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DAMAGE AND DISCRETE CRACK PROPAGATION MODELLING
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SOME RESULTS AND CHALLENGES FOR 2D AND 3D CONFIGURATIONS

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ABSTRACT

In this paper we present a technique to model damage and fracture mechanics using remeshing in 2D and 3D configurations. We use the finite element software FORGE2® and FORGE3® which can deal with elastic, elastoplastic and elastic-viscoplastic materials in large deformation. Coupled damage models (Lemaître and Gurson) have been implemented to model the progressive mechanical degradation of the material during its deformation. Once damage reaches a critical value, fracture has to be modelled. 2D remeshing technique and crack propagation criteria are presented to model automatic discrete crack propagation for different configurations. Extension to 3D modelling of fracture is also discussed.

1 INTRODUCTION

Damage and Fracture Mechanics have been studied for many years now. During the last 50 years, numerous different damage models and crack propagation techniques have been introduced and implemented in different finite element software.

On a macro-scale, **damage** is characterized by a progressive loss of rigidity in the mechanical behaviour of a material. From a micro-scale point of view, damage can be described by the three well-known stages of nucleation of micro-voids, growth of these voids and finally coalescence leading to fracture. Among the numerous models presented in the literature, the evolution of damage can be coupled to the mechanical properties of the material or not. Once damage reaches a critical value, a crack becomes initiated and has to be modelled.

Numerical modelling of **crack propagation** has been a real challenge for many years now. The initial and more natural approach was based on a discrete crack propagation modelling approach using remeshing techniques. To avoid numerical difficulties due to geometric topological changes and remeshing during crack propagation, numerous different techniques have been introduced: embedded crack models, mesh-free techniques, XFEM and so on. Each approach has its own advantages and drawbacks, and I shall not in this paper discuss or compare each technique to the others. Depending on the application, one approach can give better results than the others. Sometimes, for instance in high shearing processes such as blanking, it is even sufficient to use a simple “kill-element” technique.

After a brief description of the finite element software used for this study (§2), we introduce the notion of damage and its coupling with the material’s mechanical behaviour (§3). Finally, discrete crack propagation modelling is presented and applied to 2D and 3D configurations examples (§4).

2 FORGE2® AND FORGE3®

FORGE2® and FORGE3® have been developed to model large deformation of elastic, elastoplastic and elastic-viscoplastic materials. They are based on a mixed velocity-pressure formulation. The so-called Mini-element is used in FORGE3® (Arnold [1]). It is based on linear isoparametric tetrahedra and a bubble function is added at element level in order to satisfy the

Brezzi/Babuska condition. The space discretization based on this element associated to the incremental formulation of the virtual work principle lead to a set of discretized non-linear equations. The well-known iterative Newton-Raphson linearization method is used. A one step Euler scheme enables to compute the solution at time t+δt when the solution at time t is known.

FORGE2® and FORGE3® can both handle multimaterial structures using a nodal incremental form of the penalty technique (Pichelin [2]). Besides this, an automatic adaptive remesher enables to deal with large deformation without losing accuracy. The well-known Delaunay Triangulation is used in 2D and a topological remeshing technique enables to deal with automatic 3D remeshing (Gruau [3]).

3 DAMAGE MODELLING

Continuum damage mechanics is a constitutive theory that describes the progressive loss of material integrity due to the propagation and coalescence of microcracks, microvoids, and similar defects. Beyond a certain value of strain, void nucleation and void growth appear in the material: this phenomenon, called damage, allows to model the ductile fracture of materials. When these voids reach a critical size, they coalesce and give raise to instabilities or cracks propagation. Damage models are generally based on the study of void growth, using different parameters such as triaxiality, maximal principal stress, plastic strain and so on.

The first models to be used were **uncoupled damage models**, which means that the damage law does not influence the mechanical properties of the material. The damage parameter is computed using an integral of a strain and stress function, and its distribution can be computed in a post-processing step. This approach is easy to introduce in a numerical software, but is quite unrealistic because the damage evolution does not influence the material properties.

In order to better represent the evolution of damage in materials, **coupled damage models** have been proposed. In this approach, damage and mechanical properties are directly linked and the material fracture is modeled by a progressive decrease of the global response of the structure. Contrary to the uncoupled approach, coupled damage models are quite difficult to introduce in numerical software, but are closer to the physical phenomenon of micromechanical fracture of ductile materials.

Some of these models use the notion of effective stress which represents the actual stress transmitted by the bulk material between the microdefects. Another frequently used approach consists in introducing a damage variable f_v which represents the volumetric fraction of voids in the material. The parameter f_v is then used in the constitutive laws of the material and interacts with the others state variables. The damage model of Tvergaard-Needleman, based on the model introduced by Gurson[3] belongs to these approaches.

The well-known Lemaître model [4] and Gurson-Tvergaard-Needleman model [5, 6] have been implemented in FORGE3®. Details on these models can be found in [7].

Once damage reaches a critical value, fracture has to be taken into account. An easy way to represent fracture is the so-called “kill element” technique. When the damage parameter reaches a critical value inside an element, the element mechanical contribution to the stiffness matrix is set to zero. Coupled with adaptive remeshing, this technique enables to model fracture easily in 3D configurations. In Figure 1, a Lemaître damage model with adaptive remeshing and kill element enables to model a blanking process with accuracy.

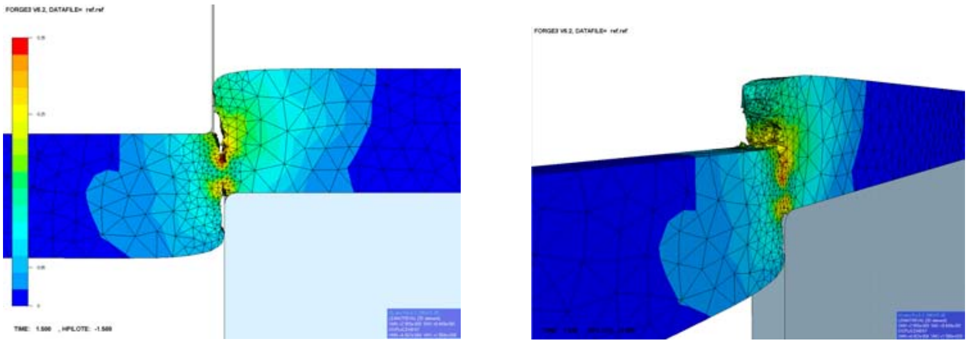


Figure 1. Blanking simulation: isovalues of damage during fracture

However this technique involves a loss of volume during the simulation and the stress singularity at the crack tip is not properly represented. In some cases, when the crack path has to be correctly modelled, a more accurate technique is preferable.

4 CRACK PROPAGATION MODELLING

Our approach is based on discrete crack propagation, and we use automatic remeshing. Crack initiation is based both on critical stress or critical damage. Once a crack is initiated the propagation direction is computed using one of the following criteria: maximum circumferential stress criterion, minimum strain energy density criterion or maximum strain energy release rate criterion (Bouchard [8, 9]). In this last criterion, the strain energy release rate is computed using the $G\theta$ method which appears to be both efficient and accurate (Bouchard [10]). However, in high shearing configurations, when mode II becomes predominant, such criteria are no more available. In such cases, a maximum shear stress criterion has to be used (Bouchard [11]).

Once the crack propagation direction has been predicted, a new outline representing the crack advance is added to the previous outline of the part. Then, a remeshing stage – based on the Delaunay triangulation - is performed and the crack opens naturally due to tensile stresses applied on its edges (Figure 2.):

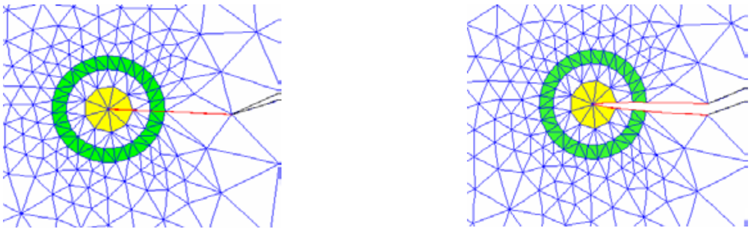
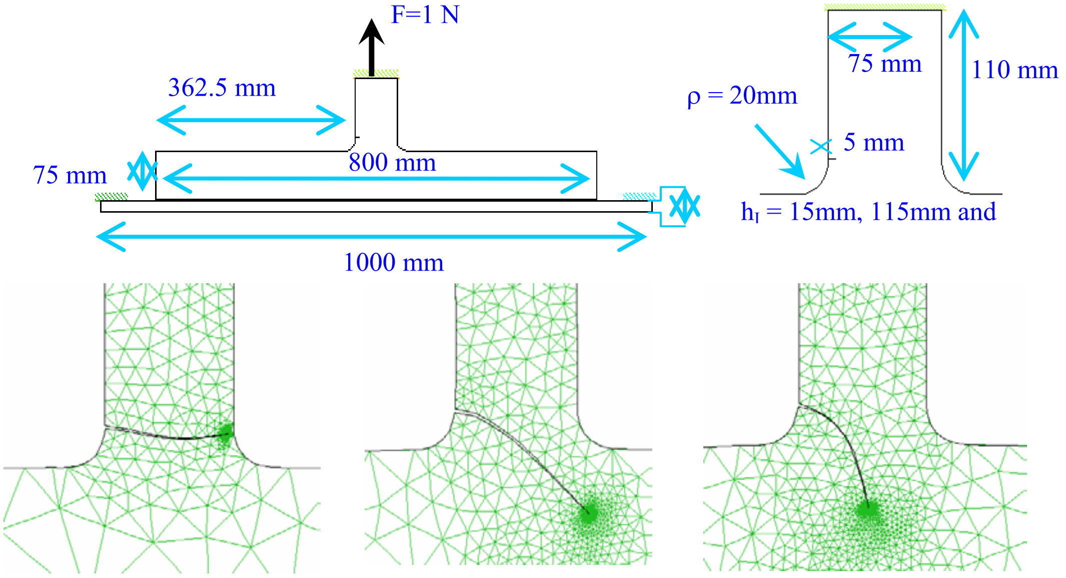


Figure 2. propagation of a crack in a 2D mesh

The example in Figure 3, performed experimentally by Sumi, shows the growth of a crack starting from a fillet in a structural member. The crack propagation depends on the welding residual stresses and the bending stiffness of the structure. For the sake of simplicity, residual stresses are not taken into account. The bending stiffness of the structure is modified by varying the size of the bottom I-beam presented in figure 2 from 15mm to 315mm with an intermediate value of 115mm. A linear elastic plane strain simulation is performed with a Young modulus and a Poisson ratio of E=200GPa, and $\nu=0.3$ respectively. The initial crack length is a_0=5mm, and the maximum circumferential stress criterion is used to compute the crack path. Numerical simulations in figure 3 show the important influence of the bottom I-beam rigidity on the crack path:



Rigid beam (h_I=315mm) Medium beam (h_I=115mm) Flexible beam

Figure 3. Crack growth from a fillet and influence of the support beam rigidity on the crack path.

The following example concerns a pre-cracked part with an inclusion. In [3] we have studied the propagation of a crack in a planar part with an off-center hole. It has been shown that the crack is attracted by the hole since it creates a stress drop in this region.

In the present example, we replace the hole by an inclusion, and we study the influence of this inclusion on the crack path. A rectangular part is pre-cracked and submitted to a tensile test. This part contains an inclusion which may be more rigid or less rigid than the matrix. If E_{matrix} is the Young modulus associated with the matrix, and E_{incl} the one associated with the inclusion, we define R as the ratio : $R=E_{matrix}/E_{incl}$.

The numerical simulation is performed in plane strain, and the maximum strain energy release rate is used. This example shows the ability of the software to deal with multimaterial applications.

Figure 4.a shows that for a soft inclusion – the inclusion is less rigid than the matrix – the crack is still attracted by the inclusion. The crack reorientation is however less pronounced than the one obtained with a hole.

Conversely, if the inclusion is more rigid (see figure 4.b), the crack is repulsed.

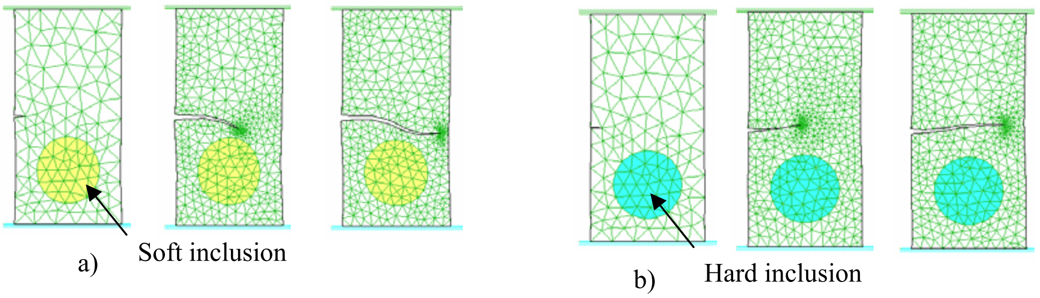


Figure 4. Crack propagation in a part with a) a soft inclusion R=10, b) a hard inclusion R=0.1

In 3D configurations, discrete crack propagation modelling is far more complex from a topological point of view since we have to deal with complex non planar surfaces representing crack faces. Finite element software that manages to model 3D discrete crack propagation are extremely rare (Carter [12], Schöllmann [13]). Our approach is still based on a modification of the part topology coupled with surface and volume remeshing. Once the new crack front has been localized, the surface mesh of the part is modified in order to insert new surface elements representing the new faces of the crack advance. If necessary, a topological improvement of the surface mesh can be performed at this stage. A volume remeshing of the new geometry is then performed. The 3D topological remeshing technique used here is both efficient and well adapted for such complex geometries [3]. Figure 5 shows a crack propagating in the same 3D T-shape structure presented in figure 3. This example is purely intended for numerical feasibility purposes, since the crack propagation direction is determined by the user in this example. However, it demonstrates the ability of the 3D topological remesher to deal with complex 3D modifications such as crack propagation.

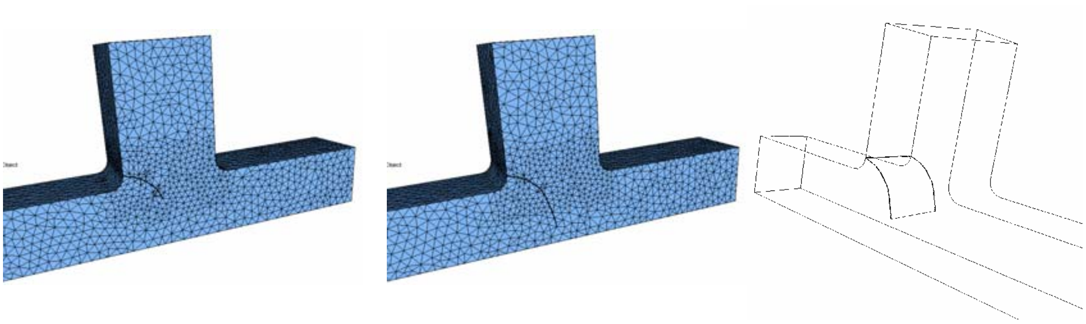


Figure 5. 3D crack growth from a fillet

5 CONCLUSION

Recent advances in finite element software enable to model 3D complex forming processes or structural analysis applications. In such simulations the use of accurate damage models and of fracture modelling is sometimes necessary. Coupled damage models enable to couple the evolution of damage with the mechanical behaviour of materials. Once a critical damage value is reached, fracture has to be modelled explicitly. Our approach is based on discrete crack propagation and automatic remeshing. In 2D, different crack propagation criteria have been implemented and enable to model automatically crack propagation with accuracy. In 3D configurations, discrete crack propagation is more complex. In some cases, a simple kill element technique is accurate enough to model fracture. When the crack path becomes important, 3D discrete crack propagation is needed. We have extended our 2D developments to 3D configurations to model crack propagation. The first results are promising and have to be generalized to more complex geometries.

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