance) 910831 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	_____
Final Report of Inventions and/or Subcontracts	Y	_____
Government Property Inventory & Related Certificate	Y	911031
Classified Material Certificate	N	_____
Release and Assignment	Y	_____
Other _____	N	_____

Comments \_\_\_\_\_

Subproject Under Main Project No. \_\_\_\_\_

Continues Project No. \_\_\_\_\_

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Management	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other _____	N
_____	N

NOTE: Final Patent Questionnaire sent to PDPI.



GEORGIA INSTITUTE OF TECHNOLOGY  
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April 23, 1990

ANNUAL LETTER REPORT-JSE-15-90

Dear Dr. Barsoum:

Please find enclosed an "Annual Letter Report" as required under the deliverables schedule for ONR Contract N0014-88-K-0496. I would also like this short letter to serve as a quarterly update since my last communication with you in January 1990. In brief, during the past year we have examined the local near tip asymptotic fields and toughening mechanisms for 3 classes of flawed ceramics, (i) nominally pure alumina as a function of grain size from 20-150 microns ( $Al_2O_3$ ), (ii) Partially Stabilized Zirconia ( $Mg-ZrO_2$ ) and (iii) hot pressed SHS Titanium Diboride ( $TiB_2$ ). Class (i), in joint cooperation with General Electric Co. investigates the nature and existence of microcracking as a mechanism to toughen ceramics. Using moire interferometry we have identified that microcracking exists below grain sizes on the order of 70 microns. Above 70 microns we have identified that crack deflection occurs along the grain boundaries and acts as the principal toughening agent. For class (ii), in joint cooperation with Oak Ridge National Laboratory, we have produced for the first time, local in plane asymptotic fields, as well as wake zones for the tetragonal to monoclinic phase transformation surrounding a propagating crack. The ultimate goal of studying classes (i) and (ii) is to understand the fracture behavior for the two phase system of  $Al_2O_3-ZrO_2$ . For class (iii), in cooperation with GTRI, we have identified that the toughening occurs by crack branching. The principal tools of investigation have been direct tensile loading of miniaturized DCB specimens optimized for straight crack growth using a small high compliance load frame which can open the crack mouth 0.2 microns in resolution, acoustic emission for microcrack activity and moire interferometry for X and Y displacement fields local to the crack tip. We are currently applying for a patent on the high compliance load frame. In addition we are using white light microscopy for direct counting of microcrack density before and after testing of the  $Al_2O_3$ . You currently have overheads that describe the outlined work performed over the past year as an additional deliverable.

As a short quarterly report, during the past 4 months since the January report and overheads, we duplicated the above test results. This has involved retesting all 6 alumina specimens as a function of grain size as well as the single  $ZrO_2$  specimen. We already have duplicated results on the  $TiB_2$ . We are now beginning to produce R curves for the alumina and Zirconia. Our initial results on the Zirconia show a rise in R curve behavior consistent with the theoretical work of Stump and Budiansky. This rise effect is quite novel and relates to the initial expansion of the phase transformation zone. We are developing local mixed mode  $K_I$  and  $K_{II}$  extraction algorithms from the local moire data as the fracture of the alumina at larger grain sizes occurs by local crack deflection and hence local mixed mode behavior. The crack branching in the  $TiB_2$  also exhibits similar effects. These results are quite interesting as normal screening and material testing results are assumed under mode I conditions. I am expecting that this work should be completed by the end of July.

Finally due to budget reductions on this program we have deleted all dynamic aspects of crack growth as the future increments were intended to begin this phase. In this manner, we may produce higher quality results on static crack growth with the remaining money. Our budget currently is projected through December 1990 at which time the last student working on this program will have finished his thesis. At that time I will begin to write up the final report.

Sincerely

Jonathan S. Epstein

**Principal Investigator:** S.N. Atluri, Center for Computational Modeling, Georgia Institute of Technology, Atlanta, GA, 30332; Tel: 404-894-2758; Fax: 404-894-2299.

**Research Sponsored by:** Office of Naval Research, **Program Manager:** Dr. Y. Rajapakse.

**Major Accomplishments of the Past Year:**

In the area of mechanics of composite materials, the following research was accomplished: (i) for the first time in literature, a successful finite element, with the least number of degrees of freedom for arbitrary number of layers, was developed for thick-section composite laminates. The element is a quadrilateral, and has only 44 degrees of freedom irrespective of the number of layers. Excellent results were obtained for stress, vibration and buckling problems for thick section composites; (ii) a finite-strip method was developed for post-buckling failure analysis of stiffened thick-section composite plates and shells; (iii) in the area of ceramic composites, consistent, continuum micro-mechanics models were developed for dilatational phase transformation and micro-cracking, and their effect on fracture-toughness enhancement. Excellent correlations were obtained for the computed crack-tip deformation fields with dynamic moire interferometry measurements.

In the area of three-dimensional fracture analysis of metal structures, extremely simple and cost-effective methods for the determination of weight-functions for surface flaws of semi-elliptical as well as circular shapes were developed. The results obtained were in excellent correlation with those obtained through more elaborate and costly finite element procedures. These weight functions make the structural integrity analysis rather routine, and are now being fabricated for a variety of crack problems.

In the area of large strain plasticity analysis, for the first time in literature, a new field-boundary-element method that leads to a full tangent stiffness approach has been developed. This method has been demonstrated to be much more versatile and efficient as compared to the standard finite element method. It alleviates the problems of locking associated with the finite element method, and leads to a much more accurate stress data. The method is being applied to the important problems of strain-localization and instability in metals.

In the area of acoustics, for the first time in literature, an effective numerical method for solving the hyper-singular integral equations that arise in the external-acoustics problem has been developed. It has been demonstrated to be far-more efficient than any other method in prior literature.

The principal investigator, S.N. Atluri, has authored the following papers with other collaborators where names are indicated in parentheses.

"Analysis of Toughening of Magnesia-Partially Stabilized Zirconia, due to Dilatational Transformation" *Acta Metallurgica et Mater.* (to appear) (with H. Okada and J.S. Epstein).

"Constitutive Modeling of a Solid Exhibiting Transformation Induced Plasticity" *Acta Metal. et Mater.* (to appear)(with H. Okada).

"Constitutive Modeling of a Solid Exhibiting Micro-cracking Due to the Dilatational Transformation of Second Phase Particles" *Jnl. Mater. Science* (to appear) (with H. Okada).

"Fracture-Toughness Enhancement Due to Transformation" Sixth Int. Conf. on Mech. Behavior of Materials, Kyoto, Japan 1991 (In Press) (with H. Okada and J.S. Epstein).

"Analytical Modeling of Thick-Section Composites" Inv. Paper, Int. Conf. on Composite Materials, Honolulu, July 1991 (with J.V. Kouri).

"On the Evaluation of Hyper-Singular Integrals Arising in the Boundary Element Method for Linear Elasticity", *Computational Mechanics*, Vol. 8, 1991 (with C.C. Chien and H. Rajiyah).

"A Finite-Difference Alternating Method for Cost-Effective Determination of Weight-Functions for Orthotropic Materials in Mixed-Mode Fracture" *Engg Fracture Mech*, Vol. 36, pp 327-340, 1990.

"A Novel Boundary-Element Alternating Method for Weight Functions, Using Bueckner's Fundamental Solution" *Int. Jnl. of Fracture*, August 1990, pp. R51-R59 (with M. Kuna and H. Rajiyah).

"Field Boundary Element Method for Nonlinear Analysis" Chapter in *Advances in Boundary Element Methods for Plates and Shells* [D.E. Beskos, Ed.], Springer 1991 (In Press) (with D.S. Pipkins).

"Analytical Modeling of Thick Section Composites" Invited Paper, in *Use of Composites in Marine Structures*, NRC-National Academy of Engineering, Sept. 1990.

"Computer Simulation of Transformation Induced Plasticity using Finite Element Method" *Acta Metallurgica* (to appear) (with N. Ramakrishnan and H. Okada).

"An Alternating Technique for Evaluating Weight Functions for 3-D Surface Flaws in Finite Solid Bodies", *Int. Jnl. of Num. Meth. in Engg* (to appear), 1990, (with C.Y. Liao).

"An Effective Method for Solving the Hyper-Singular Integral Equations in 3-D Acoustics", *Journal of the Acoustical Society of America*, Vol 88, pp 918-937, 1990 (with C.C. Chien, H. Rajiyah).

"Analysis of Embedded and Surface Elliptical Flaws in Transversely Isotropic Bodies by the Finite Element Alternating Method", *Journal of Applied Mechanics* June, 1991, (with H. Rajiyah).

"A Finite-Element-Alternating Method for Evaluation of Stress Intensity Factors for Part-Circular Cracks Subjected to Arbitrary Loadings" *Computer Meth in Appl Mech & Eng.* (to appear) 1991 (with C.Y. Liao)

"A Full Tangent Stiffness Field-Boundary Element Formulation for Geometric and Material Nonlinear Problems of Solid Mechanics" *Int Jnl of Num Meth in Engg* Vol 29, pp 15-35, 1990 (with H. Okada, H. Rajiyah)

"The First Order Variation of the Displacement Field Due to Geometrical Changes in an Elliptical Crack", *Jrl. of Applied Mechanics*, ASME, Vol. 57, No. 3, pp. 639-646, Sept. 1990, (with T. Nishioka).

"Stress Intensity Factor Variation along a Semicircular Surface Flaw in a Finite-Thickness Plate", *Engg. Fracture Mechanics* Vol. 34, No. 4, pp. 957-976, 1989, (with C-Y. Liao).

"Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 1: Formulation and Simple Numerical Examples" *Int. Jrl. of Plas.*, Vol 6 pp 169-188, 1990 (with Y. Toi)

"Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 2: Stationary and Growing Macro-Cracks Under Static Loading", *Int. Jrl. of Plasticity*, Vol. 6, pp. 263-280, 1990, (with Y. Toi).

"Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 3: Stationary & Rapidly Propagating Cracks Under Dynamic Loading", *Int. Jrl. of Plasticity*, Vol. 6, pp. 389-414, 1990, (with Y. Toi).

#### **Transitioning of Basic Research Results Obtained Under ONR Support:**

1) The work on fracture analyses performed under ONR support is now widely used in aerospace

industry, in connection with the structural integrity of aging airplanes. The U.S. Federal Aviation Administration, and the Warner Robins Air Force Base, have requested the principal investigator, for assistance in connection with multiple site damage in aging airplanes. The computer programs based on ONR research will be made available to the FAA. This work has resulted in the following book:

S.N. Atluri, S.G. Sampath and P. Tong (Eds.) "Structural Integrity of Aging Airplanes" Springer-Verlag, 1991.

2) The work performed on large deformations of beams, plates and shells, under ONR support is now being used by the NASA Marshall Flight Center in Alabama in connection with their work on tethered satellites.

3) The work on thick-section composites has attracted the attention of the Marine Board of the U.S. National Academy of Engineering, and the U.S. Army Research office. In Sept. 1990, S.N. Atluri gave a keynote lecture on "Use of Thick Section Composites in Marine Structures" at the National Symposium on Marine Structures, organized by the U.S. National Academy of Engineering.

4) The work on acoustics has attracted the attention of the structural acoustics community.