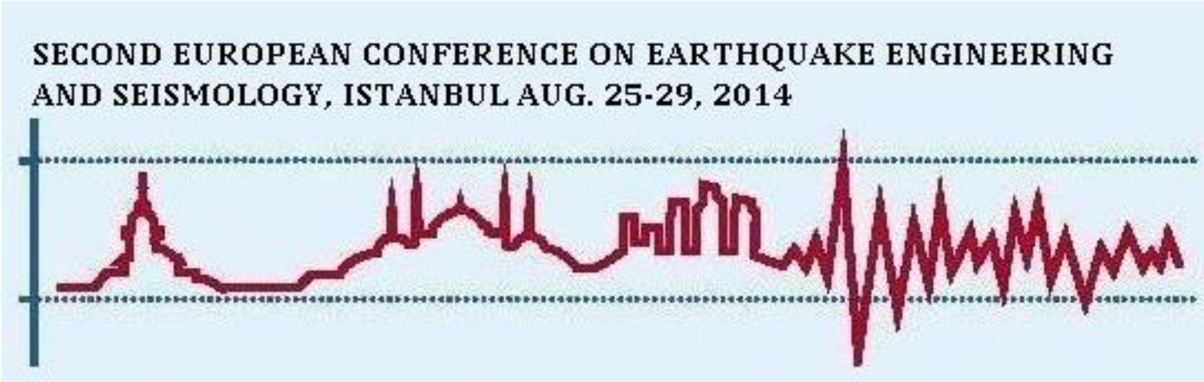

PROGRESS OF IN-PLANE SHEAR FAULTS FROM SUB-RAYLEIGH UP TO COMPRESSIONAL WAVE RUPTURE SPEEDS

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It is now known that in-plane shear faults (primarily strike-slip earthquakes) can not only exceed the shear wave speed of the medium, but can even reach the compressional wave speed, according to theoretical and numerical studies, laboratory experiments and seismic data analysis. However, steady-state calculations on singular cracks showed that speeds between the Rayleigh v_R and shear wave v_S speeds were not possible, due to the fact that in such cases there is negative energy flux into the fault edge from the surrounding medium. A steady-state singular crack would not absorb strain-energy but generate it (see Broberg (1999) for details). Andrews (1976) showed that even for non-singular 2-D in-plane ruptures which start from rest and accelerate to some terminal velocity, such a forbidden zone (between v_R and v_S) does exist. The existence of this forbidden zone in rupture speed has been supported for steady state cracks in analytical (Burridge et al., 1979) and for spontaneous rupture in numerical (Liu et al., 2008; Lu et al., 2009) studies.

Recently Bizzarri and Das (2012) showed, using an unprecedented numerical resolution of the forbidden zone, that for the 3-D ruptures, where the in-plane (mode II) and the anti-plane (mode III) modes of propagation are mixed together, obeying the linear slip-weakening governing equation, the rupture front actually does pass through this forbidden zone very fast..

Motivated by this result, we examine here the passage of the pure in-plane shear rupture from the sub-Rayleigh to the compressional wave speeds in 2-D, with a very accurate estimation of the rupture speed. This issue is interesting and important, as for very long strike-slip faults in the Earth's crust the rupture becomes primarily pure mode II when the fault length becomes much larger than its width. One hundred and twenty numerical experiments are carried out to investigate the entire range of possible rupture speeds from crack initiation to the compressional wave speed. The parameter region where super-shear rupture propagation could occur has been thoroughly scrutinized.

The geometry of the problem is shown in Figure 1. The elasto-dynamic problem is numerically solved by using the finite difference code, originally developed by Andrews (1973) and modified by Bizzarri et al. (2001). The linear slip-weakening friction law (Ida, 1972) adopted here is described by $\tau(u) = \sigma_n^{eff}[\mu_u - (\mu_u - \mu_f)\min(\mathrm{u}, \mathrm{d}_0)/\mathrm{d}_0]$, where τ is the shear stress on the fault, σ_n^{eff} is the effective normal stress, μ_u is the static friction coefficient, μ_f is the dynamic friction coefficient, u is the fault slip and d_0 is the characteristic slip-weakening distance.

Since the linear slip-weakening law requires an (artificial) procedure in order to obtain the subsequent spontaneous, dynamic rupture propagation, two rather different nucleation strategies and different initial parameters are employed. In the first strategy, referred to as the time-weakening initiation, the rupture is initially non-spontaneous and propagates at a constant (and prescribed) speed $v_r = v_{initial}$ (Andrews, 1985; Bizzarri, 2010). Values of $v_{initial}$ equal to 1.2 km/s and 0.5 km/s are tested. In the second strategy, referred to as the asperity initiation, a small perturbation in the initial stress is used

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to initiate the dynamic rupture, as described in details in Bizzarri (2010). The size of the asperity is small enough to avoid its interference with the later spontaneous rupture propagation.

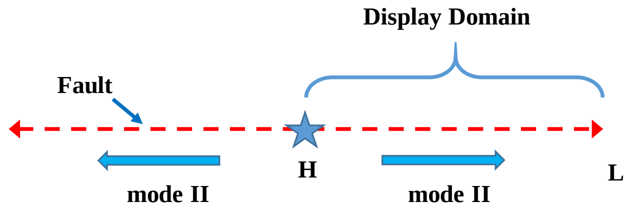

Figure 1. Geometry of the 2-D rupture problem considered here. The rupture begins at the imposed hypocenter H and then it propagates bilaterally, as shown by the arrows. *L* is the half length of the fault.

Numerical experiments are carried out to investigate the relation between the rupture speed and relative fault strength *S*, originally defined by Hamano (1974) as $S=(\tau_u-\tau_0)/(\tau_0-\tau_f)$, where τ_u is the upper yield stress, τ_0 is the initial stress and τ_f is the residual stress. These cased are sorted into 5 groups by grid size and nucleation method. In each group, 24 values of *S* ranging between 0.38 and 1.2 are considered (Table 1).

Table 1. Parameters used for the 5 different groups of cases studied

Group Label	Δx (m)	Δt (s)	Number Of Case	Nucleation Method	d_0 (m)
A	40	3.42×10-4	24	TW*: $v_{initial}$ = 0.5 km/s	0.4
B	20	1.71×10-4	24	"	"
C	10	8.57×10-5	24	"	"
D	40	3.42×10-4	24	TW: $v_{initial}$ = 1.2 km/s	"
E	40	3.42×10-4	24	Asperity rupture	"

*TW: Time-weakening with starting speed $v_{initial}$

For all the cases in Group A, we plot the rupture speed vs. time in Figure 2a. The rupture speed curves form two separate regions which are schematically demonstrated in Figure 2b. These two regions show two different mechanisms controlling the super-shear rupture transition: the direct transition (e.g., Lu et al., 2009) and the mother-daughter (or Burridge-Andrews) transition (Burridge, 1973; Andrews, 1976).

In the region of $\sim 0.38 \le S \le \sim 0.72$, the fault is weaker and the direct transition dominates. The rupture starts from rest, accelerates and passes smoothly through the formerly considered forbidden zone $[v_R, v_S]$ in a short time, then approaches the compressional wave speed. The position of the leading edge and rupture time increases smoothly during the transition. Although the forbidden zone exists in most previous studies, our study, using very fine grids with good rupture speed resolution in the interval $[v_R, v_S]$, clearly shows that penetration of the forbidden zone does really occur for every *S* in this range in 2-D. Thus, for such faults, the rupture speed continuously increases from sub-Rayleigh to super-shear without any jump.

In the region of $S \ge \sim 0.76$, the fault is stronger and the mother-daughter transition dominates. The behavior of the rupture in the sub-Rayleigh regime is quite similar to that observed for the weaker faults. However, as it approaches the Rayleigh speed, after some time, a stress peak propagating at almost the shear wave speed exceeds the upper yield stress and causes the birth of a daughter crack ahead of the main rupture front. The behaviour of the daughter crack is controlled by the peak shear stress radiated from the main crack until spontaneous rupture takes over but there is not enough time for the daughter crack to develop significant slip or slip velocity. Thus the daughter-crack is essentially a "pseudo-crack", where the two sides of the fracture have separated but do not have significant motion.

Similar results are obtained in Groups B to E, which show that these results are essentially independent of the grid sizes and the nucleation methods used.

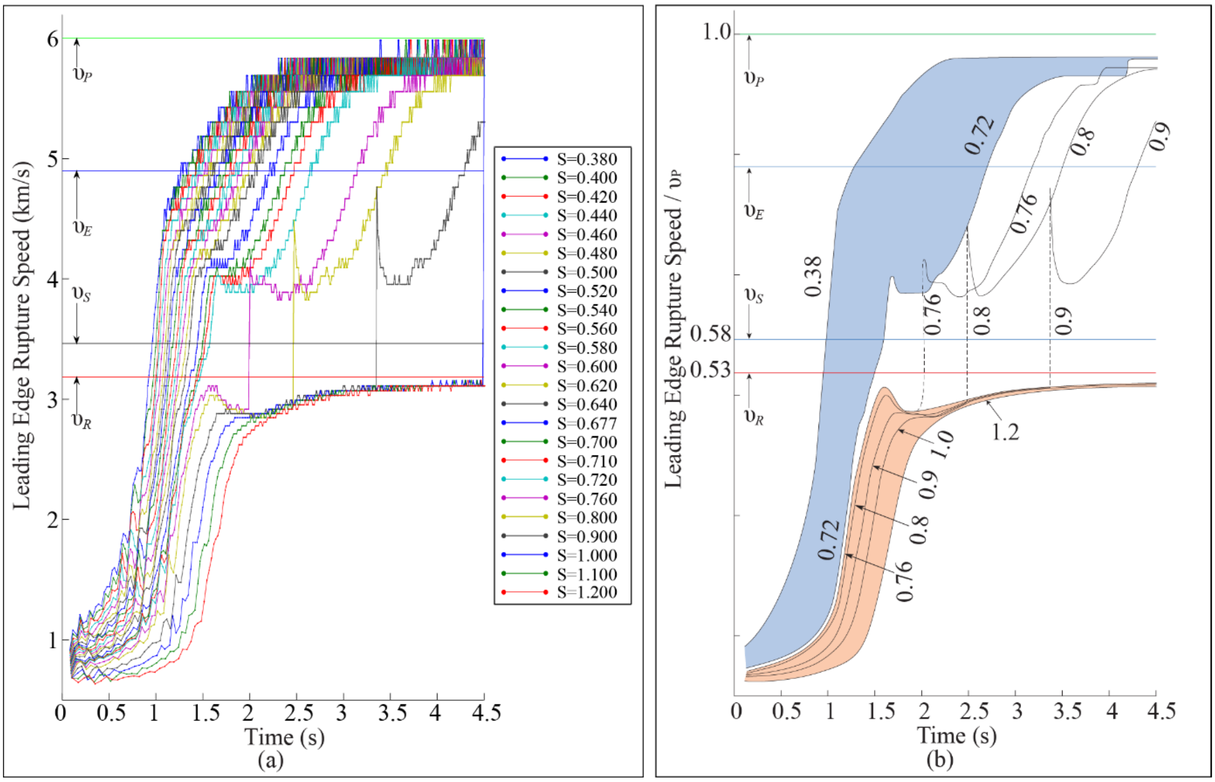

Figure 2. The two kinds of transition behaviour for the smaller and larger *S* values in Group A. The range [v_R , v_S] is marked, as well as other relevant speeds (v_E is the Eshelby speed). (a) Rupture speeds for the 24 values of *S*. (b) Schematic version of panel (a). The vertical dashed lines indicate the birth of the daughter crack. The light blue region indicates direct transition mechanism; the light orange region indicates mother-daughter transition mechanism. The numbers along the different lines indicate the various values of *S*.

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