Finite Element Simulations of Cutting Processes of Thin-Walled Structures

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Thin walled structures appear in many applications of engineering interest. The intentional or accidental cutting of this type of structures by means of a sharp object is a complex phenomenon, whose accurate description is of obvious interest in many instances. Early studies on the analysis of the mechanics of blade cutting were for example devoted to the analysis of ship grounding. The process of cutting involves several types of nonlinearities, such as large deformations, contact, crack propagation and, in the case of laminated shells, delamination, whose effective description requires state of the art computational technologies. In addition to this, a special difficulty in blade cutting is represented by the blade sharpness, whose accurate geometric resolution would require meshes with characteristic size of the order of the blade curvature radius.

The purpose of this work is to propose and discuss a computational finite element approach for the simulation of blade cutting of thin shells. As it is more convenient in the presence of highly nonlinear problems, the approach is developed in an explicit dynamics framework. Structures of this type are mostly analyzed using shell finite elements belonging to either one of two main categories: shell elements derived on the basis of the classical or degenerate shell concept, in conjunction with the assumption of plane stress state; solid-shell elements, directly derived from three-dimensional continuum elements, using displacement degrees of freedom only and allowing for the implementation of fully three-dimensional constitutive laws. Solid-shell elements are claimed to present several advantages over classical shell elements: more straightforward enforcement of boundary conditions, possibility to incorporate complex 3D material models, no need for complex update algorithms for finite rotations, easy usage in combination with 3D solid elements, possibility to obtain good accuracy in the through-the-thickness stress distribution in laminated composites. On the other hand, solid-shell elements exhibit several types of locking behavior which demand for corrections of the element kinematics. In the present work, the element proposed in [1] has been implemented in an explicit dynamics framework. In this element, shear locking and curvature thickness locking are cured by the ANS (Assumed Natural Strain) method, while Poisson thickness locking is controlled by means of an EAS (Enhanced Assumed Strain) approach by enriching the strain field with one parameter. Reduced integration with hourglass stabilization is also adopted to reduce the computational cost and to avoid volumetric locking.

The possible use of solid-shell elements in an explicit context is attracting particular attention and requires a specific treatment. In fact, in this kind of elements, usually developed in an implicit framework, the computation of the enhanced strain parameters, which are to be condensed out at element level, requires the iterative solution of a nonlinear problem in each element and at each time step, which turns out to be computationally too expensive in explicit analyses, where a very small time step size is dictated by stability requirements. To reduce the computational cost, the element formulation has therefore been reconsidered by introducing an explicit update of the enhanced variables.

Another problem connected with the use of solid-shell elements follows from the fact that the thickness dimension is often significantly smaller than the in-plane dimensions, leading to a high ratio of transverse to in-plane normal stiffnesses, with a high finite element maximum eigenfrequency. Hence, very small time-steps are required to guarantee the analysis stability in explicit dynamics. To circumvent the problem, a new selective mass scaling technique has been proposed based on a linear transformation of the solid-shell element degrees of freedom. The transformation allows to separate middle plane degrees of freedom, which govern rigid body motions, so as to be able to selectively increase the masses associated to out-of-plane degrees of freedom only, preserving the diagonal structure of the mass matrix (see e.g. [2] for a similar approach based on thickness scaling, and [3] for mass scaling). Important features of the proposed approach are that mass lumping is preserved after the transformation, allowing for a direct computation of nodal accelerations, and that only minimal modification to existing codes are required for its implementation. Furthermore, for solid-shell elements, where the thickness dimension is significantly smaller than the in-plane ones, the highest element eigenfrequency always turns out to be given by the square root of the eigenfrequency ω^2 corresponding to the thickness vibration mode. In the case of a regular parallelepiped, in [4] it has been shown that the critical time-step resulting from this eigenfrequency can be analytically computed. This allows to define a strategy for the optimal selection of the mass scaling parameter, so as to maximize the time-step without significant accuracy loss.

Special attention is required in considering the action of a sharp blade on a thin shell, since the blade can interfere with the transmission of cohesive forces between the crack flanks in the cohesive process zone. Standard cohesive interface elements are not suited for the simulation of this type of cutting, dominated by the blade sharpness, unless extremely fine meshes, with characteristic size comparable to the blade curvature radius, are used. To circumvent the problem, the use of a new type of "directional" cohesive interface element, first proposed in [5], for the explicit dynamics simulation of crack propagation in elastic shells, is further developed. According to this concept, when a fracture propagation criterion is activated at a node, the node is duplicated and a cohesive string element is introduced between the separating nodes. String elements are geometric entities which can detect contact against the blade. When this happens, the string transmits cohesive forces to the crack flanks in different directions. Specific issues connected with the use of reduced integration elastoplastic, thin solid-shell elements in connection with "directional" cohesive interface element, such as the definition of a suitable fracture activation criterion and the implementation of a computationally effective hourglass stabilization are addressed.

Applications of the proposed methodology to different types of cutting problems are shown in Figure 1. These examples, by means of comparisons with analytical and experimental results, allow to define the range of applicability of the proposed methodology and to highlight its possible limitations.

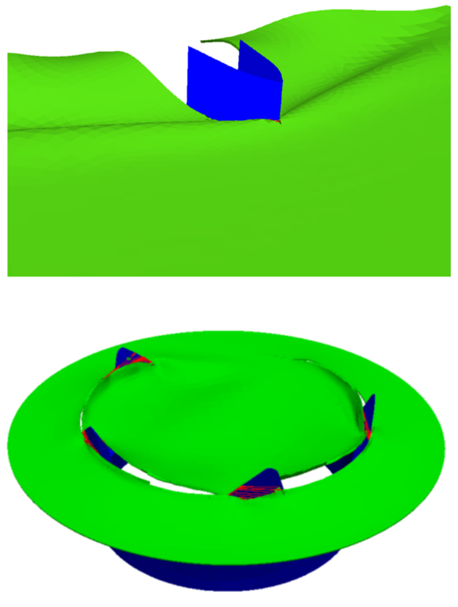

Figure 1: Application to blade cutting problems.

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