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## A COHESIVE MODEL COUPLING FRICTION AND ADHESION FOR INTERFACES AND FRACTURES AND APPLICATIONS

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**Summary** A model coupling adhesion, friction and unilateral contact taking into account viscosity effects is given. Damage is considered by using the notion of intensity of adhesion first introduced by M. Frémond. The variational formulation is given as variational inequalities for quasistatic problems. The dynamics is solved with the Non Smooth Contact Dynamics method of Moreau-Jean. This model is used to simulate both debonding interfaces and ductile crack propagation. Applications are first presented in composite mechanics (interaction of cracks and fiber/matrix interfaces), civil engineering (steel/concrete interface for reinforced concrete). An extension to healing adhesion is presented for rubber/glass contact. Results on an ongoing research related to earthquake analysis is presented where this behavior law is used to simulate the contact between tectonic plates.

### THE MODEL

In order to describe the smooth transition from a completely adhesive contact to a usual unilateral contact (Signorini conditions) with Coulomb friction, a model based on interface damage has been developed for quasi-static and dynamics problems : the RCCM model (Raous-Cangémi-Cocou-Monerie [1][2]). It is based on the notion of intensity of adhesion first introduced by Frémond [3]. The behaviour of the interface is described by the following relations, where (1) gives the unilateral contact with adhesion, (2) gives the Coulomb friction with adhesion and (3) gives the evolution of the adhesion intensity  $\beta$ .

$$-R_N^r + \beta^2 C_N u_N \geq 0, \quad u_N \geq 0, \quad (-R_N^r + \beta^2 C_N u_N) \cdot u_N = 0, \quad (1)$$

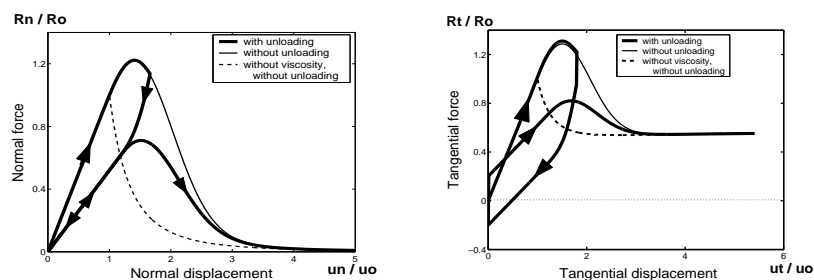
$$\begin{aligned} R_T^r &= \beta^2 C_T u_T, \quad R_N^r = R_N, \\ \|R_T - R_T^r\| &\leq \mu(1 - \beta) |R_N - \beta^2 C_N u_N|, \end{aligned} \quad (2)$$

with

$$\begin{aligned} \text{if } \|R_T - R_T^r\| &< \mu(1 - \beta) |R_N - \beta^2 C_N u_N| \Rightarrow \dot{u}_T = 0, \\ \text{if } \|R_T - R_T^r\| &= \mu(1 - \beta) |R_N - \beta^2 C_N u_N| \Rightarrow \exists \lambda \geq 0, \dot{u}_T = \lambda(R_T - R_T^r), \end{aligned}$$

$$\begin{aligned} \dot{\beta} &= - \left[ \left( w - \beta (C_N u_N^2 + C_T \|u_T\|^2) - k\Delta\beta \right)^{-} / b \right]^{1/p} \quad \text{if } \beta \in [0, 1[, \\ \dot{\beta} &\leq - \left[ \left( w - \beta (C_N u_N^2 + C_T \|u_T\|^2) - k\Delta\beta \right)^{-} / b \right]^{1/p} \quad \text{if } \beta = 1. \end{aligned} \quad (3)$$

$R_N$  and  $u_N$  (respectively  $R_T$  and  $u_T$ ) are the algebraic values of the normal (respectively tangential) components of the contact force and those of the relative displacement between the two bodies. Subscript  $r$  denotes the reversible parts. The constitutive parameters of this interface law are as follows :  $C_N$  and  $C_T$  are the initial stiffnesses of the interface (full adhesion),  $\mu$  is the friction coefficient,  $w$  is the decohesion energy,  $p$  is a power coefficient ( $p = 1$  in what follows) and  $k = 0$  in what follows. Fig. 1 gives the normal and tangential behaviour of the interface during loading and unloading ( $C_N = C_T = C$ ,  $u_0 = \sqrt{w/C}$  and  $R_0 = \sqrt{\omega C}$ ). It should be noted that the Signorini conditions are strictly imposed when compression occurs.



**Figure 1.** Behavior law of the interface

## FORMULATIONS AND SOLVERS

The quasistatic formulation is given as the coupling of two variational inequalities (see [1] [4]). Using a fixed point iteration on the sliding limit, the problem can be solved through a projected over-relaxation method or a projected conjugate gradient method ([4]).

The dynamics problem is written in terms of differential measures because of the non smooth character of the law and the Non Smooth Contact Dynamics method developed by Moreau-Jean is used [5].

Mathematical analysis can be found in [6] and an extension to finite deformations in [7].

## APPLICATIONS

### Crack in composite materials

In composite materials the behavior and the resistance of the fiber/matrix interface has a strong influence on the propagation of cracks. Within a collaboration with the ONERA, the RCCM model has been first used to simulate the behavior of this interface during micro-indentation of a single fiber [1] for quasi-static loadings. Then the RCCM model has been used to simulate also the propagation of a crack in the vicinity of a fiber in dynamics [2][8]. The influence of the characteristics of the fiber/matrix interface is shown on the various mechanisms which can occur : trapping, crack bridging or fiber breaking.

### Steel/concrete interface in Civil Engineering

A validation of the model has been conducted on pull-out experiments of a steel rod out of a concrete sample. An extension of the model with a variable friction coefficient was given. The friction coefficient depends on the sliding displacement on the interface in order to take into account the grinding phenomena which occurs with concrete [9].

### Extension to healing adhesion : rubber/glass contact

A new model taking into account reversible or healing adhesion has been recently developed in order to describe the possible recovered adhesion when the contact is prescribed again after a separation. Presently the model is used to simulate rubber/glass contacts. Adhesion acts in that case before that the contact occurs. The rolls observed at the vicinity on the rubber for the contact with a glass sphere is simulated [7]. Work on Schallamach waves is undergoing.

### Earthquake analysis

Recent results are presented on an undergoing research on earthquake analysis conducted in collaboration with J.P. Vilotte at the Institut de Physique du Globe in Paris. In order to simulate the interface between tectonic plates, the RCCM is compared to classical models such as the state and rate or the slip weakening ones ([11][12][13][14]). Alternate loadings are considered. The RCCM model allows to take into account some viscosity effects on the behavior of the interface. The comparison is conducted in dynamics and stresses the study of the occurrence of instabilities with the various interface laws.

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