INFLUENCE OF TENSILE CRACKS GENERATION DURING SHEAR RUPTURE ON SEISMIC NEAR SOURCE GROUND MOTION

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1. Preliminary considerations

- The dynamics of rupture propagation is one of the most important issues in response computations in Seismology.

- These studies are typically based on the assumptions that (a) the region surrounding the causative fault presents linear elastic behavior and (b) sliding with friction occurs along pre-existing discontinuity surfaces, identified as faults.

- Thus, fractures, in the sense of LEFM or related theories, are assumed inexistent or irrelevant and therefore are usually disregarded in response computations.
1. Preliminary considerations

In fact, in current models the stresses due to friction control the initiation as well as the end of seismic motion. The classic Coulomb model for dry friction, while accounting for the basic features of the phenomenon, is not sufficient to predict the extent of slip propagation and ensuing vibrations.

A law for the fault constitutive criteria that correctly describes the evolution of the interface stresses is hence needed for a reliable dynamic analysis. So far available laws do not explicitly account for local fractures starting at or parallel to the fault.
2. Introduction

- In recent studies the authors consider the possibility of occurrence of tensile crack generation near the free surface during faulting.
- The proposed model was able to simulate the mechanism of large cracks developed as a flower like-structure surrounding the shear fault and explain some aspects of the fracture zones found after the 2000 Tottori earthquake.
- The effects of these large cracks on the ground motion is currently being studied by the authors. The results show that the ground motion suffers drastic changes when compared with the results of standard dynamic simulations.
3. Description of Model

- For shear rupture propagation, a simple slip-weakening model was used as the friction law on the pre-existing fault. For the tensile cracks, however, fracture is assumed to follow the classical Theory of Linear Elastic Fracture Mechanics (LEFM), according to which fracture begins when the critical value of the tensile fracture surface energy is reached at a point. For this purpose the Discrete Element Method (DEM) was resorted to, because it allows the generation of *new tensile cracks* with negligible increase in computational costs.
3. Description of Model

- The Discrete Element Method (DEM) employs a mesh of 1D elements to model an arbitrary 3D orthotropic elastic solid. The model consists of a three dimensional periodic truss-like structure with a cubic arrangement.

- Initially, DEM was successfully applied to a 2D mode I dynamic crack propagation problem by Riera and Rocha (1991), who correctly predicted the propagation velocity of tensile cracks without shear slipping, and later by Dalguer et al. to 2D and 3D models of the seismic source.
DISCRETE ELEMENT METHOD

Stiffness of the longitudinal bars

\[ AE_n = \alpha EL^2 \]
\[ AE_d = 2\delta\alpha EL^2/3^{1/2} \]

\[ \alpha = (9 + 8\delta)/(18 + 24\delta), \]
\[ \delta = 9\nu(4 - 8\nu) \]

Nodal equilibrium equation
(Solve the elastodynamic problem)

\[ m\ddot{u} + c\dot{u} = f_i \]
3. Description of Model

Constitutive Relation for the Tensile Crack Propagation

Griffith's energy balance concept:

\[ G_{fc} = \int_{0}^{U_c} \sigma(U) dU \]

(After Atkinson, 1987)
3. Description of Model

Constitutive Relation for one bar of DEM

\[ \sigma_c = E \varepsilon_p \]

\[ G_{lc} = \frac{1}{2} E \varepsilon_p^2 \Delta x (k_r - 1) \]
4. Dynamic rupture and near source ground motion simulation for a vertical shallow strike slip fault.

The dynamic shear rupture, coupled to frictional sliding on a pre-existing vertical shallow strike-slip fault, is herein numerically simulated. The stress distribution along the fault is assumed to be at a given initial level. The rupture process is initiated by imposing a stress drop within a small region, which leads to a monotonic increase of the initial stresses on the fault without any relative slipping. Eventually, the interface shear stress ($\tau$) at a point exceeds the local shear strength (critical stress level $\tau_u$) and slip at a node occurs, governed by the slip-weakening model. This slip may propagate to adjacent nodes.

In the simulation, it is assumed that the pre-existing fault, in which shear rupture occurs, is embedded at a depth of 3km from the ground surface. To model a frequently encountered situation, it is also assumed that an asperity is embedded in the stratified medium at a distance of 1.5km from the top of the pre-existing fault (asperity model).
Slip-weakening Friction Law for Shear Crack propagation

Before slipping

\[ D=0 \quad \text{para} \quad \tau < T_u \]

During slipping

\[ \tau = T_u - (T_u - T_d) \frac{D}{D_c} \quad \text{para} \quad 0 < D < D_c \quad e \quad D \geq 0 \]

\[ \tau = T_d \quad \text{para} \quad D \geq D_c \quad e \quad D > 0 \]
4. Dynamic rupture and near source ground motion simulation for a vertical shallow strike slip fault.

\[ \Delta \sigma = 18 \text{MPa} \]

\[ \Delta \sigma = 2.5 \text{MPa} \]
4. Dynamic rupture and near source ground motion simulation for a vertical shallow strike slip fault.

- The parameters used for the 3D dynamic simulation as well as the geometry of the asperity fault model were shown in the Figure. The asperity is a zone with higher stress drop than the surrounding areas. The dynamic parameters for shear slipping are the following: for the asperity area the stress drop is $\Delta \tau = 18\text{MPa}$, the strength excess equals $3.0\text{MPa}$ and the critical slip $D_c = 0.5\text{m}$. For the surrounding area, i.e. the rest of the fault, the stress drop $\Delta \tau$ equals $2.5\text{MPa}$, the strength excess $3.0\text{MPa}$ and the critical slip $D_c = 0.15\text{m}$. 
4. Dynamic rupture and near source ground motion simulation for a vertical shallow strike slip fault.

- For the generation of the tensile cracks, the critical fracture energy in mode I is assumed to be $G_{Ic}=5 \times 10^5 \text{J/m}^2$ with a coefficient $k_r=1.5$. The shear wave velocities in the medium vary between 3.2 and 3.9 km/s. The fault motion is assumed to be right-lateral slip. The model used for the simulation is a prism with sides 60 km $\times$ 60 km $\times$ 40 km long. The size of the cubic cells is 0.5 km (about 5,000,000 DOF).
To assess the effect of new tensile cracks on shear slipping and near source ground motion, two dynamic rupture simulations of the asperity model were performed: (1) when no crack opens during faulting, and (2) when new cracks occur during faulting. The results of the simulation are described below.

A general view of all the tensile cracks generated during the dynamic rupture process along the pre-existing fault are presented next. It may be seen in Figure b that the surface of the new cracks forms a flower structure on top of the fault and at the bottom of the asperity. But on the sides of the fault and of the asperity, the cracks develop only on the dilatational side of the fault. Fig. c shows a top view in which the cracks that reached the ground surface are observed. A detailed explanation of the generation of cracks was explained in previous papers (Dalguer et al, 2003a,b).
Snapshots of the shear slip velocity (m/s): (a) Model without tensile cracks; (b) model in which tensile cracks are generated.
Maximum displacements on the surface caused by the spontaneous dynamic rupture: (a) Models without tensile cracks; (b) model in which tensile cracks are generated.
Peak velocity ground motion on the surface caused by the spontaneous dynamic rupture: (a) Models without tensile cracks; (b) model in which tensile cracks are generated.
Final comments and conclusions

When the two models are compared, the model with cracks shows maximum values of the normal and vertical displacements that are almost twice as large as the corresponding displacements in the un-cracked model, but the parallel components are almost the same. The peak value of the normal velocity component is also doubled in the cracked model, while the peak of the vertical velocity component reaches values almost four times that observed in the model free of cracks, but these peak values are concentrated near the cracks that reached the free-surface. The parallel component remains almost unchanged.
Final comments and conclusions

- From these results it may be concluded that the generation of tensile cracks during faulting may strongly affect the rupture process and near source ground motion. The phenomenon deserves further consideration, including field evaluations.
The so-called (DEM) was recently employed by Rios & Riera (2004) to determine the response of geometrically similar reinforced concrete beams built in different sizes, tested by Leonhart & Walter (1962) and later by Ramallo et al (1995), to assess cracking and in addition to quantify size effects in reinforced concrete. The method was also used to reproduce experimental results due to Van Vliet et al (1996) on the influence of size on the tensile strength of concrete. In all cases the agreement with experimental evidence was excellent.
In all cases, however, the mesh was sufficiently dense, since the dimensions of the smallest cracks that the model can predict do not differ significantly from the size of the elements. This condition may require large DEM models, which cannot be usually employed in practice due to cost-effectiveness considerations. The element size adopted in the preceding example, 0.5km, implies that the smallest cracks predicted in the numerical analysis extend for areas larger than 0.25km².
On the other hand, research under way suggests that accurate predictions of the rupture process of structural systems, duly accounting for size effects, can be made using larger elements not subjected to the restriction mentioned above and therefore greatly reducing computational costs, if the appropriate stress-strain relations are adopted.
Ongoing research

- Experimental verification of the fracture criteria, which has proved valid in concrete structures of dimensions smaller than about 100 times the correlation length of the random material properties. Is the criteria applicable, without modifications, to large size rock elements?
- This verification will require ingenuity as well as significant investments in field testing.
The applicability of various constitutive laws for the fault, such as the slip-weakening, velocity-weakening or rate- and state-dependent friction laws, often employed in numerical predictions of shear rupture, was recently discussed by the one of the authors in connection with results of laboratory experiments on friction (Miguel and Riera, 2003).
The results presented herein, however, point at the possibility that cracking adjacent to or springing from the fault might exert an influence on the *macro* constitutive law for the fault. This effect is being studied by modeling the region adjacent to the fault surface, including material non-homogeneities as well as the possibility of generation of new, *small* tensile cracks.