COMPUTATIONAL MODELLING OF BLANKING PROCESSES – REMESHING AND TRANSFER ISSUES

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Abstract. Finite element simulations of blanking require frequent remeshing in order to trace the evolving geometry of the problem. Remeshing must be accompanied by transfer of a set of state variables from the old mesh to the new. Inaccuracies which are inevitably introduced by this transfer may easily lead to loss of convergence in subsequent loading increments and therefore to breakdown of the simulation. In order to avoid such failures, a remeshing-transfer algorithm has been developed which is more forgiving with respect to inaccuracies and thus allows for efficient and robust simulations.
1 INTRODUCTION

Industrial metal forming processes such as blanking rely on the controlled formation of a crack in order to separate material. The trajectory followed by this crack determines the final shape and quality of the product. Numerical simulations which are used to optimise such processes should therefore be able to accurately predict crack growth in a ductile material. This not only requires accurate constitutive models and crack growth criteria, but also the computational means to trace the growth of cracks. It is the latter aspect that this contribution focuses on.

In finite element analyses a new finite element mesh must be generated in order to capture the geometry change resulting from the advancement of a crack front. Methods exist which avoid remeshing by inserting the displacement discontinuity associated to the crack into the element formulation [1,2]. However, these methods cannot yet deal with large strains and large rotations (as well as the element distortions resulting from them) and are therefore not suitable for our purpose. Automatically generating a new finite element mesh on a given geometry (in this case given by the analysis) is quite feasible nowadays; commercial software exists which can do this reliably, particularly in two dimensions. For history-dependent material models like plasticity, however, the generation of a new mesh must be followed by the transfer of the state variables of the model to the new discretisation before the simulation can be continued [3]. Algorithms to perform this transfer accurately and – particularly – robustly are much less well-developed. The difficulty is that transfer from one set of Gauss points to another inevitably leads to a certain numerical error. This error not only compromises the overall accuracy of the simulation, it may also lead to numerical instability. If this issue is not properly addressed, convergence of the loading increments following the remeshing/transfer cannot be guaranteed and the simulation may thus come to an end prematurely.

In order to be able to perform fully coupled finite element analyses of crack growth in a robust way, a new, dedicated remeshing-transfer strategy has been developed. Main feature of the algorithm is that it separates the disturbances introduced by numerical error in the transfer of variables and by crack growth. This allows to solve the governing equations in an accurate and robust way, even if large deformations and geometry changes occur.

2 CONSTITUTIVE MODELLING

The plasticity formulation which is used here is based on the hyperelastoplastic framework proposed by Simo [4] and Simo & Miehe [5]. In this framework, the elastic as well as the plastic response are formulated entirely on the spatial – or current – configuration. This is considered to be a major advantage in view of the finite element implementation, because it greatly facilitates an updated Lagrange formulation of the equilibrium problem. Furthermore, the fact that the elastic part of the deformation is truly elastic rather than hypo-elastic is believed to be an advantage when springback issues need to be addressed.

Assuming the usual multiplicative split of the deformation gradient tensor and isochoric plastic flow, the elastic response is given by

\[
\tau = \frac{1}{2} K (J^2 - 1) I + G \mathbf{b}_e^d,
\]
where $\tau$ denotes Kirchhoff’s stress tensor, $J$ is the volume ratio and $\tilde{b}_e^d$ the deviatoric part of the isochoric elastic left Cauchy-Green deformation tensor; $I$ denotes the second-order identity tensor and $K$ and $G$ are elastic constants.

As is usual also in small-strain plasticity, the elastic limit is given by a yield criterion

$$f(\tau, \varepsilon) = \tau_{\text{eq}}(\tau) - \tau_y(\varepsilon_p) = 0$$

with $\tau_{\text{eq}}$ and $\varepsilon_p$ scalar measures of the Kirchhoff stress tensor and the plastic deformation, defined in the usual way. $\tau_y$ denotes the yield stress; its dependence on the effective plastic strain describes the hardening behaviour of the material. If the yield criterion is satisfied, plastic flow is governed by the flow rule

$$\left(\nabla \tilde{b}_e^d\right) = -3\dot{\varepsilon}_p \frac{\tau^d}{\tau_{\text{eq}}}$$

This flow rule is slightly different from that of Simo & Miehe [5] but the two coincide in the limit of small elastic deformations. Note that this flow rule has been formulated in terms of the elastic part of the deformation – hence the minus sign on the right hand side; the plastic deformation rate can always be obtained by a pull-back operation to the material configuration [4]. Reference is made to [6] for implementation aspects of this plasticity formulation, as well as a coupled plasticity-damage model based on it.

Crack initiation and growth in ductile materials usually occurs by a process of nucleation, growth and coalescence of microvoids. Classical nonlinear fracture criteria do not capture this process very well. For this reason, we use an uncoupled damage approach to model the initiation and growth of cracks. This means that an additional field variable is introduced, which describes the development of voids in an average sense. Unlike fully coupled plasticity-damage models, however, this damage variable does not affect the constitutive behaviour until it reaches a critical value.

Following Goijaerts et al. [7], the evolution of the damage variable is defined here according to:

$$\dot{\omega} = \frac{1}{C} \exp \left[ A \frac{\tau_h}{\tau_{\text{eq}}} \right] \dot{\varepsilon}_p \quad \omega(t = 0) = 0$$

where $\tau_h = \frac{1}{3} \text{tr}(\tau)$ denotes the hydrostatic stress and $A$ and $C$ are constants. This relation is a generalised form of the criterion proposed by Rice & Tracey [8] on the basis of a theoretical study of void growth in an infinite plastic matrix. The theory leads to a value of $A = \frac{3}{2}$ for $A$, but it was shown by Goijaerts et al. [7] that higher values provide a much better fit of experiments.

When the damage variable $\omega$ defined above reaches unity somewhere on the computational domain, a crack is inserted. Subsequently, growth of this crack occurs whenever $\omega = 1$ at a specified distance ahead of the crack tip; this growth is in the direction of maximum damage, see reference [9] for details of the implementation.
3 REMESHING AND TRANSFER

Simulations of blanking processes require frequent remeshing to trace the newly formed surface as the crack front progresses through the material. Furthermore, remeshing ensures a sufficiently fine discretisation at the tip of the discontinuity and acceptable element shapes. Since a history dependent constitutive model is used, a certain amount of deformation history data must be transferred from the old to the new discretisation in order to be able to continue the analysis after remeshing. For the plasticity model described above, at least some information on the plastic deformation state \((b_c, \delta_p)\) is needed at each Gauss point of the new mesh. Since this information is only available in a – different – set of Gauss points on the old mesh, its transfer inevitably leads to a certain numerical error. This error not only compromises the overall accuracy of the simulation, it may also lead to inconsistencies between the different field variables, which may in turn result in numerical instability. Inconsistencies may arise in nonlinear relations between variables. For instance, if a certain stress tensor satisfies the yield condition before transfer and the stress tensor as well as the yield stress are mapped to the new mesh, it cannot be guaranteed that the transferred stress tensor is still on the yield surface given by the transferred yield stress – it might even lie outside the new yield surface. Likewise, after transfer the stress field generally will no longer satisfy the discrete equilibrium equations, particularly if the problem domain has changed due to crack extension. If these issues are not properly addressed, convergence of the loading increments following the remeshing/transfer cannot be guaranteed and the simulation may thus come to a premature end.

In order to be able to perform fully coupled finite element analyses of crack growth in a robust way, the remeshing-transfer algorithm shown in Figure 1 has been developed. Although it was developed for the plasticity formulation discussed above, it is believed to be more generally applicable. Main feature of the algorithm is that it separates the disturbances introduced by transfer of variables and by crack growth. This is achieved by reconstructing a consistent representation of the old equilibrium state on the new mesh before the new crack increment is allowed to open up. For this purpose a mesh is first prepared in which the new crack increment is geometrically present (i.e., the crack increment lies along element edges), but elements on different sides of the crack increment are still connected. A set of state variables is then transferred from the existing Gauss points to those of the new mesh using a standard transfer algorithm [3]. Inconsistencies between field variables are avoided as much as possible by transferring the smallest possible set of variables which still contains sufficient information to reconstruct the entire material state. For the plasticity model of Section 2 transfer of the stress tensor \(\tau\) and the yield stress \(\tau_y\) suffices. After this reconstruction, equilibrium is restored iteratively assuming elastic behaviour, i.e. keeping the plastic deformation fixed. Note that this assumption is allowed because the deformation which results in this balancing step is not physical, but solely aims to redistribute numerical error such that an equilibrium state is obtained. After inconsistencies have been removed which may have arisen during the elastic equilibrium equations (e.g., violations of the yield condition), a consistent representation of the situation with the crack increment still closed has been obtained.
Figure 1: Remeshing/transfer algorithm for crack growth in a history-dependent material.
In the second part of the algorithm, the crack increment is opened by introducing additional degrees of freedom and disconnecting elements on both sides the crack. If the subsequent equilibrium iterations – still at the same load level – fail to converge, a fraction of the nodal forces that were acting across the crack increment when it was still closed is applied. By decreasing this fraction in a number of substeps, the unbalance caused by the crack opening can be reduced as gradually as required to ensure convergence. When a converged state has been obtained, it is checked whether this state gives rise to further crack growth at the same load level. If so, the above steps are repeated; otherwise a new load increment can be applied.

Figure 2 shows the final finite element discretisation obtained with the above algorithm for an academic benchmark problem which mimics the deformation and stresses in a blanking process. The square specimen with two holes is loaded by imposing a vertical displacement on the top edge. As a result, a crack is initiated at the smaller hole at some stage during the deformation process. The crack subsequently traverses the plastic zone between the two holes. The remeshing/transfer algorithm had not difficulty tracing the crack growth in this analysis, despite the relatively large crack increments that were taken.

4 CONCLUDING REMARKS

Realistic finite element simulations of forming processes require constitutive models which can accurately describe the underlying physical processes. But in order to guarantee robust and accurate simulations, the numerical techniques which are used to solve the governing equations require careful consideration as well. The accuracy and robustness of blanking simulations have been found to depend critically on the remeshing and transfer operations needed in these analy-
ses. It appears that the robustness of these operations can be greatly improved by returning to a consistent equilibrium state immediately after each perturbation of the solution. Convergence of these intermediate equilibrium iterations can be ensured by assuming elasticity or by applying the unbalance in a number of substeps. Although these ideas can be applied rather generally, they are the most effective when tailored to the constitutive model and the type of disturbance at hand.
REFERENCES


