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CSM RESEARCH: METHODS AND APPLICATION STUDIES

Norman F. Knight, Jr.†

NASA Langley Research Center

INTRODUCTION

Computational mechanics is that discipline of applied science and engineering devoted to the study of physical phenomena by means of computational methods based on mathematical modeling and simulation, utilizing digital computers.[1] The discipline combines theoretical and applied mechanics, approximation theory, numerical analysis, and computer science. Computational mechanics has had a major impact on engineering analysis and design. When applied to structural mechanics, the discipline is referred to herein as computational structural mechanics.

Complex structures being considered by the NASA for the 1990's include composite primary aircraft structures and the space station. These structures will be much more difficult to analyze than today's structures and necessitate a major upgrade in computerized structural analysis technology. NASA has initiated a research activity in structural analysis called Computational Structural Mechanics ~~or~~ (CSM). The broad objective of the CSM activity is to develop advanced structural analysis technology that will exploit modern and emerging computers — such as computers with vector and/or parallel processing capabilities.

The Langley CSM activity, initiated in October 1984, is described in reference 2. The present paper describes the current research directions for the Methods and Application Studies Team of the Langley CSM activity.

† Aerospace Engineer, Structural Mechanics Branch, Structures and Dynamics Division.

LANGLEY CSM PROGRAM

Parallel Structural Methods Research - Olaf O. Storaasli

Testbed Development - Ronnie Gillian

Methods and Applications Studies - Norm Knight

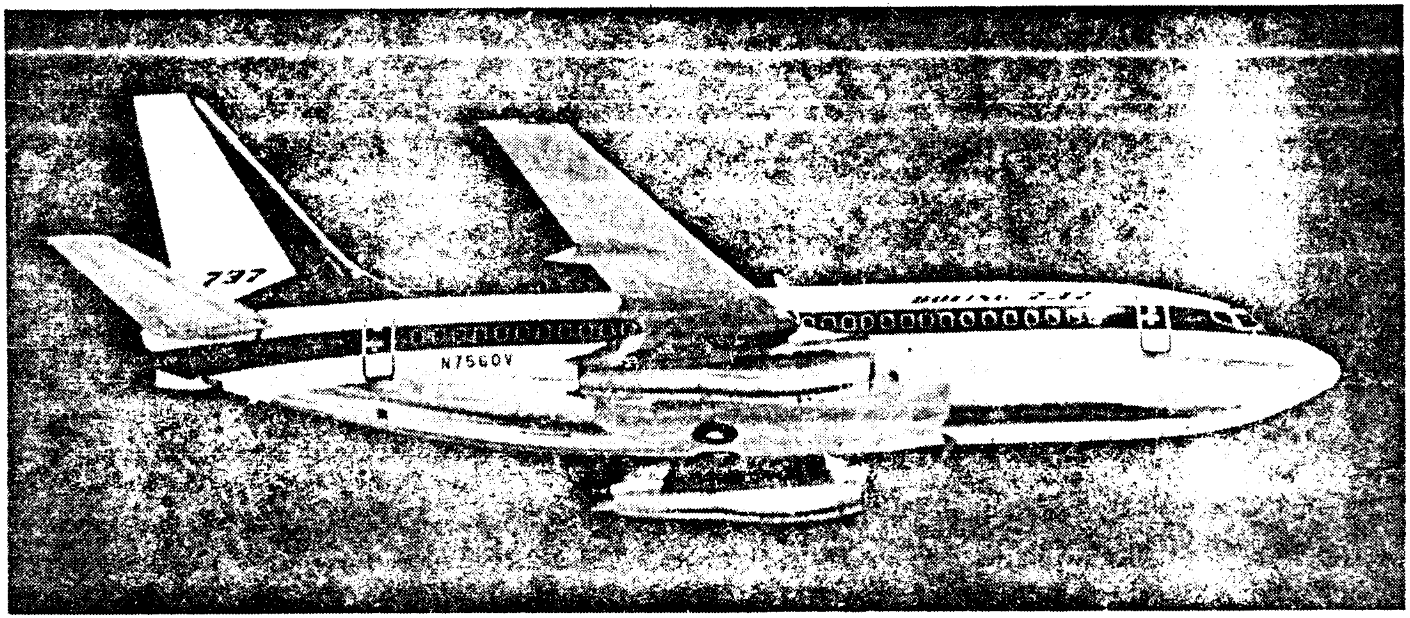
LANGLEY CSM PROGRAM

The Langley CSM program is organized as three teams. The first team's primary responsibility is parallel structural methods research. The second team's primary responsibility is testbed development. The third team's primary responsibility is methods and application studies. Each team interacts with the other teams to achieve a synergistic effect. This paper will describe the objective and research directions of the third team.

The third team's primary responsibilities are to develop structural analysis methods and carry out application studies. The third team emphasizes advanced structural analysis methods — such as 3-D stress analysis, composite laminate analysis, and error detection and control — that have application to all computers rather than focusing on methods that exploit MIMD computers, which is the responsibility of the parallel processing team.

STRUCTURAL ANALYSIS PROBLEMS

Commercial/military transport aircraft



Problem areas
- Composites
- Discontinuities
- Windows, doors, holes, damage
- Buckled skin
- Routine detailed analysis

Accurate and reliable analytical tools will lead to:
- Reduced testing needs
- Reduced weight associated with high margins for uncertainty
- Improved performance

STRUCTURAL ANALYSIS PROBLEMS

– Commercial/Military Transport Aircraft–

Structural analysis problems for commercial/military transport aircraft are indicated on this slide. These problems occur in metallic as well as composite structures. However, the brittle nature of composites requires that their strength limits and failure characteristics be well understood before composite structural components can be designed properly. In many respects, a greater need for reliable and accurate analytical predictive techniques exists for composite structures than for metallic structures. The difficulties associated with analyzing composite structures are magnified when there are discontinuities such as free edges, bolt holes, and bonded joints. Other problems are caused by windows, doors, access holes, and damage.

To save weight, many designers are proportioning structural panels so that the skin can buckle in service. Such panels are lighter than buckling-resistant panels. However, analyzing the postbuckling response of these structurally efficient panels is very difficult with today's analysis procedures. Specifically, it can be computationally difficult to track the postbuckling response; it can be frustrating and time consuming to have numerous restarts; and it can be expensive.

The problem of calculating detailed stress distributions around discontinuities in buckled, composite structural components for use with the various analytical failure prediction techniques has not been thoroughly explored. Because of the complex failure modes of composite structures, it may be necessary to perform a detailed 3-D stress analysis in a local region in order to obtain an adequate estimate of the strength. Today, carrying out such an analysis of a composite component can be a major research task. The capability to carry out, on a routine basis, a local 3-D stress analysis of a composite component within a larger 2-D analysis model is needed.

Accurate and reliable structural analysis procedures will lead to reduced time and cost for testing, reduced weight penalty associated with high margins for uncertainty, and improved performance. These technology improvements will be incorporated in structural analysis software, and that software will account for advancements in computer hardware. An appropriate match of structural analysis software and computer hardware could provide a substantial increase in computational speed.

METHODS AND APPLICATION STUDIES

OBJECTIVE: TO IDENTIFY, DEVELOP, AND EXTEND STRUCTURAL ANALYSIS AND COMPUTATIONAL METHODS THAT HAVE HIGH POTENTIAL

APPROACH: METHODS DEVELOPMENT DRIVEN BY STRUCTURAL APPLICATIONS AND ANALYSIS DEFICIENCIES

METHODS AND APPLICATION STUDIES

The objective of the methods and application studies team is to identify, develop, and extend structural analysis and computational methods that have high potential for solving critical application problems and for removing analysis deficiencies. Structural applications and analysis deficiencies drive the methods development and the application of these methods should provide new insight for complex, nonlinear structural mechanics problems. The analysis and computational methods should be amenable to error analysis. That is, given a physical problem and a mathematical model of that problem, an analyst would like to know the probable error in predicting a given response quantity. The ultimate goal is to specify the error tolerance and to use a self-adaptive procedure to adjust the mathematical model or solution strategy to obtain that accuracy.

CSM FOCUS PROBLEMS

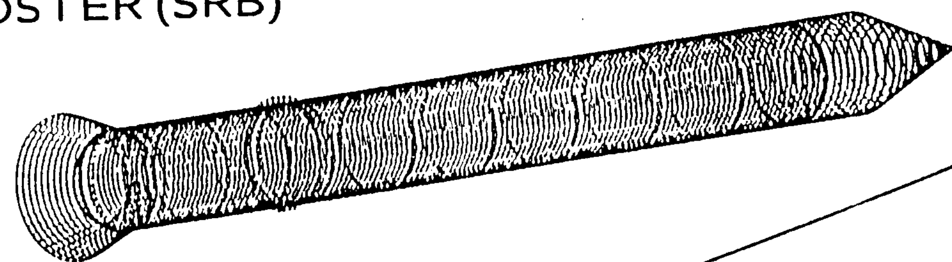
- CHALLENGING STRUCTURAL MECHANICS PROBLEMS THAT STRETCH OUR ABILITY TO PREDICT STRUCTURAL RESPONSE
- CHALLENGING COMPUTATIONAL PROBLEMS THAT STRETCH OUR COMPUTING LIMITS
- COMMON PROBLEMS FOR ALL CSM PARTICIPANTS LEADING TOWARDS FOCUSED EFFORT
- GUIDE METHODS RESEARCH AND DEVELOPMENT FOR GENERIC CLASS OF PROBLEMS
- COORDINATION WITH OTHER GROUP(S) NEEDED TO AUGMENT MANPOWER REQUIRED TO ANALYZE LARGE COMPLEX STRUCTURES

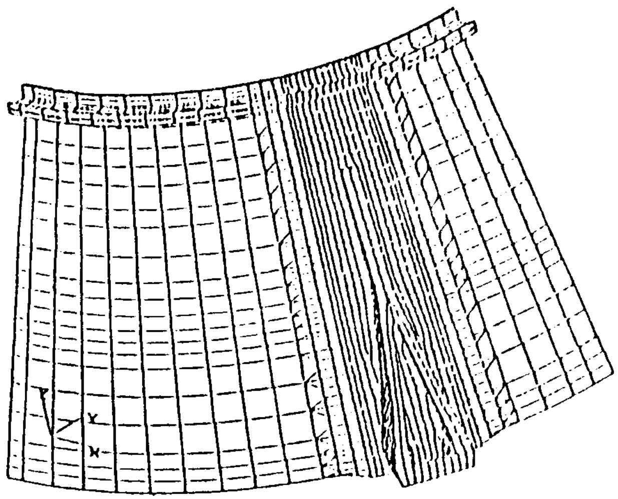
CSM FOCUS PROBLEMS

The Langley CSM activity employs the concept of focus problems to provide a common set of structural analysis problems for all CSM participants. Focus problems may be entire aerospace vehicles or various subcomponents that pose difficult structural mechanics problems. However, the problems selected as focus problems will challenge our ability to predict their structural response or will stretch our computing limits. These focus problems will help guide methods research and development for generic classes of problems. Focus problems will change as new technology evolves and computational structural mechanics methodology develops. As the size and complexity of the focus problems increase, the need for research coordination between the CSM group and other groups also increases. To use large, complex structures as focus problems requires an understanding of the structure, its loading, and life cycle as well as an understanding of the underlying computational structural mechanics issues.

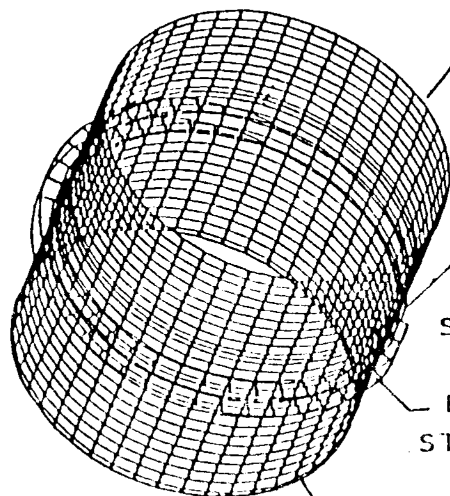
SPACE-ORIENTED APPLICATION STUDIES

SOLID ROCKET BOOSTER (SRB)





SRB AFT SKIRT



SRB/ETA RING INTERFACE

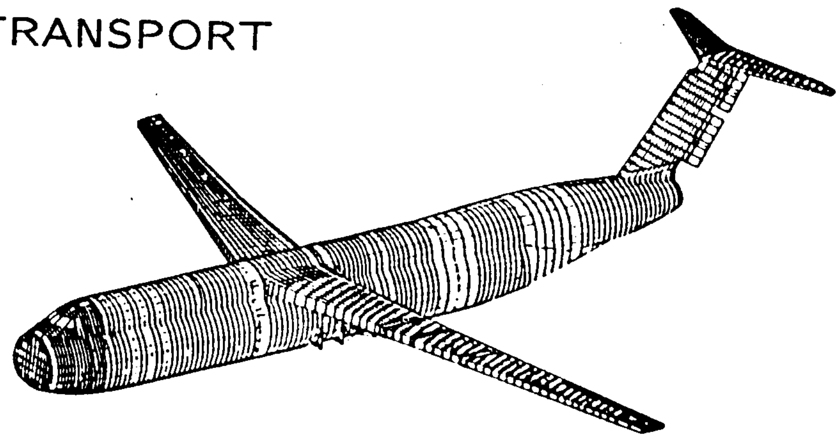
SPACE-ORIENTED APPLICATION STUDIES

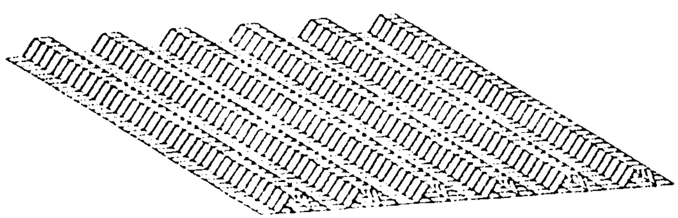
Since the Challenger disaster, many of the CSM group have been involved with the recertification of the Solid Rocket Booster (SRB) for resumption of Space Shuttle flight. Various analyses have been performed to assess the overall structural response of the SRB. Structural analyses of the tang-clevis joints[3], detailed stress analyses of the SRB aft skirt, and nonlinear shell analyses of the SRB/ETA ring interface region[4] have been performed. These critical application problems have provided new goals for computational requirements in CSM and have contributed to solving an agency problem.

The solid rocket booster analyses have substantially challenged our structural analysis software and stretched our computing limits to redefine "a big nonlinear problem." The SRB problem encompasses nonlinear shell response, contact/interface problems, inelastic response, combined thermal and mechanical loadings, and various global/local stress analysis issues.

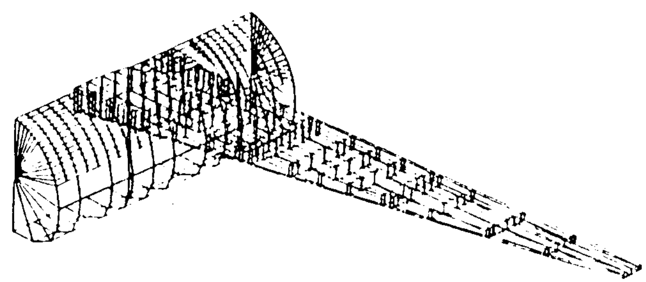
AERONAUTICS-ORIENTED APPLICATION STUDIES

GENERIC TRANSPORT





STIFFENED SHELLS



WING/FUSELAGE INTERSECTION

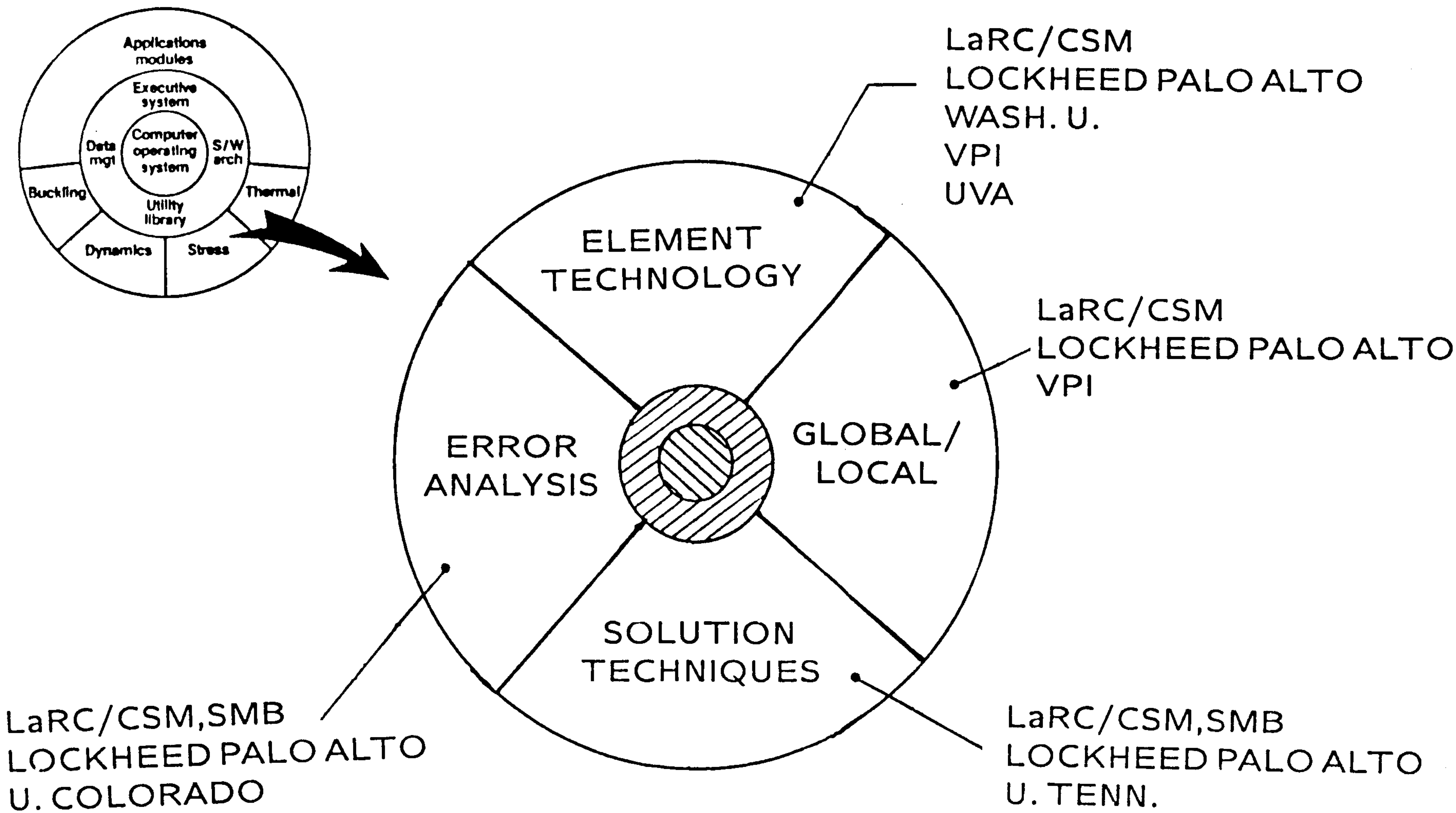
AERONAUTICS-ORIENTED APPLICATION STUDIES

Generic transport aircraft structures offer another challenge to the computational structural analysts. Detailed geometry models of a transport severely tax today's computing environment.[5,6] Detailed response models of subscale components tax today's structural analysis tools. The application of advanced composite materials to aircraft structures has introduced new challenges to the designer and analyst. These applications require advanced analysis tools and an understanding of the response and failure characteristics of laminated and filament-wound composite structures.

A generic composite transport aircraft would present challenging structural mechanics problems as well as stretch our computing limits. Subcomponents of a generic composite transport aircraft have been studied experimentally, and the results correlated with analytical results (e.g., see references 7-11). Analysis deficiencies associated with the need for including transverse shear effects, for analyzing mode coupling in the nonlinear response, for performing a progressive failure analysis, and for performing global/local stress analyses routinely have been identified. A new NASA research initiative to develop advanced structural concepts for primary aircraft structures is underway. Integration of focus problems from this new initiative with the CSM program could provide a mechanism for developing, verifying, and transferring computational structural mechanics technology to the aerospace community.

ELEMENTS OF CSM

CURRENT METHODS RESEARCH THRUSTS



ELEMENTS OF CSM

Current Methods Research Thrusts

The CSM Testbed has been depicted as three concentric circles as shown in the upper left of the figure. The Methods and Application Studies Team develops application modules or processors and analysis procedures; that is, the outer circle. The elements of the Langley CSM program in the area of current methods research thrusts are shown in this figure.

The first area is element technology. New solid hybrid elements and flat shell hybrid elements are being developed by Dr. Mohammad Aminpour of the CSM Group. Under the CSM contract with Lockheed Palo Alto Research Laboratory (NASA Contract No. NAS1-18444), new curved shell elements are being developed by Drs. Gary Stanley and David Kang. In addition, a generic element processor has been designed by Lockheed to facilitate implementation, porting, and testing of elements in the CSM testbed. Under NASA Grant No. NAG-1-639, Dr. Barna Szabó of Washington University is developing hierarchic theories and element formulations. Under NASA Grant No. NAG-1-675, Dr. Hayden Griffin of Virginia Tech is implementing various displacement-based solid elements which have been developed as part of the NASA/Virginia Tech Composites Program. Under NASA Grant No. NGT-50116, Dr. Walter Pilkey of the University of Virginia has just begun the development of variationally-based element formulations.

The second area is global/local stress analysis. The CSM group is developing a 2-D global/local (coarse/refined) analysis capability. Under the CSM contract, Lockheed researchers are investigating the structural behavior of stiffened composite panels loaded in axial compression to assess the local stress state near the skin-stiffener interface region. In addition, Dr. Griffin of Virginia Tech is developing global/local stress analysis methodology for detailed, 3-D stress analysis of composite structures.

The third area is solution techniques. Lockheed researchers are involved in evaluating and implementing nonlinear solution strategies in the CSM Testbed. In addition, the Structural Mechanics Branch of the Structures and Dynamics Division at Langley is involved with advanced analysis techniques and demonstrating their capabilities using the STAGSC-1 computer code. A CSM objective is to incorporate that work in the Testbed. Under NASA Grant No. NAG-1-803, Dr. Alan George of the University of Tennessee is developing sparse matrix methods for serial and parallel computers and implementing these methods in the CSM Testbed.

The fourth area is error analysis. The CSM group is studying the strain energy gradient approach for guiding mesh refinement. In addition, Dr. Szabó of Washington University is studying p-extensions of the finite element method. Under NASA Grant No. NAG-1-802, Dr. John Dow of the University of Colorado at Boulder is developing an error estimation procedure based on the difference between the strain energy of the finite element solution and the strain energy of the "smoothed" solution.

FINITE ELEMENT TECHNOLOGY

– DEFICIENCIES –

- HEAVY RELIANCE ON FINITE ELEMENTS IN ANALYSIS AND DESIGN PROCESS
- EXISTING FINITE ELEMENTS SENSITIVE TO MESH DISTORTION
- STANDARD TEST PROBLEMS HAVE EXPOSED NUMEROUS ELEMENT DEFICIENCIES IN ALL FINITE ELEMENT CODES
- ELEMENT PERFORMANCE FOR NONLINEAR PROBLEMS HAS NOT BEEN ESTABLISHED

FINITE ELEMENT TECHNOLOGY

– Deficiencies –

The finite element method is over three decades old and continues to serve engineers as a powerful, general-purpose analysis tool for complex structures. The aerospace industry relies heavily on finite element analysis in the design and certification of aerospace structures. Finite element computer codes are readily available with a wide range of capabilities, cost, and user support. These analysis tools are often treated as "black boxes," and the developers of these tools assume that the user understands and works within the limitations of the software. Frequently, however, the limitations of the analysis are "extended" by novice users.

A common limitation in nearly all finite element computer codes is the sensitivity of the elements to mesh distortion (i.e., element warping, aspect ratio, element taper). Many of the finite element codes do perform checks to assess element geometry and inform the user of potential problems. Standard test problems for linear elastic stress analysis have been proposed.[12,13] These tests have exposed deficiencies in many elements. Standard test problems for nonlinear stress analysis are not well established, but are under development.

FINITE ELEMENT TECHNOLOGY

– CURRENT PROGRAM –

- GENERIC ELEMENT PROCESSOR PROVIDES COMMON "PROVING GROUNDS" FOR ELEMENT RESEARCH
- ADVANCED SHELL ELEMENT FORMULATIONS
- HIERARCHIC THEORIES AND ELEMENT FORMULATIONS
- ROBUST SOLID ELEMENTS FOR DETAILED ANALYSIS OF COMPOSITE STRUCTURES
- SPECIAL ELEMENTS FOR FRACTURE PROBLEMS

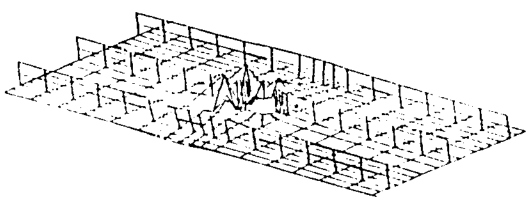
FINITE ELEMENT TECHNOLOGY

– Current Program –

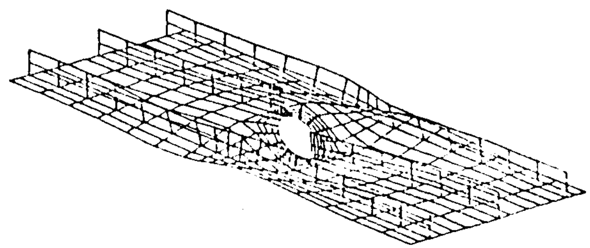
The current Langley CSM program in finite element technology has two main objectives. First, Lockheed researchers conceived and are now developing and implementing a new "generic element processor" which will enable routine assessment of new finite element formulations within the Testbed framework. Hence, the assessment will encompass not only standard test problems but also challenging focus problems, thereby establishing a "proving ground" or "obstacle course" for new elements. Second, advanced element formulations are being developed. Research topics include robust, nonlinear shell element formulations, p-version finite element technology, solid elements for detailed stress analysis of laminated composite structures, and special elements for fracture mechanics problems.

ASSESSMENT OF CSM TESTBED 2-D SHELL ELEMENTS

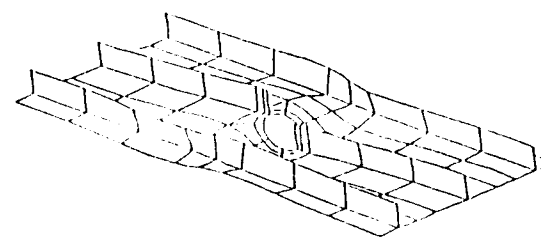
E43



EX47



EX97



- BUCKLING MODE SHAPE FOR FOCUS PROBLEM
- E43 ELEMENT SENSITIVE TO MESH DISTORTION
- EX47 AND EX97 ELEMENTS LESS SENSITIVE TO MESH DISTORTION AND INCORPORATE TRANSVERSE SHEAR

ASSESSMENT OF CSM TESTBED 2-D SHELL ELEMENTS

One of the initial focus problems of the CSM group is a composite blade-stiffened flat panel with a discontinuous stiffener. This problem has characteristics which often require a global/local stress analysis. These characteristics include a discontinuity, eccentric loading, large displacements, large stress gradients, high inplane loading, and a brittle material system. This problem represents a generic class of laminated composite structures with discontinuities in which the interlaminar stress state becomes important.

Finite element analysis of this focus problem tests the element's performance for a problem which requires a distorted mesh in order to model the region near the circular hole. Incorporating the effect of transverse shear deformation is needed to provide a 2-D assessment of the interlaminar stress state.

Linear stress analyses and bifurcation buckling analyses have been performed for this focus problem using various finite elements implemented in the CSM Testbed. The E43 element is the original hybrid stress C^1 flat shell element from SPAR Level 13.[14] The EX47 and EX97 elements are new C^0 shell elements based on the assumed natural strain formulation with four and nine nodes, respectively.[15]

The finite element grids used in these analyses have identical numbers of nodes, and therefore, each model has the same number of degrees-of-freedom. Each model predicts the stress distribution for the prebuckled stress state correctly. However, the results from the bifurcation buckling analyses differ. The models using the EX47 and EX97 elements agree with previously obtained results. The model using the E43 element does not predict the correct buckling load or mode shape. The buckling mode shape for each model is shown in the figure. These results indicate that the geometric stiffness matrix for the E43 element is sensitive to mesh distortion, while those for the EX47 and EX97 elements are not as sensitive. The EX47 and EX97 elements also incorporate transverse shear in their formulation.

GLOBAL/LOCAL STRESS ANALYSIS METHODOLOGY

– DEFICIENCIES –

- DESIGN PROCESS NEEDS ACCURATE, ROUTINE GLOBAL/LOCAL STRESS ANALYSIS CAPABILITY
- CURRENT APPROACH ASSUMES LOCAL REGION IS KNOWN A PRIORI
- NO AUTOMATED PROCEDURE
- ANALYST IDENTIFIES 2-D/3-D TRANSITION INTERFACE REGION BY TRIAL AND ERROR
- MODELING CRITERIA FOR DETAILED STRESS ANALYSIS INADEQUATE

GLOBAL/LOCAL STRESS ANALYSIS METHODOLOGY

– Deficiencies –

A myriad of definitions is associated with the term "global/local stress analysis." Herein global/local stress analysis methodology is defined as a procedure to determine local, detailed stress states for specific structural regions using information obtained from an independent global stress analysis. Furthermore, the global/local stress analysis methodology should not require a priori knowledge of the location of the local region(s) requiring special modeling. For example, the composite blade-stiffened panel with a discontinuous stiffener has an obvious local region which requires special modeling to predict accurately the stress state near the hole. However, for the curved composite panels described in reference 11, the local region requiring a detailed stress analysis is not obvious until after the global postbuckled solution is calculated.

The design and certification process for aerospace structures requires an accurate, routine global/local stress analysis capability. Several approaches are available in commercially available structural analysis codes like MSC/NASTRAN and ANSYS. These approaches include multilevel substructuring (e.g., see reference 16), spline interpolation along the local region boundaries, and transition grids (i.e., use of triangular elements) to refine locally near regions with large stress gradients. However, no automated procedure is available to the analyst for routine global/local stress analysis or to ensure that a continuous stress field results across a global-to-local transition boundary in cases where independent submodels are used. Transitioning from shell-to-solid elements is possible provided the analyst can identify the location of the 2-D/3-D transition interface region. Modeling criteria for detailed stress analysis are inadequate and require the analyst to perform numerous "pathfinder" studies to guide the modeling effort for each new application. General procedures and guidelines for 3-D stress analysis of composite structures are not readily available in the open literature.

GLOBAL/LOCAL STRESS ANALYSIS METHODOLOGY

- CURRENT PROGRAM -

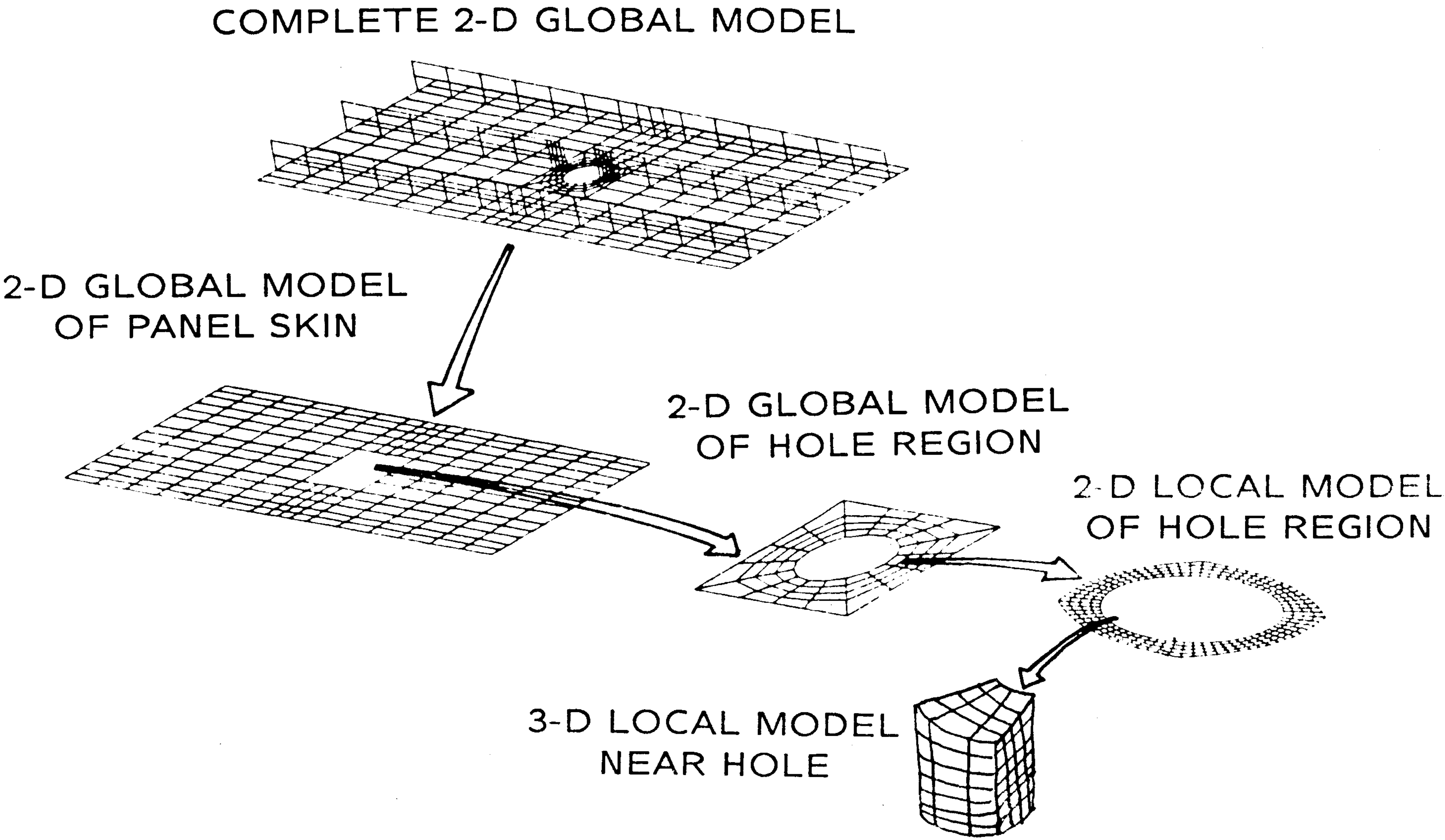
- HIERARCHIC THEORIES
  (CLASSICAL vs SHEAR FLEXIBLE vs 3-D)
- 2-D ZOOMING TECHNIQUES
- 2-D/3-D TRANSITION INTERFACE
- MODELING FOR DETAILED STRESS ANALYSIS OF COMPOSITE STRUCTURES
- TRANSITIONAL (SHELL-TO-SOLID) FINITE ELEMENTS
- MULTI-LEVEL SUBSTRUCTURING

GLOBAL/LOCAL STRESS ANALYSIS METHODOLOGY

– Current Program –

The current Langley CSM program in global/local stress analysis is primarily an inhouse activity. The approach under development utilizes the results of a global 2-D stress analysis in performing a local, refined 2-D stress analysis. The global model may use classical plate theory, and the local model may use a shear deformation theory. This approach is referred to as a zooming technique and encompasses mesh refinement as well as a hierarchy of theories. Modeling techniques for the 2-D/3-D transition interface in the same finite element model have been presented including the use of multipoint constraints (e.g., see reference 17) and transitional (shell-to-solid) elements (e.g., see references 18-19). The 2-D/3-D transition basically involves a kinematics transition across the 2-D to 3-D interface and robust procedures for identifying the proper location of the interface boundary. Modeling criteria for detailed stress analysis of composite structures are being formalized by Dr. Griffin of Virginia Tech under NASA Grant No. NAG-1-675. Implementation of a multilevel substructuring capability is being planned for the CSM Testbed.

"ZOOM-IN" APPROACH FOR GLOBAL/LOCAL STRESS ANALYSIS



"ZOOM-IN" APPROACH FOR GLOBAL/LOCAL STRESS ANALYSIS

The approach for global/local stress analysis is to predict the global nonlinear response using a complete, global 2-D model and then construct a refined, local 2-D model for a small distance away from the discontinuity to predict accurately the large stress gradient. Displacements and rotations from the global nonlinear solution obtained using the complete model are applied as boundary conditions to the refined model and the state of stress determined. This strategy is referred to as a multi-level or "zoom-in" approach. To establish the accuracy of the refined, local 2-D model near the discontinuity, a 3-D model is analyzed and the stress state determined.

This approach for global/local stress analysis does not require a priori knowledge as to the location of regions with a large stress gradient. Hence, a global nonlinear stress analysis may be performed, local regions of high stress identified, and local detailed stress analysis performed. The global nonlinear stress analysis using a refined mesh near the local regions of concern would not have to be performed.

SOLUTION TECHNIQUES

– DEFICIENCIES –

- VARIETY OF TECHNIQUES FOR LARGE DEFLECTION, LARGE ROTATION PROBLEMS
- LIMITED EVALUATION ON REALISTIC STRUCTURES
- NO WIDELY-ACCEPTED STANDARD TEST PROBLEMS
- OPTIMUM DESIGN WITH NONLINEAR RESPONSE BEYOND CURRENT COMPUTATIONAL CAPABILITIES
- PROBLEMS WITH MODE-INTERACTION BEYOND CURRENT NONLINEAR ANALYSIS CAPABILITIES

SOLUTION TECHNIQUES

– Deficiencies –

Solution techniques for nonlinear finite element analyses are emphasized in many research programs. A variety of techniques are available to solve nonlinear structural analysis problems involving large deflections and large rotations. Numerous papers and books (e.g., see references 20-22) are available that describe various techniques and demonstrate their application on structural problems. The evaluation of nonlinear solution techniques frequently involves problems with simple geometries; however, these problems usually embrace complex nonlinear response characteristics.

Standard test problems for nonlinear stress analysis are being developed, but no widely-accepted set of test problems has been adopted. Extending the evaluation of nonlinear solution techniques to realistic structures has received only limited attention to-date.

Optimum design of aerospace structures using nonlinear structural response is beyond current computational capabilities, primarily because of the computational cost of the nonlinear structural analyses. Optimized structural designs frequently result in a structure which has closely-spaced buckling loads. Consequently, predicting the nonlinear response of these structures may involve mode interaction, and thereby exceed the nonlinear analysis capabilities currently available in finite element computer codes.

SOLUTION TECHNIQUES

– CURRENT PROGRAM –

- ELEMENT-INDEPENDENT COROTATIONAL FORMULATION
  - LOW-ORDER
  - HIGHER-ORDER
- SOLUTION STRATEGIES FOR NONLINEAR PROBLEMS
  - NEWTON-RAPHSON METHOD
  - ARC-LENGTH CONTROL TECHNIQUES
  - NEWTON'S METHOD FOR ISOLATED BIFURCATION PROBLEMS
- SPARSE MATRIX METHODS

SOLUTION TECHNIQUES

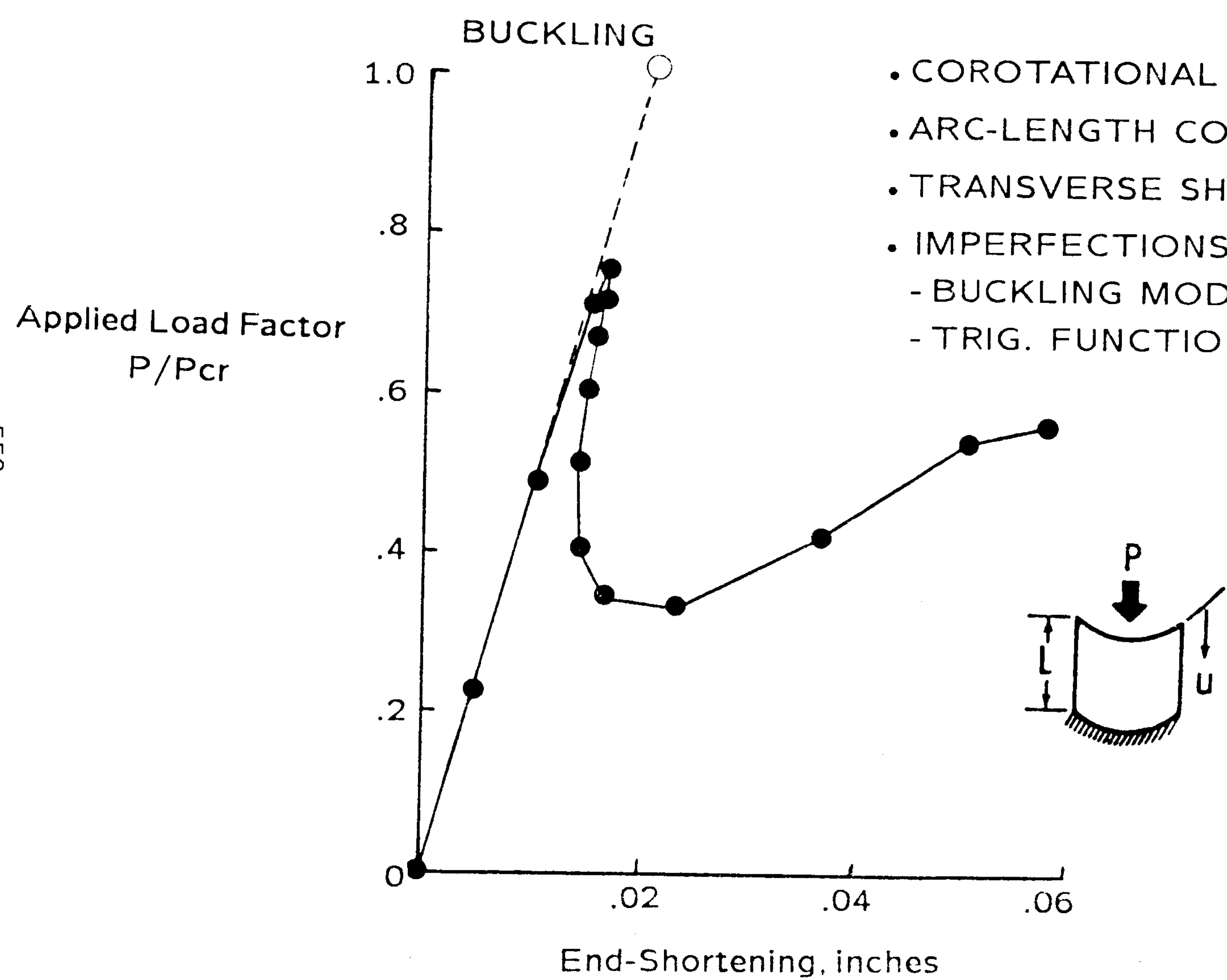
– Current Program –

The current Langley CSM program in solution techniques involves three areas. One area addresses the formulation aspects needed for large deflection, large rotation problems. The element-independent corotational formulation [23,24] developed under the STAGSC-1 contract forms the basis of the geometric nonlinear capability of the finite elements in the CSM Testbed. Some element developers supply only the linear stiffness matrix and the geometric stiffness matrix. Using these matrices and the generic element processor, the performance of new elements on nonlinear problems may be readily assessed in the CSM Testbed through the low-order corotational approach (i.e., linear strain-displacement relations within the element). In addition, the design of the generic element processor includes provisions to implement and assess higher-order corotational approaches by incorporating the nonlinear strain-displacement relations.

A second area of research deals with solution strategies for nonlinear problems. The language capability of the Testbed architecture may be utilized to explore various aspects of solution strategies such as the Newton-Raphson method and various arc-length control techniques.[25,26,27] In addition, the framework of the CSM Testbed will enable exploratory studies of Newton's method for isolated bifurcation problems as formulated in reference 28. Fundamental research using Newton's method for nonlinear finite element analysis using the STAGSC-1 general purpose nonlinear shell finite element computer code is currently being performed by Lockheed under NASA Contract No. NAS1-18101.[24,29] Incorporating this technology in the Testbed is planned.

The third area involves matrix techniques for finite element analysis. A review of the requirements and needs of finite element researchers, numerical analysts, and parallel methods developers is underway through the Lockheed CSM contract. This task is to assess matrix analysis needs by various researchers and to propose a standard set of utilities and data structure for system matrices. Currently, the system matrices in the Testbed are formatted as node-oriented, sparse matrices. Dr. George of the University of Tennessee is developing sparse matrix technology for serial and parallel computers under NASA Grant No. NAG-1-803.

POSTBUCKLING RESPONSE OF ISOTROPIC CURVED PANEL DEMONSTRATED USING CSM TESTBED



- COROTATIONAL
- ARC-LENGTH CONTROL
- TRANSVERSE SHEAR
- IMPERFECTIONS
  - BUCKLING MODE
  - TRIG. FUNCTIONS

POSTBUCKLING RESPONSE OF ISOTROPIC CURVED PANEL DEMONSTRATED USING CSM TESTBED

To demonstrate the nonlinear analysis capability of the CSM Testbed, the postbuckling response of an isotropic curved panel loaded in axial compression is predicted. This analysis incorporates the corotational formulation, an arc-length control solution strategy implemented using the CLAMP language, and the effects of transverse shear deformation through the use of the new shell elements (EX97) which are based on an assumed natural-coordinate strain formulation. Initial geometric imperfections may be incorporated as either a linear combination of eigenvectors (buckling mode shapes) or a set of trigonometric functions (e.g., see reference 8).

ERROR ANALYSIS METHODOLOGY

– DEFICIENCIES –

- SEVERAL PROPOSED TECHNIQUES; NO GENERAL PURPOSE IMPLEMENTATIONS
- AD HOC APPROACH USED TO ASSESS OVERALL MODELING ACCURACY
- REQUIRES MULTIPLE SOLUTIONS FOR MULTIPLE MESHES TO ESTABLISH ACCURACY FOR LINEAR PROBLEMS
- CRITERIA FOR NONLINEAR PROBLEMS NOT AVAILABLE

ERROR ANALYSIS METHODOLOGY

– Deficiencies –

The aerospace industry relies heavily on finite element analysis for the design and certification of aerospace structures. However, specific requirements to certify the structural analysis and the structural analysis computer code are not imposed on the structural analyst. Conceivably, countless manhours could be used during a failure investigation that may have been avoided had an accurate and appropriate pre-test analysis been performed and certified.

Although considerable research has been performed and several techniques proposed for general purpose finite element computer codes, no general purpose implementations are available for error detection and control for finite element solutions. Presently, an ad hoc approach is used to assess overall modeling accuracy, element behavior, and solution quality. Multiple solutions for multiple meshes are required to establish solution accuracy for linear problems. Criteria for nonlinear problems have not been developed to-date. The analyst must assess the finite element solution and is responsible for insuring its accuracy.

ERROR ANALYSIS METHODOLOGY

– CURRENT PROGRAM –

- ERROR ESTIMATES FOR GUIDING ADAPTIVE MESH REFINEMENT
- GRADIENT OF STRAIN ENERGY DENSITY
- STRESS SMOOTHING; COMPARE ORIGINAL AND SMOOTHED VALUES
- ASSESS ERROR IN DISCRETE SOLUTION USING EQUILIBRIUM DIFFERENTIAL EQUATIONS
- p-VERSION FINITE ELEMENT METHOD
- "REPORT CARDS" FOR ELEMENT PERFORMANCE

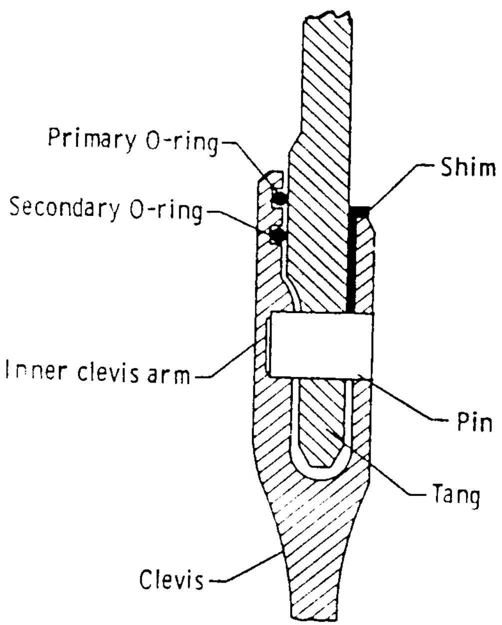
ERROR ANALYSIS METHODOLOGY

– Current Program –

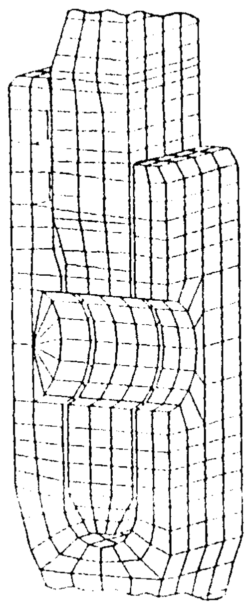
The current Langley CSM program in error analysis methodology is in its formative stage. Research in error detection and control for finite element analysis is a recent emphasis for the Methods and Application Studies Team. Given a discrete finite element solution, estimates of the error are needed to assess and improve solution quality and to provide heuristic guidelines for mesh refinement. Error estimates will be used to guide adaptive mesh refinement strategies and to provide measures of solution quality to the analyst. At present, a posteriori error estimates are being assessed in-house. Techniques associated with the strain energy, its gradient, and stress smoothing are being evaluated and implementation within the Testbed framework is planned. The Structural Mechanics Branch is evaluating the error in discrete finite element solutions by employing a "recontinuization" procedure and the nonlinear equilibrium differential equations.[30] Rigorous mathematical analyses have provided error estimates for the p-version finite element method, and convergence rates for the solution may also be calculated. In addition, numerous test problems are being solved; still many more have been proposed. These results may serve as "report cards" for element performance to the analyst by proving an assessment of finite element model convergence (e.g., see reference 31).

MESH DESIGN
FOR ACCURATE STRESS PREDICTION

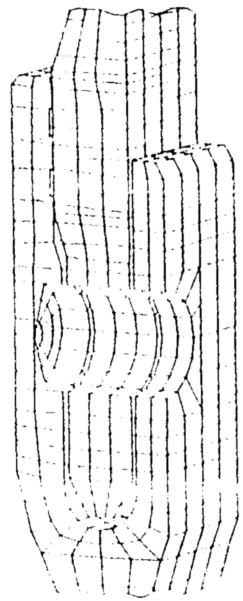
TANG-CLEVIS JOINT



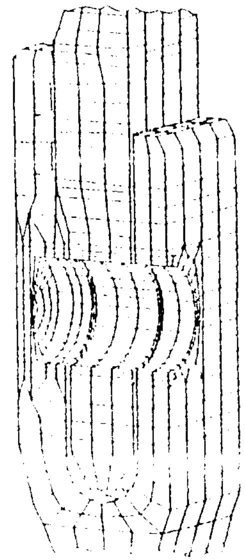
INITIAL



INTERMEDIATE



FINAL



MESH DESIGN FOR ACCURATE STRESS PREDICTION

Mesh design for complex structures requires the analyst to plan the analysis and to decide on the analysis objectives. An analysis to study only deflections has different requirements on spatial discretization than an analysis to determine the stress state. An example of such a problem is the tang-clevis joints on the Space Shuttle solid rocket motor shown on the left side of the slide. Relative motion between the inner arm of the clevis and the O-ring sealing surface on the tang has been identified as a potential contributor to the Challenger failure. Finite element structural analyses have been performed to predict both deflections and stresses in the joint under the primary, pressure loading condition. These analyses, reported in reference 3, demonstrate the difficulty of accurately predicting the structural behavior of the tang-clevis joint. To help understand the structural behavior of the tang-clevis joint, the sensitivity of the joint response to finite element mesh refinement in the area surrounding the pin is needed. The pin regions from three different finite element models are shown in the figure. There are two reasons for refining the initial model shown on left center side of the figure to the intermediate model shown in the right center of the figure. The first reason is to better account for pin flexibility. The second reason is to better model the bending of the inner clevis arm. The model refinement from the intermediate model shown in the right center to the final model shown on the right side of the figure is motivated by a need for a better prediction of gap motion and also for better stress predictions in the vicinity of the pin. A main feature of the final model is two additional rings of elements in the region where the pin contacts the inner clevis arm. These additional elements allow better modeling of the contact force distribution. The pin itself is also considerably more refined. Although the average gap motion did not vary much for these three discretizations, the predicted stress state near the pin regions did change significantly as the mesh was refined.

CSM TESTBED ENHANCEMENTS

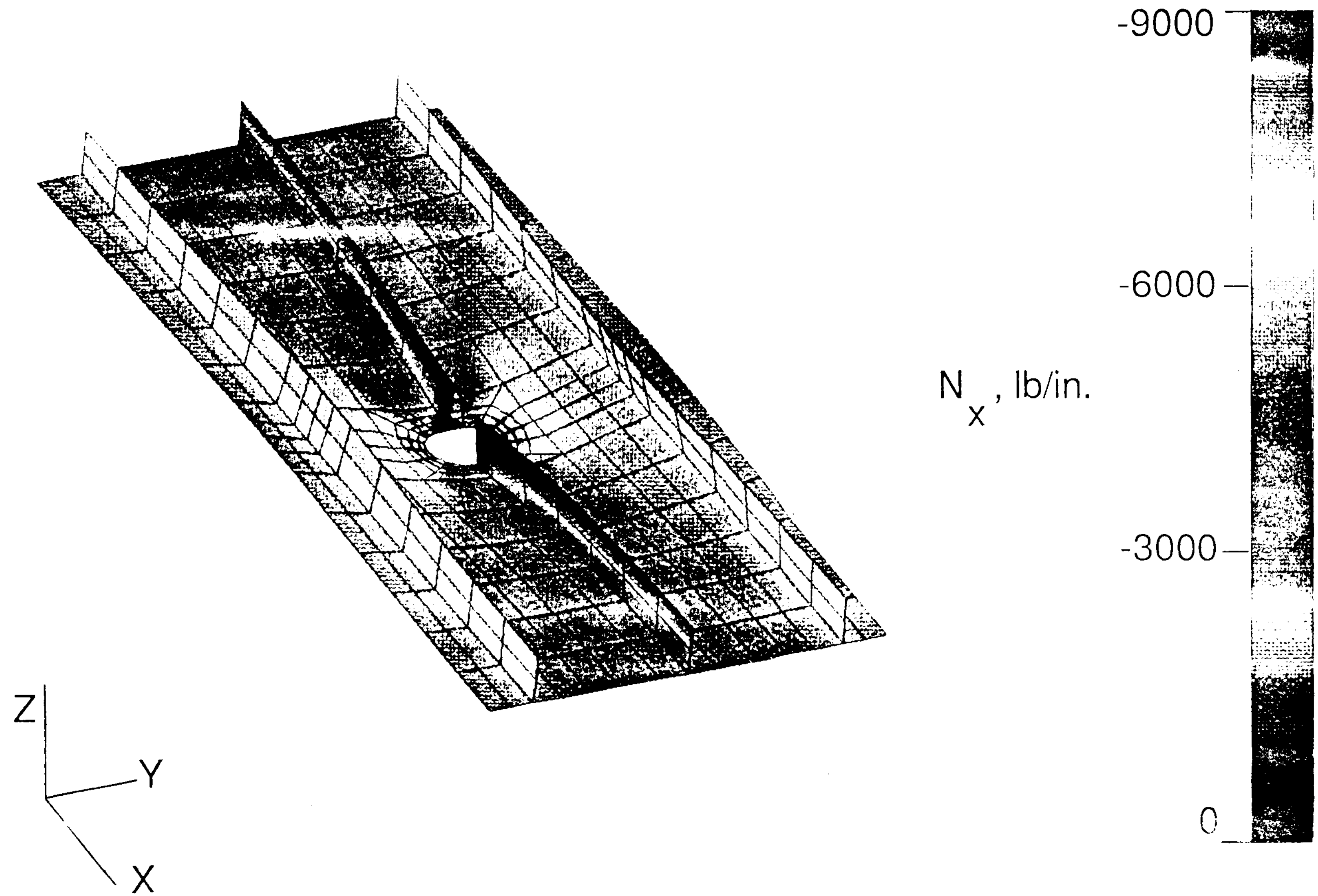
- RESEQUENCING ALGORITHMS FOR EQUATION SOLVER
- ARBITRARY STRESS REFERENCE FRAME FOR COMPOSITES
- LAMINATE ANALYSIS AND FIRST-PLY FAILURE UTILITIES
- PRELIMINARY 2-D GLOBAL/LOCAL STRESS ANALYSIS
- PRE- AND POST-PROCESSING INTERFACES FOR PATRAN

CSM TESTBED ENHANCEMENTS

Enhancing the CSM Testbed is an ongoing activity. New and improved features are periodically added by various researchers. Five major enhancements were added in FY87. First, a processor was developed which provides four resequencing (renumbering) algorithms to enhance the performance of the equation solver. Second, an arbitrary stress reference frame capability was added for the analysis of composite structures using 2-D elements. Third, two utility processors were developed for the analysis of composite structures. Processor LAU performs laminate analyses to generate material stiffnesses; processor FPF performs a first-ply failure analysis. Fourth, two processors (SPLN and INTS) were developed for spline interpolation of the solution and for the generation of applied displacements along the local boundaries. Fifth, two processors (PT2T and T2PT) were developed to interface PDA/PATRAN neutral files with the CSM Testbed for both pre-processing (model generation) and post-processing (results interpretation).

In addition, substantial emphasis has been placed on generating the initial documentation for the CSM Testbed. A draft of the CSM Testbed User's Manual has nearly been completed.

INPLANE STRESS RESULTANT N_X DISTRIBUTION ON DEFORMED STRUCTURE



INPLANE STRESS RESULTANT N_x DISTRIBUTION ON DEFORMED STRUCTURE

The old adage that "a picture is worth a thousand words" is especially true in stress analysis of complex structures. The inplane stress resultant N_x distribution on the deformed geometry of the composite blade-stiffened panel with a discontinuous stiffener is shown in the slide. Color-coded stress contours can be extremely helpful to the structural analyst for determining the location of critical regions with high stresses.

ROLE OF CSM TESTBED

- SERVES AS FRAMEWORK FOR METHODS RESEARCH
  - GENERIC ELEMENT PROCESSOR FOR ELEMENTS
  - CLAMP LANGUAGE FOR SOLUTION ALGORITHMS
  - FPF PROCESSOR FOR FIRST-PLY FAILURE PREDICTION
- SERVES AS COMMON "PROVING GROUND" AND INTEGRATOR FOR METHODS RESEARCH
- WILL PROVIDE <u>PROVEN</u>, STATE-OF-THE-ART STRUCTURAL ANALYSIS METHODS TO AEROSPACE COMMUNITY

ROLE OF CSM TESTBED

The role of the CSM Testbed in methods research is threefold. First, the Testbed serves as a framework for methods research. The generic element processor enables easy, routine implementation of new finite element formulations and their evaluation. The CLAMP language provides a convenient mechanism for testing nonlinear solution strategies or direct time integration algorithms in a general purpose finite element code. The first-ply failure analysis provides composite structures analysts with information needed in design and test/analysis correlation studies. The CSM Testbed provides the opportunity to conduct advanced structural analysis research that exploits new and future computer hardware developments.

Second, the Testbed serves as a common "proving ground" and integrates various CSM researchers. Assessment of finite element technology, equation solvers and eigensolvers, nonlinear solution strategies, and other areas of methods research may be performed in a single, common software system, namely the CSM Testbed.

Third, the Testbed will provide proven, state-of-the-art structural analysis methods to the aerospace community. New methods will mature in the Testbed through application to selected challenging focus problems.

SUMMARY

- EMPHASIZING APPLIED STRUCTURAL MECHANICS RESEARCH TO ACCELERATE METHODS TECHNOLOGY TRANSFER TO INDUSTRY

- DEVELOP PROBLEM-ADAPTIVE SOLUTION STRATEGIES WITH ERROR CONTROL FOR **ROUTINE** GLOBAL/LOCAL STRESS ANALYSIS

- INCLUDE REALISTIC COMPLEX STRUCTURES AS FOCUS PROBLEMS TO EVALUATE NEW METHODS AND TO DEFINE COMPUTATIONAL STRUCTURAL ANALYSIS REQUIREMENTS

SUMMARY

The Langley CSM methods research efforts emphasize applied structural mechanics research to accelerate the transfer of methods technology to industry. Structural analysis and computational methods that have reached a level of maturity to demonstrate high potential for solving realistic, practical structural problems will continue to be a focus.

A goal is to develop problem-adaptive solution strategies with error control for routine global/local stress analysis. To meet this goal, four research areas have been identified. These research areas include finite element technology, solution techniques, global/local stress analysis methodology, and error analysis methodology.

As methods mature and computational structural mechanics technology develops into software, the focus problems will change to continue challenging our structural analysis capabilities and stretching our computing limits. Realistic complex structures like an SRB or a generic composite transport aircraft are needed as focus problems to evaluate new methods and to define new computational structural analysis requirements.

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