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FRACTURATION AS A NON SMOOTH CONTACT DYNAMIC PROBLEM

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Summary. *In the present paper we will demonstrate how CZM approach, with complex interaction laws, can be treated in the NSCD framework. Some results of the fracture of a metal matrix composite, with heterogeneous behavior, will be presented.*

1 THE NSCD METHOD

The *Non Smooth Contact Dynamics* method (*NSCD*) deals with frictional unilateral contact between rigid or deformable bodies. It was originated around 1984 by J.J. Moreau as the *Contact Dynamics* method (*CD*) [1]. It was extended as the (*NSCD*) method by M. Jean to deal with more general applications, such as finite element modeling [2].

The dynamic equation of a body in the presence of contact (but without shock) may be written in the following classical synthetic form:

$$\mathbb{M}\dot{u} = \mathbb{F}(q, u, t) + \mathbb{P}(t) + r \tag{1}$$

where q denotes some parametrization (for example position of the center of gravity of a rigid body, rotation parameters of this body or displacements of the nodes of a finite element mesh), u the velocity function and r indicates the contribution of the unknown contact forces. The n-vectors $\mathbb{F}(q, u, t)$ and $\mathbb{P}(t)$ encompass the internal and external efforts and also the velocity-dependent terms commonly referred to as *centrifugal* and *gyroscopic.*

In the NSCD method the basic interaction laws such as Coulomb's law and the unilateral contact law are described as non smooth laws in terms of multi-mappings. Due to the non smoothness of the velocity function, the dynamical equation should only be discretized according to a low order implicit algorithm. Considering a time interval $]t_i, t_f]$ of length h we obtain :

$$\left\{ \begin{array}{l} \mathbb{M}(u_f - u_i) = \displaystyle\int_{t_i}^{t_f} (\mathbb{F}(q, u, s) + \mathbb{P}(s))ds + hr_f \\ q_f = q_i + \displaystyle\int_{t_i}^{t_f} uds \end{array} \right. \tag{2}$$

where $hr_f = \int_{]t_i,t_f]} r d\nu$ represent the total contact impulse over the time-interval, an unknown of the problem.

In the NSCD method the main unknowns are the relative velocities ($U = H^* \; u_f$) between contacting boundaries at some overlapping moments with the time steps (leap frog technique) and the mean reaction impulses ($hr = H \; hR$)during the time steps. In the followings one supposes that it is possible to condense the total system (2) in the form:

$$WhR - U = -U_{free} \tag{3}$$

where $W = H^* \mathbb{M}^{-1} H$ and $U_{free} = H^*(\mathbb{M}^{-1}(\int_{ti}^{t_f} (\mathbb{F}(q,u,s) + \mathbb{P}(s))ds) + u_i)$ for rigid bodies. See [2] for details concerning deformable bodies.

Assuming provisional values for contacts neighboring of a given contact, values of the reactions for this given contact are obtained discussing the intersection of the graphs of affine mappings. Values of the reactions are updated, and all contacts are processed successively as long as necessary to obtain a satisfactory convergence. This may be described as a non linear block Gauss Seidel method.

The NSCD method has been successfully used to study the behavior of granular materials such as the stability of slopes, the segregation or compaction phenomenon, or the railway ballast fatigue [8]. But it has been also used to study the behavior of buildings made of blocks [7], biomechanics, tensegrity cell models.

2 DYNAMICAL FRACTURE AS A NSCD PROBLEM

Furthermore, one can use the NSCD method for the numerical simulation of dynamic fracture in a wide variety of materials and structures. It concerns the entire fracture process from crack initiation, growth, propagation, rupture to post fracture behavior when fragments interact.

The approach is based on a cohesive zone model (CZM) which is enhanced in order to deal with complex phenomena as friction or wear on the crack lips, possibly with finite slips [3]. Regarding advantages and disadvantages of the local methods devoted to model fracture, CZM need reasonable computer facilities and their main parameters are mechanically meaningful: the peak traction stress drives the initiation of fracture and the cohesive energy drives the crack propagation.

The Frictional Cohesive Zone Model used is a model coupling unilateral contact and Coulomb friction with cohesion. Therefore, a cohesive force , is added on the Signorini-Coulomb complementary problem :

$$g \geq 0, \; (R_N - R_N^{coh}) \geq 0, \; g(R_N - R_N^{coh}) = 0 \tag{4}$$

$$\begin{array}{l} ||R_T - R_T^{coh}|| < \mu(R_N - R_N^{coh}) => U_T = 0 \\ ||R_T - R_T^{coh}|| = \mu(R_N - R_N^{coh}) => U_T = -\lambda(R_T - R_T^{coh}), \lambda \geq 0 \end{array} \quad (5)$$

At this stage various cohesive models, giving R^{coh}, can be used. It has no influence on the classical way of solving the Signorini-Coulomb problem. In the following we use a model proposed by Monerie [3] and implemented in a dedicated software [6].

3 ILLUSTRATION

This approach has been successfully used in various fields : delamination [3], fragmentation [4] or wear modeling [5].

In the present paper we present the results of the fracture of a metal matrix composite, with heterogeneous behavior [6]. In Pressurized Water Reactor (PWR), most of the structural parts of fuel cladding tubes consist of zirconium alloys such as Zircaloy-4. In these examples, we simulate an irradiated Zircaloy-4 plate with rectangular hydride inclusions which represent a part of a fuel cladding tube. Hydrides are distributed randomly (with a volumic fraction of 20 %) and oriented horizontally. Two different levels of bonding strength values, weak ($w^i/w^h \equiv 10^5$) and strong ($w^i/w^h \equiv 10^4$), between the two phases are considered. w^i and w^h denote the surface energy of interface Matrix/Hydride and Matrix/Matrix respectively. Matrix is assumed to be elastoplastic (J2 plasticity, hardening modulus) and hydrides elastic. The material properties and the cohesive coefficients, used in the present simulations, are given in [6]. Figures 1,2 show that the crack path is significantly influenced by the interface Matrix/Hydride bonding strength. For the strong interfaces, cracks propagate through hydride inclusions due to its high cohesive strength with the matrix. In case of weak interfaces, cracks propagate inside the matrix and along the inclusions boundaries due to the formation of microcracks along weak interfaces.

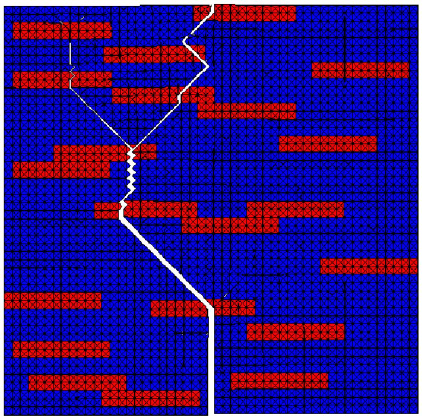

Figure 1: Strong matrix/hydride interface : crack path

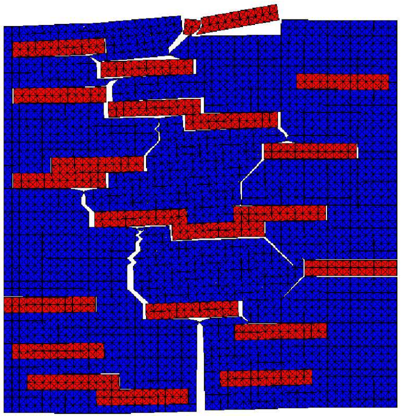

Figure 2: Weak matrix/hydride interface : crack path

4 CONCLUSION

This paper has presented a numerical framework for the simulation of the dynamic fracture of heterogeneous materials. This approach is based on the coupling between the Cohesive Zone Model concept and the Non-Smooth Contact Dynamics method. The ability of this approack has been illustrated on the dynamic crack propagation of hydrided Zircaloy-4. A damage elastoplastic behavior has been simulated for the Zircaloy-4 and the weakening effect of the hydrides has been emphasised.

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