On the State of Finite Element Procedures for Forming Processes

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Abstract. The solution of forming processes requires reliable and efficient finite element methods to model the various complex physical phenomena encountered. The objective in this presentation is to focus on the current state of finite element methods with respect to reliability and efficiency in modeling forming processes. The finite element procedures pertain to the simulation of sheet metal forming, bulk forming, extrusion and drawing, rolling, welding, cutting processes, etc. It is emphasized that the appropriate finite element methods for a specific problem should be used, and that indeed procedures are available which are effective in many situations. The presentation briefly considers the state of modeling of solids, shell structures, contact conditions, friction, inelastic material response in large strains, thermo-mechanical coupling and fluid-solid interactions, as encountered in forming process simulations. The solutions of the governing finite element models are obtained using sparse direct or iterative solvers. The oral presentation will include the results of various example simulations.

INTRODUCTION

The finite element method has truly gone through a remarkable development. Since the early inception of the method for engineering use in the 1950's, the method has evolved into a most powerful procedure for general engineering analysis. Finite element programs are used today in a routine manner for the analysis of complex structures, solids, fluids, multi-physics problems and so on. Indeed, the method has become an integral part of computer-aided engineering [1 - 4].

However, while there is a wide use of the finite element method, the simulation of forming processes still provides a great challenge because of the complex physical phenomena to be simulated. In such analyses, for example, large deformations, large strain anisotropic material behavior, contact conditions including friction, and fluid-structure interactions need be modeled. These conditions and the frequently complex geometries require fine finite element discretizations and considerable computing resources. Of course, as the available finite element procedures, and available hardware, are being advanced, more complex physical conditions can be modeled accurately.

The objective of this presentation is to give a brief overview – indeed just a snapshot – regarding the current state of finite element analysis of forming processes. The presentation focuses on the experiences of the author and therefore gives, in various ways, a rather subjective (indeed personal) view regarding finite element analyses of these complex problems.

THE NEED FOR RELIABLE FINITE ELEMENT METHODS

A most important aspect of a finite element technique and its program implementation — if the method is to be used in a research study or in an industrial environment — is that the method and implementation be reliable. In particular, the finite element formulation must be mechanistically clear and well-founded, the discretization must be stable and convergent and must not depend on adjustable numerical factors [1, 5]. In addition, of course, efficient solutions are important, in particular, in industrial applications. However, it is quite inappropriate to aim for results in "acceptable" computer run times if these results are not reliable (

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and therefore might have to be disregarded in any case).

Of course, the development of solution methods that are reliable and efficient is a very difficult task. However, for many applications such techniques are now available and we concentrate in this presentation on such procedures.

SOME RESEARCH AND DEVELOPMENTS

The research and developments briefly mentioned in this section, and pursued by the author and his students and collaborators, are not given in any order of importance, but merely in a natural order from rather general to more specific developments.

Selection of Models

The selection of an appropriate mathematical model for the solution of a physical problem is the key step of any analysis. It is clearly a difficult task in nonlinear analysis and in particular in forming simulations. Here the possibilities to use hierarchical modeling are very attractive and can lead to effective analyses of complex phenomena [1, 6, 7].

Mathematical Conditions on Finite Elements

In many simulations, and notably in the analysis of forming processes, the use of mixed finite elements is necessary. These formulations should satisfy the ellipticity and consistency conditions, and ideally the relevant inf-sup conditions. If the consistency and ellipticity conditions are not satisfied, large unnoticed errors may occur in the finite element simulations.

The importance of the ellipticity and inf-sup conditions has been researched and the shortcomings of rules too simple for an assessment of stability have been delineated [1, 5, 8].

Shell Analysis

In many forming processes shell finite element discretizations are used. As mentioned above, the reliability of the shell elements for practical analysis is of primary concern [1, 5, 9]. Our research resulted in the development of the MITC shell elements which have general applicability, are reliable and have good predictive capability [1, 5, 10]. The quadrilateral shell elements are now abundantly used in simulations. Of course, we are still continuing our research to improve these shell elements [11]. We also work to improve, as well, the effectiveness of triangular elements [12] and to include three-dimensional through-the-thickness effects [13]. In metal forming, it can be important to include the through-the-thickness stress and strain effects, and shell elements with quadratic displacement interpolations through the thickness are then effective [13].

Inelastic Large Strain Analysis

Effective large strain elasto-plastic analysis procedures are most important to analyze forming processes. The procedures need to include various ingredients. Firstly, a stable and effective solution scheme for incompressible analysis is necessary. We have developed and use the displacement/ pressure (u/p) formulation [1, 14]. Secondly, an effective large strain formulation must be employed. We use the updated Lagrangian Hencky formulation, which is a solution approach based on the total elastic strain computed from the total deformation gradient and an evolution of the plastic deformation gradient. The stresses are calculated using the effective-stress-function algorithm and consistent tangent matrices are used in the Newton-Raphson iterations [1, 15-18].

Analysis of Contact Problems

Many simulations of forming processes involve contact between bodies and an effective contact algorithm must be used. The constraint function method is an attractive scheme for general contact analysis [1, 19 – 21]. The solution procedure computes the actual areas of contact and the conditions on the contact surfaces. The normal and tangential (frictional) contact conditions are satisfied using constraint functions. The method has been developed for efficient static and implicit dynamic solutions. For increased accuracy, a consistent segment algorithm has been proposed [22, 23].

Analysis of Fluid Flows and Fluid-Structure Interactions

During the recent years, we have dedicated a considerable effort to the development of solution techniques for fluid flows and fluid-structure interactions [24 - 27]. These methods can be used to solve very complex fluid flows (modeled by the full Navier-Stokes equations) and fluid-structure interactions in forming processes. The flow-condition-based interpolation (FCBI) procedure with control volumes in the finite element mesh is more effective than earlier published finite element techniques [28].

Error Evaluation and Mesh Selection

The automatic evaluation of finite element discretization errors is an important ingredient of a comprehensive analysis tool. Based on the identified discretization errors, the analyst – or an algorithm – can construct with the available mesh generation procedures new refined meshes and thus continue the analysis process until the required accuracy is achieved. We use extensively the iso-bands of stresses as a basis of error measures [1, 29, 30], but it should be noted that theoretically “sharp” and effective error measures are not yet available [31, 32].

Solution of Large Systems

A most significant aspect is that effective sparse direct and iterative solvers are now available for the simultaneous solution of large sets of finite element equations on PCs and engineering workstations. Compared to just a decade ago, a reduction of storage by factors of 10 and more, and a reduction of solution times by factors of 100 and more for large systems – without taking into account the increase in computer processing speeds – has been reached. This increase in efficiency, added to the increase in efficiency of the finite elements and contact solution methods, and added to the increase in hardware efficiency, makes it possible to simulate today much more complex forming processes than a decade ago [2, 3].

EXPLICIT VERSUS IMPLICIT TIME INTEGRATION

The recently reached increased capabilities/ efficiencies in simulating forming processes, referred to above, imply in particular that the physical conditions of forming processes can now be much more accurately simulated than a decade ago. In particular, there is frequently no need to use explicit time integration to simulate slow forming processes.

Because of the difficulties in implicit and static solutions, the common practice has been to use explicit integration not only when the physical process is a fast dynamic phenomenon, but also for almost static situations. Then no iterations to establish equilibrium at the solution steps are performed and a simple forward-marching solution is carried out. However, increased velocities, mass scaling, etc. need be used and the solutions obtained must be studied carefully to assess whether the artificial assumptions did not destroy the accuracy of the predicted response. Indeed, some experimentation with the artificial analysis assumptions may be necessary and lead to a number of additional experimental runs.

Of course, ideally, slow forming processes are simulated using static or implicit dynamic analysis methods. An important point of this presentation is that with the powerful analysis features mentioned above, this more accurate (and appropriate) modeling can now frequently be employed, e.g. [33, 34].

Hence while, of course, for many fast transient processes, explicit time integration should be used – but with reliable finite element methods – slow processes should be modeled using implicit time integration (or even static analysis conditions).

CONCLUDING REMARKS

The objective of this paper was to briefly give some views on the current state of finite element methods available for the simulation of forming processes.

Since the early developments of finite element procedures for forming processes, many advances have taken place, as illustrated in the references below and the references therein. The research and development efforts regarding finite element methods have been very exciting, and these efforts are of course continuing in many research centers. Significant further enhancements must be anticipated, and eight key challenges in finite element research and development have been summarized in the Preface of ref. [2]. These challenges include:

- The further improvement of finite element methods, in practically all fields of analysis, but in particular for fluid flows, multi-physics and multi-scale problems.

- The development of mesh-less methods; some advances are already available, see e.g. refs. [35-37] and the references therein.
- The capability to include uncertainties in the input data and solution results.
- The extensive development of virtual laboratories to simulate complete life cycles of structures and systems.
- The teaching of finite element analysis and related fields in an exciting and attractive manner to the young generation.

In all these areas, significant advances must be expected during the years to come that indeed will lead to a "new level of mathematical modeling and numerical solution" that will greatly enhance the possibilities for simulating forming processes.

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