Project No. E-20-645

Project Director: Dr. S. N. Atluri

Sponsor: Air Force Office of Scientific Research, Bolling AFB, D.C.

Type Agreement: Grant No. AFOSR-81-0057, Amend. D (03 year)

Award Period: From 2/15/83 to 12/15/83 (Performance) 12/15/83 (Reports)

Sponsor Amount: Total Estimated: $ 59,918

Cost Sharing Amount: $ 10,610

Cost Sharing No: E-20-336

Title: Advanced Stress Analysis of Aircraft Structures

ADMINISTRATIVE DATA

1) Sponsor Technical Contact: Program Manager
   Dr. A. K. Amos
   AFOSR/NA
   Bolling AFB, D.C. 20332
   (202)-767-4937

2) Sponsor Admin/Contractual Matters: Negotiator
   Christopher E. Yancey, 1LT, USAF
   AFOSR/PKD
   Bolling, AFB, D.C. 20332
   (202) 766-5008

Defense Priority Rating: N/A

Military Security Classification: N/A

RESTRICTIONS

See Attached AFOSR Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT. Prior written authorization required for items over $1,000 if not specifically included in approved budget.

COMMENTS:

Continuation of E-20-671, Total Grant amount now $345,959.

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Atlantic
Date 12/18/84

Project No. E-20-645  

Includes Subproject No.(s)  

Project Director(s) Dr. S. N. Atluri  

Sponsor Air Force Office of Scientific Research,  

Bolling AFB, DC  

Title Advanced Stress Analysis of Aircraft Structures  

Effective Completion Date: 12/1/83 (Performance) 2/1/84 (Reports)  

Grant/Contract Closeout Actions Remaining:  

☐ None  

☐ Final Invoice or Final Fiscal Report  

☐ Closing Documents  

☐ Final Report of Inventions  

☐ Govt. Property Inventory & Related Certificate  

☐ Classified Material Certificate  

☐ Other  

Continues Project No. E-20-671  

Continued by Project No.  

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Research Communications (2)  

Project File  

Other A. Jones; M. Heyser
FINAL SCIENTIFIC REPORT
AFOSR Grant 81-0057

"Computational Methods in Advanced Stress and Durability Analysis"

Supported by
Air Force Office of Scientific Research
Building 410
Bolling Air Force Base D.C. 20332
(Dr. Anthony Amos, Program Manager)

Principal Investigator
S.N. Atluri
Regents' Professor of Mechanics
Center for the Advancement of Computational Mechanics
School of Civil Engineering
Georgia Institute of Technology, Atlanta, Georgia 30332

November 1984
I. Introduction:

In this report, research accomplished under AFOSR grant 81-0057, titled "Computational Methods in Advanced Stress and Durability Analyses" during the period November 1980 - February 1984, is summarized. The research was performed at the Center for the Advancement of Computational Mechanics, Georgia Institute of Technology, with S.N. Atluri, Regents' Professor of Mechanics, as the principal investigator.

The report is organized as follows. In Section II, the results of research on computational methods for advanced stress analysis are summarized. In Section III, the results of research pertaining to fracture and durability analyses are summarized. A list of publications and presentations arising out of this research is given in Section IV. Finally, Section V contains a list of students and post-doctoral fellows who participated in this research effort.

II. Computational Methods for Advanced Stress Analysis:

In Ref. [1], a significant development of a new shell theory has been presented, wherein attention has been focused on: (i) definitions of alternate measures of 'stress-resultants' and stress-couples in a finitely deformed shell (finite mid-plane stretches as well as finite rotations), and mixed variational principles for shells, undergoing large mid-plane stretches and large rotations, in terms of a stress function vector and the rotation tensor. In doing so, both types of polar-decomposition of the shell deformation gradient were considered. Ref. [1] contains a comprehensive discussion of the shell constitutive relations, objective stress measures, and objective strain measures. This new theory has been applied in the development and implementation of hybrid-mixed finite element methods for
finite deformation analysis of plates and shells in Refs. [2-7].

An area of significant research accomplishment has been the analysis of, and remedies for, kinematic modes in hybrid-stress finite elements and the rational selection of stable, invariant stress-fields [8]. Fundamental studies into the stability of hybrid/mixed finite element methods for Navier-Stokes equations in solid/fluid mechanics have been carried out [9]. Symmetry group theory has been used to guarantee the essential non-orthogonality of the stress and strain fields, resulting in a set of least-order selections of stable invariant stress polynomials for three-dimensional elements [10]. The theory of the least-order stable stress fields has been successfully applied in the development of isoparametric curvilinear 2- and 3-D hybrid stress elements which have been demonstrated to be far superior in performance to the standard displacement elements [11]. The general theory of the use of stress functions and asymptotic solutions in finite element analysis of continua has been comprehensively discussed in [12].

The progress made in the basic theory of hybrid and mixed finite element methods in solid and fluid mechanics, and their advantages over standard displacement methods in linear as well as nonlinear problems, has been succinctly summarized in [13]. A philosophically broader class of hybrid methods of analysis, involving a combination of analytical-numerical methods, numerical-experimental methods, and a combination of two or more distinctly different numerical schemes, has been discussed in [14].

A major summary work dealing with present status and future directions in computational solid mechanics (finite elements and boundary elements) has been prepared [15]. In this work, the following topics were discussed: (i) LBB conditions for general finite element methods; (ii) least-order, stable, hybrid/mixed elements; (iii) use of symbolic manipulation; (iv) adaptive mesh refinement; (v) boundary-element methods for linear elasticity, as well as for
finite strain problems of inelastic materials; (vi) constitutive modeling of inelastic material behavior; and (vii) control of dynamic response of solids.

In Ref. [16], computational techniques, which preserve the objectivity of incremental constitutive relations, for finite elastic or inelastic materials, for finite time steps, during which the material elements may undergo finite rotations, have been presented and their efficiency has been demonstrated.

The theoretical background of mixed finite element models, in general for nonlinear problems and in particular for plate bending problems, has been examined in detail [17]. It was concluded that mixed finite element formulations, wherein the interpolants for stress fields satisfy only a part of the domain equilibrium equations, are not only consistent from a theoretical viewpoint, but are also preferable from an implementation viewpoint. A new mixed finite element for plate-bending analysis has been developed [18], and its performance has been shown to be superior to most elements in existing literature.

Another area of significant research accomplishment has been in the area of development of finite element methods based on complementary work principles for problems with constraint such as incompressibility in solid and fluid mechanics. Hybrid finite element methods for analysis of incompressible viscous creeping flow (Stokes flow), analogous to the problem of incompressible elasticity, has been successfully developed [19,20] and has been demonstrated to be far superior to the currently popular methods based on reduced-integration-penalty formulations involving only kinematic variables. Fundamental studies pertaining to the stability and convergence of these hybrid methods to treat material incompressibility have been completed [21].

A formulation of a mixed finite element method for the analysis of unsteady, convective, incompressible viscous flow has been presented [22] in which: (i) the deviatoric stress, pressure, and velocity are discretized in
each element; (ii) the deviatoric stress and pressure are subject to the constraint of homogeneous momentum balance condition in each element, a priori; and (iii) the convective acceleration is treated by the conventional Galerkin approach. A fundamental analysis of the stability of the scheme is also presented. The method has been shown to be a superior alternative to the popular reduced-integration penalty methods in a variety of Navier-Stokes flow problems [23]. An analysis of flow over a backward facing step using the present assumed stress mixed method has been presented in [24]. While extending the concept of using the complementary energy approach to treat problems of incompressibility, certain new algorithms for analyzing large strain plasticity were presented in [25].

III. Computational Methods for Advanced Fracture and Durability Analysis:

In Ref. [26], the development of 'special-hole-elements' to enable an efficient and accurate analysis of stress concentration around holes in angle-ply laminates has been presented. In these 'hole-elements', the development of which is based on a modified complementary energy principle, the analytical asymptotic solutions for the stress-state near the hole are embedded. the fully 3-D stress state in the laminate is accounted for. This procedure leads to a very efficient and accurate evaluation of stress concentration around holes in laminates. Later, in Ref. [27], a simplified method for estimation of stress-intensity factors for through-cracks, or for stress-concentration factors for holes, in angle-ply laminates has been presented. The simplicity of this method [27] makes it a practical and viable design tool.

One of the major and significant accomplishments of this research has been the development of a highly accurate, yet one of the most computationally efficient, technique for the analysis of surface flaws in aerospace structures. This is the enhanced alternating technique which employs the
complete solution for an embedded elliptical crack in an infinite solid and subject to arbitrary tractions on the crack-surface as derived in the current research [28,29]. The general procedure for evaluating the necessary elliptic integrals has been systematically derived [29]. The finite element alternating technique that is thus developed leads to a highly accurate yet inexpensive method for analyzing surface flaws in complex three-dimensional geometries of aerospace structural components. This new method has been extensively tested in its ease of applicability and accuracy in solving problems of surface flaws near fastener holes in aircraft attachment lugs [30] and in the analysis of surface flaws near the inner and outer surfaces of pressure vessels [31]. The analytical solution for the embedded elliptical crack in an infinite solid has recently been extended to the case of multiple coplanar as well as nonplanar elliptical cracks in an infinite solid subject to arbitrary crack-free tractions [32]. This analytical solution for multiple embedded flaws has been successfully implemented in a finite element alternating technique for analyzing multiple surface flaws in complicated geometries [33] — thus rendering the multiple crack 3-D problem feasible for analysis for the first time in literature. These solutions for multiple surface flaws in complex geometries were also derived in the more readily usable form of K-factor influence functions for various types of polynomial crack-face loadings [34].

The work on 3-dimensional fracture mechanics has been documented in a comprehensive summary [35] to appear in a forthcoming book [36] on computational fracture mechanics. Invited summaries of this work have also appeared in [37,38].

In Ref. [39], an analysis of fatigue growth of cracks in center-cracked panels and cold-worked fastener holes was presented, and a quantitative evaluation of the effect of cold-working on fatigue life was presented in
In Ref. [40], a comprehensive study of certain path-independent integrals, of relevance in the presence of cracks, in elastic and inelastic solids was presented. A new set of crack-tip parameters, \( T^* \) and \( \Delta T^* \) and their path-independent integral representations, were newly given. The physical interpretations of these integrals, either in terms of crack-tip energy release rates or simply energy differences in two comparison cracked bodies, were explored. The use of the rate integral (\( \Delta T \)) was explored in the analysis of steady as well as non-steady state creep crack growth in structures operating under elevated temperature environments [41,42].

In [43] a path-independent integral, \( J' \), which has the precise meaning of energy release rate per unit crack-extension in elasto-dynamic crack propagation, was introduced. Also, the general asymptotic solution in mixed-mode dynamic crack propagation, and the relation of the \( J' \) integral to the mixed-mode dynamic stress-intensity factors, were given [43]. Simple numerical methods based on a moving mesh of non-singular isoparametric elements were devised and extensively tested [44,45] to analyze dynamic crack propagation using the \( J' \) integral.

A general summary of path-invariant integrals in dynamic fracture and the distinguishing features of the \( J' \) integral were given in [46].

The moving-mesh finite element algorithms developed for analyzing dynamic crack propagation have been extensively tested in their analysis and predictive capability modes [47]. Based on these studies, a simple formula for determining the dynamic k-factor near a propagating crack-tip, through extrapolation from the measured crack-mouth opening displacement, has been given [48].

A number of presentations based on the above research were made. These are listed in Section IV.
IV. List of Publications and Presentations:

IV.A Publications:


IV.B. Presentations


In addition, about 25 invited as well as contributed papers were presented at national conferences of ASME, ASCE, and AIAA and at several universities in U.S.A. and Japan.

V. List of Participants in Research:

a. S.N. Atluri, Principal Investigator
   Regents' Professor of Mechanics
   Georgia Institute of Technology
b. Edward F. Punch, Graduate Student  
   Received Ph.D: 1983, Georgia Tech  
   Currently: General Motors Research Labs, Warren, Michigan

c. C-T. Yang, Graduate Student  
   Received Ph.D: 1983, Georgia Tech  
   Currently: Detroit Diesel Allison, Indianapolis, Indiana

d. P.E. O'Donoghue, Graduate Student  
   Ph.D Student, in progress

e. R.B. Stonesifer, Graduate Student  
   Received Ph.D: 1981, Georgia Tech  
   Currently: President, Computational Mechanics, Inc.  
              College Park, Pennsylvania

f. R. Rubinstein, Post-Doctoral Fellow  
   Currently: General Electric Co., Cincinnati, Ohio

g. T. Nishioka, Post-Doctoral Fellow and later Visiting Assistant Professor  
   Currently: Returned to Japan as Associate Professor  
              Kobe University of Mercantile Marine

h. D. Karamanlidis, Post-Doctoral Fellow from Germany  
   (Primarily supported by German Science Foundation)  
   Currently: Visiting in University of Rhode Island

i. J. Webb, Technical typing and administrative assistance
Computational Methods in Advanced Stress and Durability Analyses

S.N. Atluri

Center for the Advancement of Computational Mech.
School of Civil Engineering
Georgia Tech, Atlanta, GA 30332

AirForce Office of Scientific Research
Bldg. 410
Bolling Air Force Base, D.C. 20332

November 1984

Unlimited


In this report, research accomplished under AFOSR grant 81-0057 titled "Computational Methods in Advanced Stress and Durability Analyses" is summarized. A list of about 50 publications in open literature arising out of this research is given. Salient conclusions from this research are briefly given.