Improved Robust Low Order Solid and Solid-Shell Finite Elements with Incompatible Modes / Enhanced Assumed Strains for Explicit Time Integration

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1 Introduction

High-speed crash and impact scenarios are perfectly solved by explicit schemes, which are in addition very successfully applied for quasi-static problems where convergence with implicit schemes tends to be problematic. A high demand for robust results of the underlying already sufficiently refined finite element discretization exists in scenarios like sheet-metal forming where mixed explicit-implicit schemes are widespread. Simple to operate and suited to model sharp edges or beadings low order finite elements remain popular and improvements beyond fully and selectively underintegrated 8-node solid and solid-shell (in LS-Dyna referred to as 'thick shell') elements are highly desirable. A most popular element technology providing better accuracy for low order finite elements in general nonlinear analysis is the well known method of non-conforming or incompatible modes (IM) [1] which is closely related to so-called enhanced assumed strain (EAS) elements [2]. For both types effective 8-node solid and solid-shell elements for 3D analysis have been discussed extensively in the literature. Limits for usage in explicit time integration tend to be numerical efficiency and particularly the issue of numerical robustness - as shown in Fig. 1 - which are both discussed in this contribution.

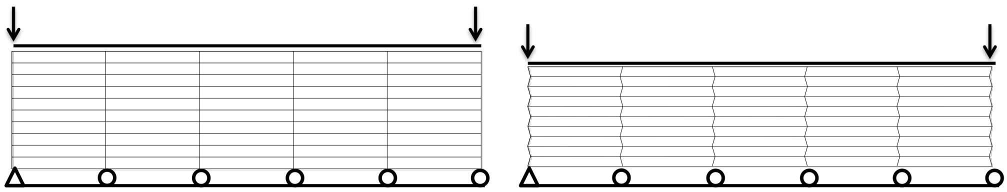

Fig.1: Setup of an academic test case [3] in undeformed (left) and deformed (right) state showing a typical hourglassing pattern as a result of a kinematic mode caused by incompatible modes.

2 Numerical efficiency and robustness of incompatible mode elements

2.1 Circumventing static condensation

Standard treatment of incompatible modes require the condensation of extra degrees of freedom (which are incompatible modes respectively EAS terms) via the solution of an extra equation system which may considerably affect the computational efficiency in explicit schemes that are strictly related to element computations, as very small time steps are required.
A key step in an approach [4] to overcome the necessity of the numerically costly condensation procedure is the assignment of artificial mass to the incompatible parameters. In the case of incompatible mode elements the additional parameters are represented by incompatible displacements, thus the construction of a corresponding mass matrix appears to be a straightforward discretization operation analogously to the mass matrix of standard displacement degrees of freedom. Finally the incompatible mass allows integrating the incompatible displacement parameters in time allowing a fully explicit solution instead of condensation. For any type of EAS-elements a generalization technique allows to reformulate the strain parameters as displacement parameters of corresponding IM elements for which again an incompatible mass matrix can be formulated.

2.2 Incompatible mass scaling

Since the incompatible parameters are not condensed but integrated in time additional frequencies defined by the incompatible mass and incompatible stiffness appear which may affect the size of the critical time step. Since incompatible modes are essentially higher order modes the size of the critical time step determined by the highest frequency of the critical element may be considerably reduced, particularly by the incompatible modes leading to enhancements of volumetric strains, compared to an element formulation without additional incompatible inertia. To recover the original time step size incompatible mass scaling or the solution of the IM displacements in subcycles are possible remedies.

2.3 Numerical robustness – Energy control and rate formulation

Major instability problems first reported in the nonlinear regime [5] and later also for small displacement finite elements [3] limit the application of IM/EAS elements considerably up to now. Within the suggested approach, however, it is possible to use the incompatible mass and velocity to monitor the kinetic energy related to any individual incompatible term inside of an element. Analogously to monitoring the so-called hourglass energy, which is well known from explicit analysis with one point integrated element formulations, instabilities may be detected and reduced or removed by simply scaling the mass related to the them. If the incompatible mass scaling exceeds a limit the incompatible parameter gets insignificant and the original element behaviour as if this incompatible mode was not present is restored. Interestingly incompatible mode elements formulated in the framework of rate and total formulations show significant differences in their instability behaviour which is due to the difference in the discretized element force computation. First results indicate that the mentioned instabilities are not triggered inside the rate formulation.

3 Implementation in LS-Dyna

A set of different IM/EAS-formulations based on 8-node solid discretizations is implemented via the LS-Dyna user element interface. The implementation is rather straightforward since the incompatibility of the extra degrees of freedom allows the solution of the latter on element level as demonstrated in Fig. 2. Further, the IM/EAS approach may be without restrictions extended by other techniques like assumed natural strains or reduced integration for further improvement of the element performance.

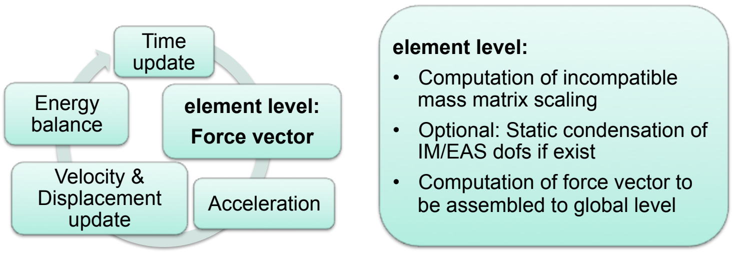

Fig.2: Typical explicit cycle with an overview of necessary computations on element level.

4 Summary

In this contribution we present an implementation of a modified method of incompatible modes - also applicable to enhanced assumed strains – allowing a fully explicit computation of the extra incompatible degrees of freedom. Different IM and EAS-formulations are implemented using the user element interface of LS-Dyna with the aid of AceGen [4] as an important code generation tool. Occurance and techniques to efficiently avoid instabilities related to incompatible modes are examined on geometrically linear and nonlinear academic test cases and more demanding realistic examples. First studies on measuring the computational efficiency in terms of CPU-time are carried out. Further merits and limits of the presented scheme and its possibilities are discussed.

5 Literature

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