Theoretical constraints on dynamic pulverization of fault zone rocks

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SUMMARY
We discuss dynamic rupture results aiming to elucidate the generation mechanism of pulverized fault zone rocks (PFZR) observed in 100–200 m wide belts distributed asymmetrically across major strike-slip faults separating different crustal blocks. Properties of subshear and supershear ruptures are considered using analytical results of Linear Elastic Fracture Mechanics and numerical simulations of Mode-II ruptures along faults between similar or dissimilar solids. The dynamic fields of bimaterial subshear ruptures are expected to produce off-fault damage primarily on the stiff side of the fault, with tensile cracks having no preferred orientation, in agreement with field observations. Subshear ruptures in a homogeneous solid are expected to produce off-fault damage with high-angle tensile cracks on the extensional side of the fault, while supershear ruptures between similar or dissimilar solids are likely to produce off-fault damage on both sides of the fault with preferred tensile crack orientations. One or more of these features are not consistent with properties of natural samples of PFZR. At a distance of about 100 m from the fault, subshear and supershear ruptures without stress singularities produce strain rates up to 1 s⁻¹. This is less than required for rock pulverization in laboratory experiments with centimetre-scale intact rock samples, but may be sufficient for pulverizing larger samples with pre-existing damage.

Key words: Microstructures; Rheology and friction of fault zones; Dynamics and mechanics of faulting; Fractures and faults; High strain deformation zones; Mechanics, theory, and modelling.

1 INTRODUCTION
Pulverized fault zone rocks (PFZR) denote highly damaged fault rock products, primarily of crystalline and metamorphic origin, that were mechanically shattered to micrometre or finer scale, while preserving most of their original fabric and crystal boundaries with little evidence of shear strain (e.g. Brune 2001; Wilson et al. 2005; Dor et al. 2006). They have been observed in 100–200 m wide belts along sections of the San Andreas fault in California, the North Anatolian fault in Turkey and the Arima-Takatsuki tectonic line in Japan (Dor et al. 2006, 2008; Mitchell et al. 2011), and in somewhat narrower zones also along the Garlock and San Jacinto faults in California (Rockwell et al. 2009; Morton et al. 2012). Prominent belts of PFZR appear to be associated only with major faults that separate different crustal blocks, and are strongly asymmetric with respect to the fault trace, existing primarily on the side with faster seismic velocity at depth (e.g. Dor et al. 2006; Mitchell et al. 2011).

Doan & Gary (2009) performed split Hopkinson pressure bar (SHPB) experiments and found that producing in intact centimetre-scale crystalline rocks microstructures similar to those seen in natural pulverized rocks requires strain rates higher than 150 s⁻¹. Yuan et al. (2011) reported a strain rate of 250 s⁻¹ or higher for pulverizing centimetre-scale rocks in their SHPB experiments, and found that confining pressure could significantly suppress the transition of rock failure mode to pulverization. Doan & d’Hour (2012) and Aben et al. (2016) showed in later SHPB experiments that pre-existing rock damage can reduce significantly the strain rate required for pulverization (e.g. a 50 per cent reduction has been reported in these studies). Doan & d’Hour (2012) explained the higher susceptibility of pre-damaged rocks to pulverizations using key aspects of fracture mechanics, statistical distribution of rock properties and inertial effects during dynamic loadings (Denoual & Hild 2000; Hild et al. 2003).

Given the unusual properties of PFZR, they are assumed to provide a clear signature of dynamic earthquake ruptures (Rowe & Griffith 2015, and references therein). However, the rupture speed and other conditions associated with producing the observed prominent belts of PFZR are not yet clear. The spatial association of PFZR with large bimaterial faults, asymmetric distribution across the faults and signatures of tensile isotropic stresses, led to the suggestion that they are generated by repeating bimaterial ruptures with a preferred propagation direction (Ben-Zion & Shi 2005; Dor et al. 2006). On the other hand, the existence of pulverized rocks in 100–200 m wide zones and the experimental high strain rate...
for pulverization of small rock samples led to the suggestion that PFZR are produced by supershear ruptures (Doan & Gary 2009; Yuan et al. 2011).

In this paper, we analyse stress and strain fields generated by several types of dynamic ruptures to improve the theoretical constraints on dynamic pulverization of fault zone rocks. We consider basic features from Linear Elastic Fracture Mechanics (LEFM) and results generated by numerical simulations of dynamic ruptures. The theoretical results are examined in relation to the available field and laboratory observations, and expectations based on multiscale physics of repeating ruptures that occur on large faults. In the next section, we discuss the loading conditions that may produce natural PFZR, after a brief review on rock failure under quasi-static and dynamic loadings. We then examine how such loading conditions may exist during the passage of various types of dynamic ruptures. This is shown in Section 3 with basic expectations from LEFM and in Section 4 using more realistic results from numerical simulations with bounded stress and strain rate. The implications of the results for earthquake ruptures that may generate natural PFZR and suggestions for additional constraints from future laboratory experiments and dynamic rupture models are provided in the final section.

2 LOADING CONDITIONS AND FAILURE CRITERION

To evaluate the potential of earthquake ruptures to pulverize rocks, a failure criterion that captures the physics of the macroscopic loading and microscopic failure process is needed. The observed microstructures in PFZR are dominated by tension (e.g. Dor et al. 2006; Rockwell et al. 2009; Mitchell et al. 2011; Rempe et al. 2013), suggesting that local tensile stress field is involved in pulverizing the rocks. Below we briefly review relations between a local tensile stress field and applied macroscopic loading in a quasi-static or low-rate loading regime, and discuss related ideas in a dynamic or high-rate loading regime.

Experiments on rock failure under quasi-static loadings show that tensile failure can be produced, at least locally, under both macroscopic tensile and compressive loadings. The latter is less intuitive and involves internal flaws (microcracks, defects, pores, etc.) that can locally concentrate stress and induce tensile failure (Kranz 1983). Among many proposed mechanisms, the so-called wing-crack model has been widely used to study induced microscopic tensile cracks (Brace & Bombolakis 1963; Hori & Nemat-Nasser 1986; Ashby & Sammis 1990). In this model, tensile wing cracks can be induced at the tips of larger pre-existing cracks that slide under remotely applied compression. In such cases, the rock fails due to the growth, interaction and coalescence of many tensile cracks, with possible involvement of other types of cracks (Bobet & Einstein 1998).

One fundamental difference between tensile crack behaviour under macroscopic tension and macroscopic compression is that in the former the crack growth is unstable under constant remote loading, while in the latter tensile crack growth requires increases of the remote compression to ensure continuation. This can explain why rock strength (defined as the peak loading stress at failure) is usually lower under tension than under compression. The basic reason is associated with Mode-I stress intensity factor $K_I$ at the crack tip. Under remote tension $K_I$ increases as the tensile crack grows, whereas $K_I$ produced by a concentrated tensile loading near the origin of the mother crack decreases as the induced tensile crack grows (Ashby & Sammis 1990; Tada et al. 2000). It is also known that the failure mode can be significantly affected by the confining pressure (Jaeger et al. 2007), ranging from unstable localized splitting or shear banding under low confining pressure to stable distributed bulk deformation under high confinement.

The above results apply to rock failure under slow loading where macroscopic failure is usually dominated by a single or a few failure planes (except for high confining pressure). This is attributed to the fact that the growth of the weakest/longest flaws has higher probability of dominating the overall failure process (Paterson & Wong 2005). This also explains the well-known observation, dating back to Galileo that the strength of material generally decreases with increasing sample size, because larger samples have larger initial flaws. However, under fast loadings, numerous cracks can grow simultaneously and facilitate fragmentation and pulverization (e.g. Grady & Kipp 1987; Hild et al. 2003; Sammis & Ben-Zion 2008). The fragmentation model of Grady & Kipp (1987) is often used to explain the rock response under high loading rates where multiple flaws can be activated simultaneously by the supplied energy. Recent experiments with various types (compressive, tensile, or shear) of high-rate loadings indicate that rock strength generally increases with the applied loading rate, once it exceeds a certain threshold value (Zhang & Zhao 2014; Xia & Yao 2015). The large number of activated flaws under fast loading and the higher degree of internal stress concentrations explain why the resulting fragment sizes tend to be smaller and the apparent strength at failure tends to be higher.

The basic concept of rock fragmentation is typically discussed for tensile loadings (Grady & Kipp 1987), but multiple fragments and pulverization have also been observed with dynamic compressive loadings (Li et al. 2005; Doan & Gary 2009; Yuan et al. 2011). Under fast uniaxial compression, initial flaws that are stronger or less optimally oriented can be activated to induce tensile cracks. Effects associated with 3-D sample geometry and lateral boundary condition can also contribute to inducing tensile cracks (e.g. loading-induced radial compressive stress wave can reflect as tensile stress wave from the lateral free surface of a cylindrical sample, with a potential to produce radial and circumferential cracks in planes perpendicular to the loading direction). The rock sample fails when pervasive tensile cracks with diverse orientations interact and coalesce. We note that current uniaxial high-rate tension experiments only result in splitting rock fragments, rather than pulverized rock powder. Numerical simulations suggest that dynamically activated tensile cracks under rapid uniaxial tension show a preferred growth direction roughly perpendicular to the applied load (Cho et al. 2003), but have no preferred direction under an applied isotropic tension (Daphalapurkar et al. 2011).

Current dynamic experimental observations of pulverized rocks are available only under macroscopic compressive loading, but we focus below on regions where rocks are expected to experience dynamic tension. This is because rock pulverization should be easier under dynamic tension based on the following reasons. (1) Stress level under compressive loading is often limited by the plastic yielding strength, whereas under dynamic loading it is free from plastic yielding and mainly depends on the supplied energy (Sammis & Ben-Zion 2008). (2) Distributed local tensile loading is expected to drive growth of isotropic tensile cracks consistent with observations of PFZR (e.g. Rockwell et al. 2009; Mitchell et al. 2011). (3) Based on the available dynamic experimental data (Zhang & Zhao 2014; Xia & Yao 2015), tensile strength of rock (~10 MPa) is considerably lower than the compressive strength (~100 MPa). (4) We expect that experiments with multiaxial dynamic tensile loading or alternating principal tension directions will produce pulverized rocks without preferred crack orientation.
Having threshold values of stress and strain rate for pulverization can facilitate a quantitative analysis of pulverization. However, so far there are few direct experimental constraints for threshold values under dynamic tension. We therefore focus in Sections 3 and 4 on predictions of stress and strain rate at various locations using different dynamic rupture models. By comparing predicted features with field observations of pulverized rocks, we discuss in Section 5 how threshold values of stress and strain rate may be estimated by taking into account several factors.

3 PERSPECTIVES BASED ON LEFM

We start with theoretical results based on LEFM to discuss some basic properties of dynamic ruptures relevant to generation of pulverized rocks. In addition to basic results, we outline the assumptions and limitations of LEFM, such as steady state associated with a constant rupture speed, asymptotic rather than full stress expressions and small-scale yielding approximation (Freund 1990).

3.1 LEFM-based subshear rupture

The expression for the asymptotic stress field near a steady-state subshear crack tip (Freund 1990, chap. 4.3.3) has the form

$$\sigma_{ij} (r, \theta) = \frac{K^2_{II}}{2\pi r} \Sigma_{ij}^{II} (\theta, v_1, \alpha_P, \alpha_S)$$

where $K^2_{II}$ is the dynamic stress intensity factor, $r$ and $\theta$ are polar coordinates with respect to the crack tip, $\Sigma_{ij}^{II}$ characterizes the angular pattern of stress variations, $v_1$ is rupture speed, $\alpha_P = \sqrt{1 - (v_1/c_P)^2}$, $\alpha_S = \sqrt{1 - (v_1/c_S)^2}$ and $c_P$ and $c_S$ denote the $P$- and $S$-wave speeds, respectively. We typically assume $c_P = 6000 \text{ m s}^{-1}$, $c_S = 3464 \text{ m s}^{-1}$ and mass density $\rho = 2700 \text{ kg m}^{-3}$ unless mentioned otherwise. To illustrate classical features, we assume a subshear rupture propagating at a constant speed $v_1 = 0.97c_R$ with $c_R$ being the Rayleigh wave speed ($=0.919c_S$). A fracture energy density of $G_c = 6.25 \text{ MJ m}^{-2}$ (balanced by the energy release rate at the crack tip) is used to calculate the stress intensity factor (Freund 1990, chap. 5.3). We transform stress expressions from dependency on space to time, using $\partial/\partial t = (-v_1) \cdot \partial/\partial x$, and convert stress to strain. There are alternative ways to view the temporal evolution of deformation induced by a propagating rupture (e.g. Reches & Dewers 2005), but the one adopted here is sufficient for a first-order understanding.
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Figure 3. Results for a homogeneous subshear rupture propagating at \( v_r = 0.89 c_S (=0.97 c_R) \). (a) Map of rupture hypocentre and observation points (dashed line) of stress and strain. (b) Temporal evolutions of slip rate and on-fault normal stress change \( \Delta \sigma_n \) at the location indicated in (a). (c) Temporal evolutions of various stress components and the principal stress orientation at the locations indicated in (a). The principal stress orientation is evaluated hereafter by the inclination angle \( \Phi \) of the maximum compressive stress \( \sigma_1 \) relative to the fault following Xu et al. (2012). It is understood that if tensile cracks are about to be induced (e.g. when the minimum compressive stress \( \sigma_3 \) becomes tensile), they will be preferentially aligned parallel to \( \sigma_1 \) (Scholz 2002; Jaeger et al. 2007), unless \( \sigma_1 \) also becomes tensile and is comparable to \( \sigma_3 \) (i.e. isotropic tension).

in a homogeneous intact solid. In particular, a very high strain rate comparable to 100 s\(^{-1}\) is not likely to be produced at an off-fault distance of 100 m.

3.2 LEFM-based supershear rupture

The expression for the asymptotic stress field near a supershear crack tip (Freund 1990, chap. 4.3.4) has the following form

\[
\sigma_{ij} (\eta_1, \eta_2) \sim K_{II}^{\infty} \left[ \frac{\Sigma_{ij}^{\infty} (\theta_P, \nu, \alpha_P, \hat{\alpha}_S)}{r_p^\nu} - \frac{M_{ij}^{\infty} (\eta_1, \nu, \alpha_P, \hat{\alpha}_S)}{(\eta_1 - \hat{\alpha}_S \eta_2)\sqrt{\eta_1}} H (\eta_1 - \hat{\alpha}_S \eta_2) \right] \tag{2}
\]

where \( \eta_1 \) and \( \eta_2 \) are Cartesian coordinates with respect to the crack tip, \( r_p = \sqrt{\eta_1^2 + \alpha_P^2 \eta_2^2} \), \( \theta_P = \tan^{-1} (\frac{\alpha_P \eta_2}{\eta_1}) \) are scaled polar coordinates, \( K_{II}^{\infty} \) is the relevant stress intensity factor in the supershear regime, \( \Sigma_{ij}^{\infty} \) and \( M_{ij}^{\infty} \) are two functions that characterize the spatial patterns of stress variation near the leading supershear rupture front and the following Mach front, respectively, \( H() \) is the Heaviside function, \( \hat{\alpha}_S = \sqrt{(v_r/c_S)^2 - 1} \) and \( q = (1/\pi) \tan^{-1}[4\alpha_P \hat{\alpha}_S(1 - \hat{\alpha}_S)^2] \). We can in principle apply similar calculations as done in Section 3.1 to estimate representative strain and strain rate associated with the current supershear rupture. This involves overcoming a difficulty in determining the stress intensity factor in the supershear regime (Rosakis 2002). In particular, the relation between energy release rate and rupture speed in the full range of supershear regime can depend strongly on model assumptions (Fukuyama et al. 2016, and references therein). We therefore simply summarize some key features that distinguish supershear ruptures from subshear ones.
One feature of supershear ruptures is associated with the first term in the bracket of eq. (2). Since $0 < q \leq 1/2$, the off-fault decaying rates of both strain and strain rate are slower than those associated with a subshear rupture, except for the special case $q = 1/2$ when $v_s = \sqrt{2}c_s$. A second feature comes from the second term in the bracket of eq. (2). The variable $-\eta_2 - \gamma_2 |\gamma_2|$ in the denominator and in the Heaviside function, when becoming zero, defines a Mach front that represents coherent alignment of numerous $S$-wave fronts emitted from different locations. The stress field at and around the Mach front does not decay significantly with off-fault distance, at least up to a level comparable to the depth of the seismogenic zone (Dunham & Bhat 2008). Using a space–time transformation shows that the Heaviside function produces upon the arrival of the Mach front a stressing rate described by a delta-type function.

The two features mentioned above have been used to argue that supershear rupture provides a robust mechanism for producing off-fault rock damage (Bhat et al. 2007), and particularly pulverized rocks at distances up to several hundred metres from the fault (Doan & Gary 2009; Yuan et al. 2011). However, the following issues limit the application of these theoretical aspects of supershear ruptures to pulverized rocks. (1) Real materials can sustain only limited stressing rate, and the full history of deformation following a suddenly applied loading (or unloading) should be analysed rather than just the initial response (Freund 1990, chap. 3; Aben et al. 2016). (2) In realistic situations, energy dissipation on and off the fault, and effects caused by heterogeneities, can prevent the rupture speed from being precisely constant and can smear out the rupture and Mach fronts (e.g. Dunham 2007). (3) The weakly attenuated part along the Mach front (involving the second term in the bracket of eq. 2) only contains deviatoric deformation. The relation of this to possible rock pulverization characterized by pervasive microscopic tension is not clear. Moreover, if this term is responsible for pulverizing rocks at relatively large off-fault distances, the generic resulting distribution of pulverized rocks should be on both sides of the fault rather than primarily on one side. In the next section we present more realistic results on dynamic stress and strain fields based on numerical simulations of dynamic ruptures that do not have the singular features of LEFM.

### 4 Perspectives Based on Numerical Simulations of Dynamic Ruptures

To analyse further the ability of dynamic ruptures to generate pulverized rocks with the features observed in nature, we perform simulations of Mode-II dynamic ruptures on a fault governed by slip-weakening friction. We focus on conditions representative for the top few kilometres of large crustal strike-slip faults, such as background normal stress of $-50$ MPa (negative for compression) corresponding to a depth of 3 km under hydrostatic conditions (Table 1). This is consistent with field estimates of the likely depth range of PFZR (e.g. Dor et al. 2006). We conduct simulations for six different rupture scenarios (Table 2) and discuss general features of the dynamic stress and strain rate for each case.

The simulations employ the 2-D spectral element code SEM2D Pack (Ampuero 2002), with added capability of recording time evolution of strain at various locations obtained by interpolation from nearest nodes. The model setup shown in Fig. 2 represents a map view of a strike-slip fault. Rupture is nucleated by a time-weakening friction in a nucleation zone starting at the origin (yellow star) and expanding with a constant speed of 1000 m s$^{-1}$. When the nucleation zone reaches a size that allows spontaneous propagation, a linear slip-weakening friction controls the subsequent rupture on the fault. We keep the numerical model as simple as possible to focus on the most fundamental features around a propagating rupture front. Data recorded at points along lines normal to the fault 18 km from the hypocentre along the strike (dashed line in Fig. 2) are used to monitor the near-fault deformation during the passage of the rupture front. This distance represents a saturation effect of finite seismogenic depth, beyond which a 3-D propagating rupture is dominated by the Mode-II component and the associated stress intensity factor no longer increases with along-strike propagation distance (Day 1982).

#### 4.1 Subshear rupture in a homogeneous solid

We first show results for a frictional fault in a homogeneous solid using the parameters summarized in Tables 1 and 2. Due to the symmetry of this case, results are shown only for the right half. Fig. 3 displays the temporal evolutions of various on-fault (Fig. 3b) and off-fault quantities (Fig. 3c) recorded at $x = 18$k. The following features are evident at different off-fault locations. (1) Very close to the fault (e.g. $y = -5$m), the evolution of $\sigma_y$ still reflects an overall crack feature consistent with the assumed slip-weakening friction, while that of $\sigma_{xy}$ shows a single peak related to the particle velocity at the examined location. The latter can be explained by the space–time transformation between strain component $\varepsilon_{xy}$ and particle velocity component $u_x$ (Svetlizky & Fineberg 2014). (2) At larger off-fault distances, the evolution of $\sigma_{xy}$ can include a pseudo-pulse indicated by an apparent overshoot below the final residual level (e.g. at $y = -37.5$m), while that of $\sigma_{xy}$ can display double peaks separated by a local trough (e.g. at $y = -400$m). These features have been reported in other laboratory and numerical studies of dynamic ruptures (Svetlizky & Fineberg 2014; Svetlizky et al. 2016).

The examined strain rate (hereafter estimated by $\dot{\varepsilon}_{xy}/\mu$, where $\mu$ is the rigidity of the material below the fault) is overall low,
reaching 0.16 s⁻¹ at y = −5 m and rapidly decreasing to the order of 10⁻³ s⁻¹ at y = −400 m. These values are generally consistent with the earlier theoretical estimates in Fig. 1(b) assuming similar fracture energy density and rupture speed. For the current homogeneous subshear case, σₓ, can remain above 20 MPa in absolute tension at and behind the rupture front propagating in the passage of the rupture. This is a larger magnitude change than a complete relaxation of the background stress at shallow depth used to assess aspects of rock failure (Rockwell et al. 2015). The total tensile stress or stress change is dominated by σₓ, due to a large fault-parallel strain εₓ, promoted by the Lorentz contraction (e.g. Rice 1980). This indicates a preference for high-angle tensile cracks on the extensional side of a fault in a homogeneous solid (fifth panel of Fig. 3c). Such tensile cracks were observed in laboratory experiments with subshear ruptures (Griffith et al. 2009; Ngo et al. 2012), as well as along natural faults inferred to sustain subshear ruptures (Di Toro et al. 2005).

4.2 Supershear rupture in a homogeneous solid

The rate of occurrence and generation mechanisms of supershear ruptures are still debatable, and it is not fully clear if supershear ruptures in laboratory experiments or numerical simulations are similar to those occurring in nature (e.g. Dunham 2007; Sammis et al. 2009; Passelegue et al. 2013; Fineberg & Buchbinder 2015). In particular, recent numerical (Bruhat et al. 2016) and experimental (Xu et al. 2015b) studies reported supershear ruptures under heterogeneous conditions, revising the traditional view that supershear generation requires relatively homogeneous conditions and simple fault geometries (e.g. Bouchon et al. 2010). Given our focus on generation of prominent belts of PFZR, we simulate in this section prominent long-lived supershear rupture. We distinguish between two fundamental supershear rupture modes that differ significantly around the trailing Rayleigh front (Festa & Vilotte 2006). One mode involves a direct transition (Geubelle & Kubair 2001; Liu & Lapusta 2008; Lu et al. 2009) and the other is associated with a mother–daughter mechanism (Burridge 1973; Andrews 1976; Abraham & Gao 2000; Dunham 2007). For simplicity, we generate the two modes of supershear ruptures by tuning the seismic S parameter (e.g. Andrews 1976; Das & Aki 1977; Lu et al. 2009; Liu et al. 2014). In practice, this is realized by adjusting the initial shear stress on the fault (Table 2), while keeping all other parameters unchanged.

Fig. 4 shows the temporal evolutions of on-fault (Fig. 4b) and off-fault quantities (Fig. 4c) during the passage of a supershear rupture with a direct transition mechanism. As before there are progressive differences in stress quantities with increasing off-fault distance. Very close to the fault (e.g. y = −5 m), σₓ, is almost a constant around the arrival of the trailing Rayleigh phase at ∼ 6.25 s (as it must reflect the on-fault source behaviour constrained by the slip-weakening friction), while σₓ shows a single peak near the leading supershear rupture front that is well correlated with the slip rate function (Fig. 4b) projected on the extensional side. At a larger off-fault distance (e.g. y = −400 m), σₓ displays a clear disturbance around the arrival of the trailing Rayleigh phase (as it must reflect the Rayleigh phase when recorded not close to the fault plane y = 0), while σₓ shows a clear separation of the following Mach front from the leading supershear rupture front. The relative changes in σₓ and σᵧ at the Mach front have opposite polarities (fourth panel of Fig. 4c), consistent with the theoretical expectation in Section 3.2 that the Mach front only contains deviatoric deformation.

The magnitudes of both stress and strain rate associated with the simulated supershear rupture (Fig. 4) are larger overall than those simulated for the subshear case (Fig. 3), while being bounded within a physical range. The off-fault decaying rates of stress and strain rate associated with the supershear rupture are also significantly slower, in agreement with the theoretical expectation (Section 3.2) for supershear ruptures (we note that vᵢ = 1.69cₛ > √2cₛ so the exponent q in eq. (2) is less than 1/2). The contribution to stress and strain rate from the trailing Rayleigh phase is small compared to that from the leading supershear rupture front and the following Mach front. The total tensile stress or stress change is still dominated by σₓ, both at the supershear rupture front and at the Mach front (see also Bhat et al. 2007, Fig. 3). Therefore, induced tensile cracks are likely to be oriented at high angles on the extensional side of the fault (fifth panel of Fig. 4c), as was observed in laboratory experiments with supershear ruptures (Rosakis 2002; Samudrala et al. 2002).

Fig. 5 shows deformation features during the passage of a supershear rupture involving a mother–daughter transition mechanism. Such rupture mode has been reported in laboratory experiments with Homalite-100 (Xia et al. 2004), PMMA (Svetlizky et al. 2016) and rock samples (Xu et al. 2015b). Previous studies focusing on near-fault ground motion characteristics suggest that this type of rupture can be considered as a compound mode (Mello et al. 2010, 2016), with a leading supershear rupture front (as in Fig. 4) followed by a strong trailing phase that resembles a subshear rupture front (as in Fig. 3). The latter is supported by the stress characteristics between the strong trailing phase in Fig. 5(c) (around 6.5 s) and the pure subshear rupture front in Fig. 3(c) (around 8.3 s), particularly for the decay of stress and strain rate with off-fault distance. Therefore, one can use the previous discussions of features in Figs 3 and 4 to understand the basic results of Fig. 5. In the simulated compound-mode rupture, the sequential passage of the supershear rupture front followed by the Mach front and the trailing subshear front can provide successive high-rate loadings during a single supershear event. This somewhat complicates the evaluation of mechanisms generating off-fault rock damage.

4.3 Subshear rupture on a bimaterial interface

Ben-Zion & Shi (2005) suggested that the generation mechanism of PFZR is associated with bimaterial ruptures. To analyse this, we use a configuration with 20 per cent contrast of P- and S-wave speeds and mass density across the fault. The bottom side of the fault is assumed to be stiffer (faster seismic velocities) with the same properties as in the homogeneous case (Fig. 2 and Table 1). The generalized Rayleigh wave (cᵣ₈₉ = 0.825cₘ₈₉) exists for the assumed contrast of properties (e.g. Weertman 1980; Ben-Zion 2001). A normal stress regularization with a characteristic timescale of tᵣ = 4 × 10⁻³ s (about 10 times of the time step) that delays the normal stress response (equivalent to eq. (6) of Ampuero & Ben-Zion 2008) is used to ensure the stability of bimaterial rupture simulations. The rupture-induced stress characteristics are expected to be a superposition of features in a homogeneous solid and features associated with dynamic coupling between slip and changes of normal stress σᵣ, unique to the bimaterial configuration. The dynamic change of σᵣ is tensile at and behind the rupture front propagating in
Figure 4. Results for a homogeneous supershear rupture propagating after a direct transition mechanism at $v_r = 1.69c_S$. (a) Map of rupture hypocentre and observation points (dashed line) of stress and strain. (b) Temporal evolutions of slip rate and on-fault normal stress change $\Delta \sigma_n$ at the location indicated in (a). (c) Temporal evolutions of various stress components and the principal stress orientation at the locations indicated in (a).

The direction of slip on the compliant side of the fault (referred to as the positive direction), and compressive in the opposite (negative) direction (e.g. Weertman 1980; Andrews & Ben-Zion 1997; Shi & Ben-Zion 2006).

The along-strike asymmetry of the dynamic changes of $\sigma_n$ modifies considerably the off-fault stress field in the opposite rupture directions (Fig. 6). In the positive direction, $\sigma_{yy}$ has a prominent tensile change with much larger amplitude (Fig. 6c, after 8 s) than for a subshear rupture between similar solids (Fig. 3c, around 8.3 s). The dynamic variations of $\sigma_{yy}$ produce a transient state of absolute tension at least up to an off-fault distance of 100 m. At locations close to the fault (e.g. $y = -37.5$ m), the change of $\sigma_{xx}$ is much smaller than that of $\sigma_{yy}$ (this can be explained by the ratio of two elastic moduli related to the bimaterial problem, see Rubin & Am- punching 2007, section 3.2.2), but the difference between the two is much smaller than that generated by subshear rupture in a homogeneous solid (e.g. second panel in Fig. 3c). For $y = -100$ m, the peak amplitude and rate of change of $\sigma_{xx}$ and $\sigma_{yy}$ become comparable during the passage of the bimaterial subshear rupture front, suggesting a possibility of simultaneous activation of both low-angle and high-angle tensile cracks. A closer view reveals that around the peak values (dashed ellipse), $\sigma_{yy}$ has a rapid decrease followed by a rapid increase, while $\sigma_{xx}$ has a rapid increase followed by a rapid decrease. These dynamic variations suggest that the time-averaged effect could approach conditions of ‘isotropic tension’, due to an overprinting of a wide range of principal stress orientations (e.g. see the yellow dots in the fourth panel of Fig. 6c), although at each particular time the transient stress state is different from isotropic tension. Regardless of this interpretation, the transient stress field in the positive direction has a high potential for inducing tensile cracks with diverse orientations that may approach a near isotropic pattern.

In the negative direction, the stress changes have lower amplitudes than in the positive direction, due to slower rupture speed caused by the compressive normal stress change on the fault (Fig. 6e). The dynamic tensile stress is dominated by $\sigma_{xx}$ in all examined locations (Fig. 6f). Based on these results, we expect less off-fault damage in the negative direction dominated by high-angle tensile cracks.
4.4 Supershear rupture on a bimaterial interface

Similar to the cases in a homogeneous solid (Section 4.2), we distinguish between two basic bimaterial supershear ruptures, based on the transition mechanism in the positive direction. The polarity of normal stress change $\sigma_n$ on a bimaterial fault and the preferred rupture direction are reversed in the supershear regime, compared to those in the subshear regime (e.g. Weertman 2002; Shi & Ben-Zion 2006; Shlomai & Fineberg 2016). These reversed on-fault features are expected to influence the off-fault stress behaviour in the opposite rupture directions.

Fig. 7 summarizes results of various on-fault and off-fault quantities for a bimaterial supershear rupture associated with a direct transition in the positive direction. A comparison between the two rupture directions reveals that the magnitudes of both stress and strain rate are much higher in the negative direction than in the positive one. This is because of the prominent tensile change of $\sigma_n$ and faster rupture speed in the negative direction (compare Fig. 7e with Fig. 7b). Focusing on the negative direction, there is a sharp tensile change in $\sigma_{yy}$ (Fig. 7f) that can potentially drive some off-fault region into a transient state of absolute tension. However, the overall tension is still dominated by the fault-parallel component, which shows extremely large magnitudes in stress and strain rate that only weakly decay with off-fault distance (note that $v_r = 1.72c_{slow} \approx c_{slow}$ in the negative direction, so the exponent $q$ in eq. (2) is close to zero when applied to the compliant side of the fault). These results suggest extensive off-fault rock damage on the compliant side of the fault, with induced tensile cracks preferentially inclined at high angles to the fault. In the positive direction, the total tensile stress or stress change is also dominated by $\sigma_{xx}$ (Fig. 7c). The results suggest relatively narrow damage mainly on the stiff side of the fault dominated again by high-angle tensile cracks.

Fig. 8 presents corresponding results for a bimaterial supershear rupture associated with a mother–daughter transition mechanism in the positive direction. Similar to the analysis made for the homogeneous solid (Section 4.2), the rupture in the positive direction can be considered as a combination (Figs 8a–c) of a leading supershear...
Figure 6. Results for a bimaterial subshear rupture propagating (a)–(c) at $v_r = 0.82c_{GR}^{\text{fast}} (=0.99c_{GR})$ in the positive direction, and (d)–(f) at $v_r = 0.79c_{GR}^{\text{fast}} (=0.96c_{GR})$ in the negative direction.

front followed by a strong subshear front (with a speed approaching $c_{GR}$). Near the leading supershear front (Fig. 8c, around 5.0 s), the total tensile stress or stress change is dominated by $\sigma_{xx}$, favouring induced tensile cracks on the stiff side inclined at high angles to the fault. Near the trailing subshear front (Fig. 8c, around 6.9 s), a transient stress state with alternating principal directions exists (similar to Fig. 6c, between 8.0 and 8.1 s), which can induce tensile cracks (on the stiff side) without a preferred orientation. In the negative
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Figure 7. Results for a bimaterial supershear rupture propagating (a)–(c) at $v_r = 1.66c_{Ps}^{fast}$ in the positive direction after a direct transition mechanism, and (d)–(f) at $v_r = 1.72c_{P}^{slow} (\approx c_{P}^{low})$ in the negative direction after a direct transition mechanism.

Direction (Figs 8d–f), rupture is characterized by a supershear mode involving a direct transition mechanism, similar to that in Figs 7(d–f). The total tensile stress or stress change is dominated by $\sigma_{xx}$ that decays slowly with off-fault distance (also due to a rupture speed close to the $P$-wave speed of the compliant side). This is expected to produce extensive off-fault tensile cracks (on the compliant side) that are preferentially inclined at high angles to the fault.

5 DISCUSSION AND CONCLUSIONS

The numerical results shown in Figs 3–8 indicate that high strain rates of the order of 150 s$^{-1}$ cannot be directly produced by any type of realistic ruptures (at least for the cases considered in this study) at a distance of 100 m from the fault, assuming the off-fault region is a solid. This leads to a discrepancy with the strain-rate threshold (150 s$^{-1}$ or higher) necessary for pulverizing intact centimetre-scale
Figure 8. Results for a bimaterial supershear rupture propagating (a)–(c) at $v_r = 1.59c_{fast}$ in the positive direction after a mother–daughter transition mechanism, and (d)–(f) at $v_r \approx c_{slow}$ in the negative direction after a direct transition mechanism.

rocks based on SHPB experiments (Doan & Gary 2009; Yuan et al. 2011). However, natural PFZR have been subjected to numerous episodes of fault activity and more realism is needed to clarify the mechanisms producing belts of PFZR that are hundreds of metres wide. Obvious possible solutions are reduction of the strain rate required for pulverization of pre-damaged material, as observed by Doan & d’Hour (2012) and Aben et al. (2016), and generation of PFZR by multiple successive ruptures rather than a single event.

Doan & d’Hour (2012, eq. 20) provided a formula quantifying the inverse relation between loading rate threshold and the initial rock damage density. Aben et al. (2016) proposed a schematic model for a progressive widening of the off-fault pulverization zone
by successive repeating earthquakes. Ben-Zion & Andrews (1998) noted that the higher mechanical efficiency of bimaterial ruptures may lead to migration of ruptures to the edge of the damage zone, generation of additional damage and widening of the damage zone. This is supported by numerical simulation results that ruptures tend to migrate to bimaterial interfaces (Brietzke & Ben-Zion 2006) and field observations that earthquakes tend to localize at the edge of well-developed cataclase and damage zones (e.g. Sibson 2003; Dor et al. 2008; Di Toro et al. 2009). Generation of wide damage zone by single events requires high initial shear stress along the fault, leading not only to supershear rupture but also to significant damage-related isotropic radiation (Ben-Zion & Ampuero 2009). Such events are possible but not very likely. Generating wide damage zone by single events may also require high dynamic strength along the fault. However, this would lead to significant frictional heat, not observed along the San Andreas and other large strike-slip faults, and a rather uniform crack orientation inside the damage zone (Rice et al. 2005). It is possible to generate considerable damage at particular locations, such as near abrupt terminations of ruptures (e.g. Madariaga 1983; Rousseau & Rosakis 2003; Xu & Ben-Zion 2013), but this would not produce belts of pulverized rocks of the type observed.

Limited successive high-rate loadings may be realized during single events, as illustrated by the supershear mode with a mother–daughter transition mechanism (Figs 5 and 8a–c). Such rupture mode was inferred to have occurred during the 2002 Denali earthquake (Dunham & Archuleta 2004) and was observed in laboratory experiments (Mello et al. 2014). Limited successive high-rate loadings may also be realized by wave reflections within the fault zone (e.g. Ben-Zion & Huang 2002; Huang et al. 2014), rupture and wave reflections from the free surface on a dip-slip fault (Ide et al. 2011; Gabuchian et al. 2014), and more complex constitutive laws such as double-slip-weakening friction (Galvez et al. 2016) and rate- and state-dependent friction (Coker et al. 2005; Shi et al. 2008). It will be useful to have additional laboratory estimates of strain-rate threshold required for pulverization under successive loadings during single and multiple events.

Apart from successive loadings, we also expect lower strain-rate threshold for rock failure under tensile loading, rather than compressive of the type used in the SHPB experiments. Experimental rock pulverization may be realized by dynamic multiaxial tensile loadings (in particular of pre-damaged rock samples). Multiaxial tension can also produce a more isotropic failure pattern that matches better the microstructure typically seen in natural pulverized rocks. The mud cracks discussed in Sammis & Ben-Zion (2008) provide an example of near isotropic failure pattern under quasi-static multiaxial tension. Related numerical results under dynamic multiaxial tension can be found in Dapalapurkar et al. (2011). As noted by Sammis & Ben-Zion (2008), tensile cracks generated by macroscopic compressive or shear loading tend to have a preferred orientation to the fault, not consistent with properties of natural PFZR (e.g. Rockwell et al. 2009; Mitchell et al. 2011).

As mentioned in Section 2, rock strength in the quasi-static loading regime generally decreases as the rock sample size increases, due to the intrinsic heterogeneous properties of rocks (Scholz 2002). We expect a similar relation between rock strength and rock sample size for high-rate loadings. The mentioned scaling relation of Doan & d’Hour (2012, eq. 20) connecting loading rate threshold with initial damage density also includes a contributing factor involving the rock volume. This suggests that a larger rock sample is more likely to be fragmented than a smaller one for a given loading rate. The scale dependence of strain-rate threshold for fragmentation limits the application of laboratory results to natural fault zone rocks. It is not clear how to extrapolate the strain-rate threshold obtained from the centimetre-scale samples in the SHPB experiments (Doan & Gary 2009; Yuan et al. 2011) to natural fault zone rocks at larger scales. Such scaling should account also for other differences (loading style, boundary conditions, initial damage density, strength distribution, etc.) between the laboratory experiments and natural faults. From a theoretical point of view, it is important to consider in future studies more realistic models of brittle rock damage such as those used by Dapalapurkar et al. (2011), Bhat et al. (2012), Xu et al. (2015a) and Lyakhovsky et al. (2016). Clearly, stress concentration and high strain rate can exist locally near a propagating crack front, but the integrated quantities over a volume should remain relatively low. Dynamic ruptures in models accounting for brittle damage can provide better constraints on rupture-induced loadings and threshold values for rock pulverization.

Fig. 9 illustrates schematically the ingredients needed to generate PFZR with properties similar to those observed in the field. The numerical results shown in Figs 3–5 indicate that standard ruptures between similar solids (Fig. 9a) tend to produce a transient tensile stress field dominated by the fault-parallel component. This standard model is expected to produce tensile cracks on both sides of the fault (though only one side is illustrated), preferentially inclined at high angles to the fault. These two features are generally inconsistent with field observations of pulverized rocks, which are primarily distributed on one side of the fault and are characterized by near isotropic damage microstructures. Bimaterial ruptures between dissimilar solids (Fig. 9b) are expected to produce strongly asymmetric damage across the fault (Ben-Zion & Shi 2005; Xu et al. 2012). This is related to the tendency of bimaterial ruptures to have a statistically preferred propagation direction (e.g. Ben-Zion & Andrews 1998; Ampuero & Ben-Zion 2008; Brietzke et al. 2009; Erickson & Day 2016; Shlomai & Fineberg 2016). The numerical results shown in Figs 6–8 indicate that subshear bimaterial ruptures propagating in the positive direction can greatly enhance tension along fault-perpendicular direction, in addition to that along fault-parallel direction. This can lead to a transient stress field that can be described approximately as time-averaged isotropic tension. Repeating bimaterial ruptures can produce prominent asymmetric off-fault damage (primarily on the stiff side at depth) consisting statistically of randomly oriented tensile cracks. Generating relatively wide zones of PFZR consistent with observations is facilitated by pre-existing flaws, which can become activated, grow, or even develop their own branches under the dynamic loading of the main rupture (zoom-in view in Fig. 9b). Due to the activation and propagation of many flaws and their branches, locally high stress or high strain rate can extend to off-fault distances well beyond the original boundary controlled by the main rupture.

We finally summarize some limitations of the approach used in this study. In addition to not simulating off-fault damage (e.g. using a brittle damage rheology) and other model simplifications, we considered a limited range of model parameters. A more detailed understanding can be achieved by considering a fully permissible range of model parameters (Rice et al. 2005; Griffith & Prakash 2015) and performing 3-D dynamic rupture simulations (e.g. Ma & Andrews 2010). We mainly focused on the extensional quadrants to examine properties of likely induced tensile cracks. However, tensile cracking can also occur in the compressional quadrants, as reported during the 2001 Kunlunshan earthquake that was inferred to be a supershear event (Bhat et al. 2007). We also did not consider the possibility of tensile cracking due to the unloading of earlier applied compressive stress even without reaching a state of absolute tension (Nemat-Nasser 1997). The combined effects
of compressive and tensile loadings, including the phenomena produced by the SHPB experiments and rock spalling (Cho et al. 2003), can contribute to pulverization. Additional effects not considered in our analysis include the competition between shear and tensile failures (Rice et al. 2005; Rempe et al. 2013) and the transitions between coseismic generation of rock damage and interseismic healing (Richard et al. 2015; Lyakhovsky et al. 2016). These factors should be examined in future studies aiming to improve the understanding of the conditions associated with generation of PFZR.

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