Earthquakes as dynamic fracture phenomena

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September 14, 2022

Abstract

A large earthquake unlocks a fault-zone via dynamic rupture while releasing part of the elastic energy stored during the interseismic stage. As earthquakes occur at depth, the analyses of earthquake physics rely primarily on experimental observations and conceptual models. A common view is that the earthquake instability is necessarily related to the frictional weakening that is commonly observed in shear experiments under seismic slip velocities. However, recent experiments with frictional interfaces in brittle acrylics and rocks have explicitly demonstrated that no characteristic frictional strength exists; a wide range of stresses ('overstresses') are sustained prior to rupture nucleation. Moreover, the experimentally observed singular stress-fields and rupture dynamics are *precisely* those predicted by fracture mechanics. We therefore argue here that earthquake dynamics are best understood in terms of dynamic fracture mechanics: rupture dynamics are driven by overstresses, but not directly related to the fault frictional properties.

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Commentary by

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ABSTRACT

A large earthquake unlocks a fault-zone via dynamic rupture while releasing part of the elastic energy stored during the interseismic stage. As earthquakes occur at depth, the analyses of earthquake physics rely primarily on experimental observations and conceptual models. A common view is that the earthquake instability is necessarily related to the frictional weakening that is commonly observed in shear experiments under seismic slip velocities. However, recent experiments with frictional interfaces in brittle acrylics (Svetlizky & Fineberg, 2014) and rocks (e.g., Passelegue et al., 2020) have explicitly demonstrated that no characteristic frictional strength exists; a wide range of stresses ('overstresses') are sustained prior to rupture nucleation. Moreover, the experimentally observed singular stress-fields and rupture dynamics are *precisely* those predicted by fracture mechanics (Freund, 1998). We therefore argue here that earthquake dynamics are best understood in terms of dynamic fracture mechanics: rupture dynamics are driven by overstresses, but not directly related to the fault frictional properties.

PLAIN-LANGUAGE SUMMARY

A large earthquake occurs when a "locked" fault becomes unlocked and starts slipping rapidly while releasing stored elastic energy. As earthquakes occur at depth, earthquake analyses rely primarily on experimental observations and conceptual models. One common view attributes the earthquake instability to the transition from the strong 'static friction' to the weaker 'dynamic friction'. Recent observations of experimental earthquakes along brittle faults cause us to challenge this common view. These experiments have explicitly demonstrated that faults may stay locked under a wide range of stress levels making the assumption of a characteristic 'static friction' irrelevant. Moreover, the features of these earthquakes fit *precisely* the predictions of fracture mechanics theory (Freund, 1998), by taking these stress differences into account. We therefore argue here that earthquake dynamics is best understood in terms of dynamic fracture mechanics, a process not directly related to the fault frictional properties.

INTRODUCTION

A large earthquake is preceded by an interseismic period during which the fault-zone stays "locked", and elastic energy is "stored" in the crustal rocks. The earthquake will unlock the fault-zone via dynamic rupture of the fault while releasing part of the stored elastic energy. Earthquake physics analyses rely primarily on experimental observations and conceptual models, because we have ". . . . .near zero direct constraints on the dynamic processes . . . associated with . . . earthquake ruptures" (Ben-Zion, 2019). In this commentary, we examine the rupture character of earthquakes in light of recent experimental observations; we start by inspecting the earthquake process in the framework of dynamic fracturing.

Figure 1 displays three idealized cases of dynamic fracturing: tensile fracturing (mode I), shear fracturing without friction (mode II), and shear fracturing along a frictional fault, that is an idealized earthquake rupture. The processes of tensile and shear fracturing (modes I and II) have been under detailed investigation since (Griffith, 1920) and are well understood by the theory of 'fracture mechanics' (Freund, 1998). This theory indicates that both tensile and shear fractures will propagate when the rate of elastic energy flow towards the tip of a rapidly moving fracture surpasses the rate of local energy dissipation required for creating the new fracture surfaces (Freund, 1998; Svetlizky et al., 2017). In modes I and II, resulting fractured surfaces (white slits in Fig. 1a, b) are stress-free, and thus, the only site where energy is dissipated is within the fracture tip zone (yellow zone in Fig. 1a, b). Fracture mechanics theory provides analytical solutions of the stress-field around the fracture as a function of the available energy and propagation velocity. The predicted stress-field indicates a distinct stress singularity at the tip, and a stress-free zone in the wake of the tip (dark blue zone of $\sigma = 0$ in Fig. 1d).

As anticipated, the situation becomes more complicated for a shear fracture in which both sides of the fracture surfaces remain in frictional contact (Fig. 1c). This configuration is the relevant one for an earthquake rupturing a frictional fault. Theoretical work (Barras et al., 2020; Palmer & Rice, 1973) has suggested that even this case can, in general, be described by the same fracture mechanical framework as the pure mode II case (Fig. 1b).

RUPTURING ALONG EXPERIMENTAL FRICTIONAL FAULTS

Recent experimental analyses use advanced high-speed techniques to monitor dynamic ruptures along experimental faults (Svetlizky & Fineberg, 2014; Wu & McLaskey, 2019; Xu et al., 2019; Passelegue et al., 2020; Chen et al., 2021). These analyses revealed three fundamental characteristics of shear rupturing along frictional faults with significant implications for earthquake physics.

1. **Stresses and control of dynamic rupturing** . It was demonstrated (Svetlizky & Fineberg, 2014) that propagating ruptures along a fault can be *precisely* described by fracture mechanics theory (Freund, 1998). Fig. 2 displays the results for an experimental fault (Fig. 2a) that was subjected to shear and normal loads where ruptures were monitored by high-speed photography and strain-gages. In a series of nine experiments, the fault was overstressed prior to rupture initiation over a range of shear stresses that exceeded the minimal stress for frictional sliding (about 1MPa) by 0.1-0.4 MPa (the normal load was identical in all experiments) (Fig. 2b). Once slip nucleated, spontaneous ruptures propagated at velocities that were governed by the pre-slip overstress (Fig. 2c). The lowest overstress triggered relatively slow ruptures, while the highest values gave rise to rapidly accelerating ruptures that approached the limiting Raleigh wave speed, C_R. (Svetlizky et al., 2017) used the measured elastic energy to show that all the propagation velocities and accelerations in these experiments *perfectly* fit the fracture mechanics predictions (black curve in Fig. 2d). Most importantly, this perfect fit does not include any consideration of the fault's frictional properties. These experimental observations are in agreement with fracture mechanics formulations which indicated that fault friction does not affect

the rupture characteristics (Barras et al., 2020; Palmer & Rice, 1973). This quantitative agreement with fracture mechanics theory, which was documented in both brittle acrylics (Svetlizky & Fineberg, 2014; Bayart et al., 2016; Svetlizky et al., 2017) and rocks (Wu & McLaskey, 2019; Xu et al., 2019; Passelegue et al., 2020), requires a modification of the predicted stress-field: the stress in the frictional zone equals the residual frictional strength of the fault, τ_R, (grey area of $\sigma = \tau_R$, Fig. 1e).

2. **Energy balance of dynamic rupturing** . The section above indicates that the elastic energy dissipation can be separated into two, quasi-independent entities (Fig. 1): (A) Localized dissipation (fracture energy) at the near-singular tip zone of a shear fracture (yellow zone, Fig. 1c), and (B) distributed energy dissipation by frictional resistance of the sliding surfaces in the wake of the rupture-front (red fault-zone, Fig. 1c). The rupture front may propagate at velocities of a few km/s (Fig. 2c) while generating extreme stresses, strain-rates and slip velocities, in the immediate vicinity of rupture tip (Svetlizky & Fineberg, 2014). The near-tip, cohesive zone of a typical earthquake dissipates only ~5-6% of the earthquake energy (Kanamori & Brodsky, 2004), but the extreme stresses developed there are expected to "breakdown" the fault-zone by fragmentation and pulverization (Reches & Dewers, 2005; Wilson et al., 2005). The trailing frictional zone, which does not constrain the rupture front, is thought to dissipate 70-90% of the earthquake energy. The above observations and associated discussion raise a central question: What are the effects of *friction* on the earthquake process?
3. **Fault frictional properties and the earthquake process** . A common view is that earthquake instability is controlled by frictional weakening manifested by the drop from static to dynamic friction (Di Toro et al., 2011; Dieterich, 1979). This view is used in earthquake simulations with velocity weakening (Lapusta & Rice, 2003; Madariaga et al., 1998) assuming experimentally derived friction laws, e.g., rate-and-state friction (Dieterich, 1979). Frictional weakening is indeed observed in multiple experiments: a rock's frictional strength may decrease with increasing slip-velocity and/or slip-displacement. Strengths drop particularly rapidly under seismic slip velocities of a few m/s (Di Toro et al., 2011; Hirose & Shimamoto, 2005). We argue that the utilization of frictional weakening as the controlling mechanism of earthquake dynamics may lead to a few central contradictions. Sections I and II above indicate that the dynamic nature (e.g., stored energy, stress field, or propagation velocity) of a rupture along experimental faults can be fully understood in terms of fracture mechanics formulation without consideration of the fault's frictional properties. The only requirement for earthquake rupture propagation is the ability of a frictional system to develop and sustain sufficient stored elastic energy, or 'overstress', prior to rupture nucleation (e.g. Fig. 2b). This has been amply demonstrated (Ben-David et al., 2010; Ben-David & Fineberg, 2011; Passelegue et al., 2020) in experiments: for a given normal stress, an experimental fault can sustain a large range of applied shear stresses. Therefore, the concept of a characteristic static-friction that governs the onset of instability is misleading (Ben-David & Fineberg, 2011), and a fault system can store varying amounts of elastic energy above limits imposed by friction-based models; mechanisms of overstress are discussed later. It is certainly possible to incorporate frictional weakening in rupture dynamics simulations that correspond to fracture mechanics formulations (Lapusta & Rice, 2003; Madariaga et al., 1998). However, the required dependence on a 'friction law' and associated weakening is *not necessary* , and, in fact, could impose unnecessary restrictions. For example, the friction-based idea that an earthquake cannot propagate under velocity *strengthening* is inaccurate, because an earthquake can propagate if the fault system is sufficiently overstressed. For instance, the mineral talc dominates the composition of active fault-zones, e.g., the central San Andreas fault (Moore, D. & Rymer, M., 2007) and mining–induced faults. Yet, even though talc is documented as frictional-strengthening mineral for both dynamic velocity and displacement (Chen et al., 2017), earthquakes do occur along these zones.

DISCUSSION

We propose here that earthquakes should be described as dynamic ruptures controlled by fracture mechanics processes that are unrelated to the friction even though fault frictional properties do dominate the energy dissipation processes. We refer to this concept as Fracture Earthquake Rupture Mechanics, FERM. Beyond the experimental observations, the proposed view can resolve a few paradoxical features of earthquake processes.

Overshoot is a rupture state that can inherently be explained by the FERM concept. Dynamic overshoot refers to the case of "...shear stress reduction below dynamic friction" (Ide et al., 2011), and according to common friction laws, an earthquake should be arrested in such a case. A field example of overshoot is the Mw2.2 earthquake at 3.6 km depth in Tautona mine, South Africa. The in-situ mapping at the focal depth revealed a rupture-zone of 3 to 4 non-parallel slip-surfaces (Heesakkers et al., 2011), and the associated in-situ stress measurements (Lucier et al., 2009) revealed that the [shear stress/normal stress] ratio on these slip-surfaces ranges 0.05-0.13. These measured stress ratios are significantly lower than the dynamic friction, and according to FERM, this earthquake was facilitated solely by the of potential elastic energy generated by mine operations regardless of the resolved shear stresses and fault-zone strength. Overshoot has also been experimentally documented (Bayart et al., 2016) where rupture propagation was shown to continue at stress levels well below measured values of τ_R.

Overstress. In FERM, the development of a dynamic rupture only requires a measure of overstress, namely, mean stress levels that exceed those necessary to overcome τ_R . Overstress can be achieved by a strong barrier (Gvirtzman & Fineberg, 2021), fault-zone healing (Heesakkers et al., 2011; Muhuri et al., 2003) ahead of an arrested rupture (Ben-David et al., 2010; Passelegue et al., 2020) or due to fault heterogeneities, whose strength may approach the theoretical rock strength (Savage et al., 1996).

The stored elastic energy due to the overstress drives dynamic rupture and controls the rupture velocity, style and energy dissipation after the rupture nucleation (Fig. 2) (Svetlizky et al., 2017; Svetlizky & Fineberg, 2014). The timing and location of rupture nucleation are governed by local failure in regions of high local stress and/or low local strength.

Complex fault system. A single seismic event may be complex e.g. 2016 Mw 7.8 Kaikōura earthquake (Ulrich et al., 2019)

In conclusion, we believe that rupture fronts efficiently (~5% of the total energy) control earthquake dynamics by unlocking a fault, generating the requisite breakdown stress-drop, and damaging the rock-blocks. An earthquake's size and speed is controlled by the magnitude of the elastic energy available relative to the interface strength (fracture energy), while the overall dissipation is primarily due to frictional processes along slipping faults.

ACKNOWLEDGMENTS

We thank the many colleagues who through countless discussions unknowingly contributed to our understanding of earthquake processes. ZR thanks the funding support by NSF grant EAR-1620330 "Investigating earthquake source processes in the laboratory", and partial support by NSF grant EAR-1345087 "Experimental simulation of earthquake rupture processes." JF acknowledges the support of the Israel Science Foundation (ISF Grant No. 840/19). Open Research and Data Availability: No unpublished data was used in this commentary.

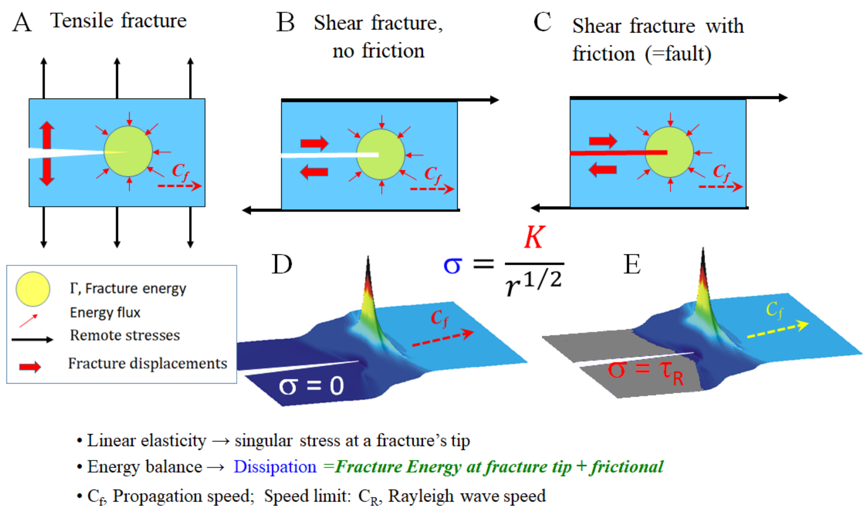

Figure 1 : Schematic representations of (A) tensile (mode I) fracture, (B) shear fracture (mode II); in both A and B the crack faces formed behind the leading edge (crack tip) are stress-free. (C) Shear fracture with a frictional interface; a frictional residual shear stress, τ_R, remains in the wake of the fracture tip. In all three cases the elastic energy flowing into the tip is focused to a stress singularity of the form $\sigma = \frac{K}{r^{1/2}}$ where K is the stress-intensity factor and r is the distance from the tip. This stress-field is shown schematically in D (for cases A and B) and in E for case C.

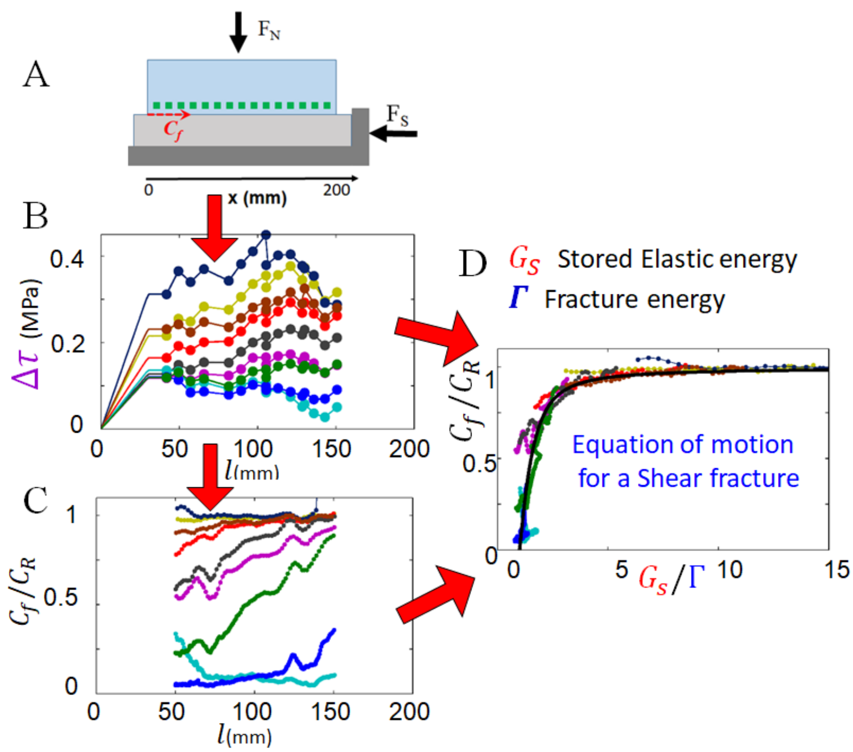

Figure 2 : Experimental rupture dynamics along a frictional fault. A, A schematic representation of an

experimental system where two contacting acrylic blocks form a frictional interface. A normal force,F_N, (typically 3 MPa) is applied initially, then shear force,F_S, is increased quasi-statically until the development of stick-slip ruptures and frictional sliding. The rupture propagation velocity and strains are monitored by real-time measurements of the interface contact area with an optical method (Svetlizky & Fineberg, 2014), and a rapid measurements (1MHz rate) of the strain gauges (green squares). B. The measured shear stresses along the interface *prior to* rupture is presented for nine experiments conducted for identical values of F_N. The shown over-stresses, $\Delta\tau$, are the shear stress values in excess of the residual stress, τ_R, that is measured in the wake of the rupture front. For each of these stress profiles, a rupture was nucleated and propagated along the fault (Svetlizky et al., 2017). C. The rupture propagation velocity,C_f , and acceleration along the interface of the nine experiments in (B); shown the C_f normalize by the limiting wave speed, C_R for ruptures. D. Using the equation of motion (energy balance) predicted by fracture mechanics, all of the different velocity measurements collapse onto a single curve (black line) that depends on the ratio of the available elastic energy G_S and the fracture energy, Γ. Note that there are no adjustable parameters to the theory's predictions.

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3. **Fault frictional properties and the earthquake process**. A common view is that earthquake instability is controlled by frictional weakening manifested by the drop from static to dynamic friction (Di Toro et al., 2011; Dieterich, 1979). This view is used in earthquake simulations with velocity weakening (Lapusta & Rice, 2003; Madariaga et al., 1998) assuming experimentally derived friction laws, e.g., rate-and-state friction (Dieterich, 1979). Frictional weakening is indeed observed in multi-

ple experiments: a rock's frictional strength may decrease with increasing slip-velocity and/or slip-displacement. Strengths drop particularly rapidly under seismic slip velocities of a few m/s (Di Toro et al., 2011; Hirose & Shimamoto, 2005). We argue that the utilization of frictional weakening as the controlling mechanism of earthquake dynamics may lead to a few central contradictions.

Sections I and II above indicate that the dynamic nature (e.g., stored energy, stress field, or propagation velocity) of a rupture along experimental faults can be fully understood in terms of fracture mechanics formulation without consideration of the fault's frictional properties. The only requirement for earthquake rupture propagation is the ability of a frictional system to develop and sustain sufficient stored elastic energy, or 'overstress', prior to rupture nucleation (e.g. Fig. 2b). This has been amply demonstrated (Ben-David et al., 2010; Ben-David & Fineberg, 2011; Passelegue et al., 2020) in experiments: for a given normal stress, an experimental fault can sustain a large range of applied shear stresses. Therefore, the concept of a characteristic static-friction that governs the onset of instability is misleading (Ben-David & Fineberg, 2011), and a fault system can store varying amounts of elastic energy above limits imposed by friction-based models; mechanisms of overstress are discussed later.

It is certainly possible to incorporate frictional weakening in rupture dynamics simulations that correspond to fracture mechanics formulations (Lapusta & Rice, 2003; Madariaga et al., 1998). However, the required dependence on a 'friction law' and associated weakening is *not necessary*, and, in fact, could impose unnecessary restrictions. For example, the friction-based idea that an earthquake cannot propagate under velocity *strengthening* is inaccurate, because an earthquake can propagate if the fault system is sufficiently overstressed. For instance, the mineral talc dominates the composition of active fault-zones, e.g., the central San Andreas fault (Moore, D. & Rymer, M., 2007) and mining–induced faults. Yet, even though talc is documented as frictional-strengthening mineral for both dynamic velocity and displacement (Chen et al., 2017), earthquakes do occur along these zones.

DISCUSSION

We propose here that earthquakes should be described as dynamic ruptures controlled by fracture mechanics processes that are unrelated to the friction even though fault frictional properties do dominate the energy dissipation processes. We refer to this concept as Fracture Earthquake Rupture Mechanics, FERM. Beyond the experimental observations, the proposed view can resolve a few paradoxical features of earthquake processes.

Overshoot is a rupture state that can inherently be explained by the FERM concept. Dynamic overshoot refers to the case of "…shear stress reduction below dynamic friction" (Ide et al., 2011), and according to common friction laws, an earthquake should be arrested in such a case. A field example of overshoot is the Mw2.2 earthquake at 3.6 km depth in Tautona mine, South Africa. The in-situ mapping at the focal depth revealed a rupture-zone of 3 to 4 non-parallel slip-surfaces (Heesakkers et al., 2011), and the associated in-situ stress measurements (Lucier et al., 2009) revealed that the [shear stress/normal stress] ratio on these slip-surfaces ranges 0.05-0.13. These measured stress ratios are significantly lower than the dynamic friction, and according to FERM, this earthquake was facilitated solely by the of potential elastic energy generated by mine operations regardless of the resolved shear stresses and fault-zone strength. Overshoot has also been experimentally documented (Bayart et al., 2016) where rupture propagation was shown to continue at stress levels well below measured values of τ_R.

Overstress. In FERM, the development of a dynamic rupture only requires a measure of overstress, namely, mean stress levels that exceed those necessary to overcome τ_R . Overstress can be achieved by a strong barrier (Gvirtzman & Fineberg, 2021), fault-zone healing (Heesakkers et al., 2011; Muhuri et al., 2003) ahead of an arrested rupture (Ben-David et al., 2010; Passelegue et al., 2020) or due to fault heterogeneities, whose strength may approach the theoretical rock strength (Savage et al., 1996).

The stored elastic energy due to the overstress drives dynamic rupture and controls the rupture velocity, style and energy dissipation after the rupture nucleation (Fig. 2) (Svetlizky et al., 2017; Svetlizky & Fineberg, 2014). The timing and location of rupture nucleation are governed by local failure in regions of high local stress and/or low local strength.

Complex fault system. A single seismic event may be complex e.g. 2016 Mw 7.8 Kaikōura earthquake (Ulrich et al., 2019)

In conclusion, we believe that rupture fronts efficiently (~5% of the total energy) control earthquake dynamics by unlocking a fault, generating the requisite breakdown stress-drop, and damaging the rock-blocks. An earthquake's size and speed is controlled by the magnitude of the elastic energy available relative to the interface strength (fracture energy), while the overall dissipation is primarily due to frictional processes along slipping faults.

ACKNOWLEDGMENTS

We thank the many colleagues who through countless discussions unknowingly contributed to our understanding of earthquake processes. ZR thanks the funding support by NSF grant EAR-1620330 "Investigating earthquake source processes in the laboratory", and partial support by NSF grant EAR-1345087 "Experimental simulation of earthquake rupture processes." JF acknowledges the support of the Israel Science Foundation (ISF Grant No. 840/19). Open Research and Data Availability: No unpublished data was used in this commentary.

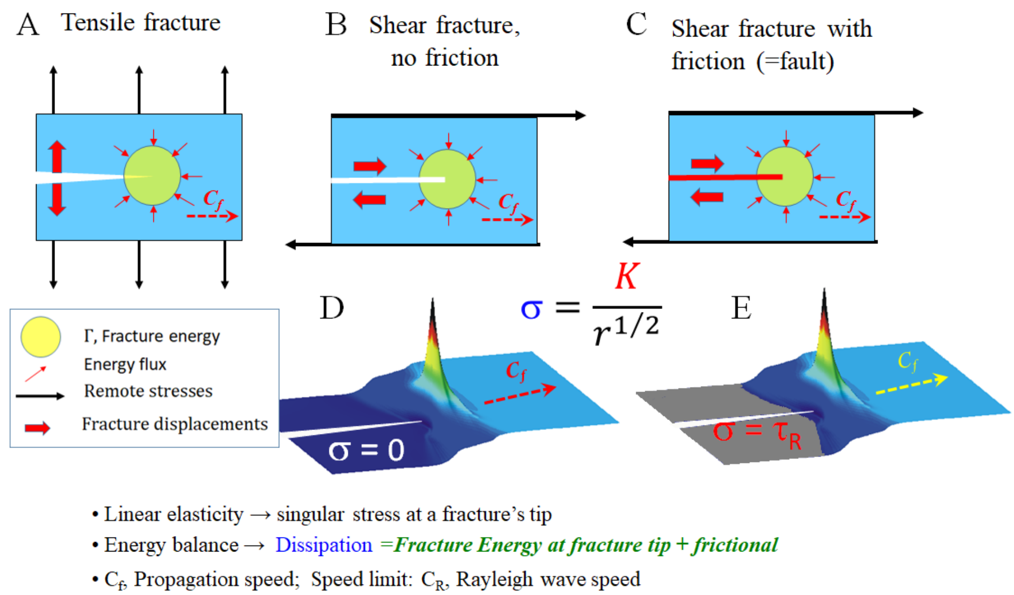

Figure 1: Schematic representations of (A) tensile (mode I) fracture, (B) shear fracture (mode II); in both A and B the crack faces formed behind the leading edge (crack tip) are stress-free. (C) Shear fracture with a frictional interface; a frictional residual shear stress, τ_R, remains in the wake of the fracture tip. In all three cases the elastic energy flowing into the tip is focused to a stress singularity of the form $\sigma = \frac{K}{r^{1/2}}$ where K is the stress-intensity factor and r is the distance from the tip. This stress-field is shown schematically in D (for cases A and B) and in E for case C.

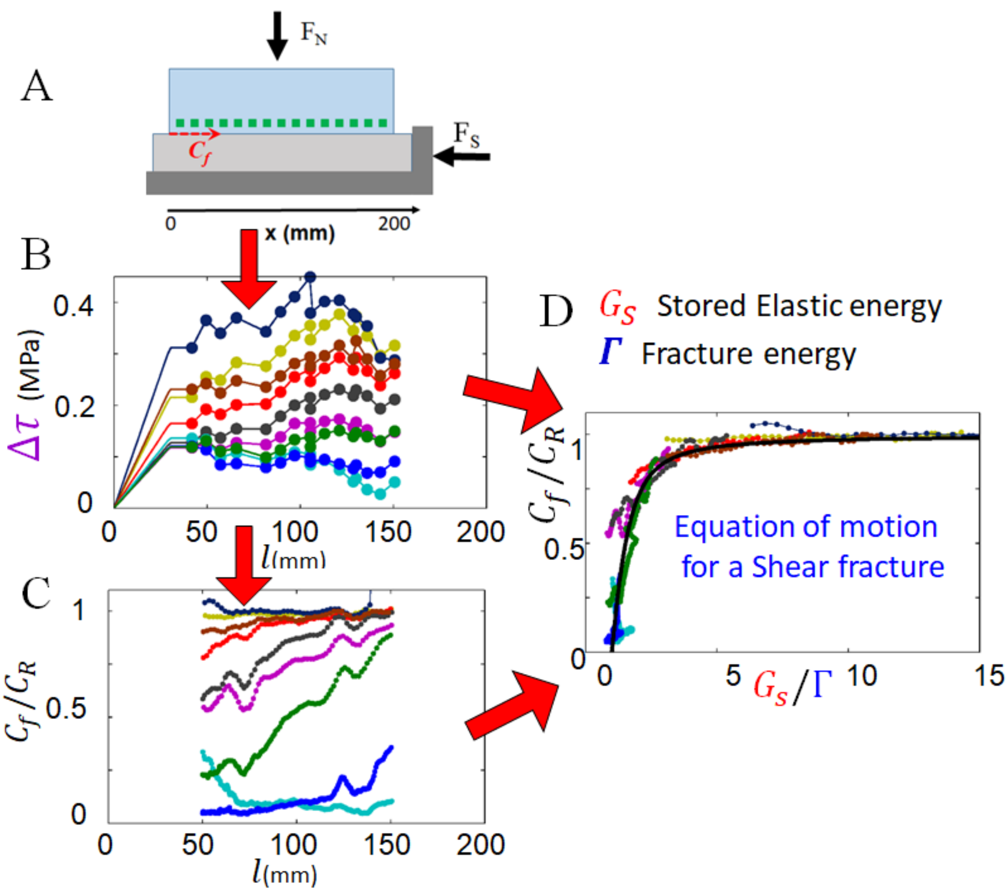

Figure 2: Experimental rupture dynamics along a frictional fault. A, A schematic representation of an experimental system where two contacting acrylic blocks form a frictional interface. A normal force, F_N, (typically 3 MPa) is applied initially, then shear force, F_S, is increased quasi-statically until the development of stick-slip ruptures and frictional sliding. The rupture propagation velocity and strains are monitored by real-time measurements of the interface contact area with an optical method (Svetlizky & Fineberg, 2014), and a rapid measurements (1MHz rate) of the strain gauges (green squares). B. The measured shear stresses along the interface *prior to* rupture is presented for nine experiments conducted for identical values of F_N. The shown over-stresses, $\Delta\tau$, are the shear stress values in excess of the residual stress, τ_R, that is measured in the wake of the rupture front. For each of these stress profiles, a rupture was nucleated and propagated along the fault (Svetlizky et al., 2017). C. The rupture propagation velocity, C_f, and acceleration along the interface of the nine experiments in (B); shown the C_f normalize by the limiting wave speed, C_R for ruptures. D. Using the equation of motion (energy balance) predicted by fracture mechanics, all of the different velocity measurements

collapse onto a single curve (black line) that depends on the ratio of the available elastic energy G_S and the fracture energy, Γ. Note that there are no adjustable parameters to the theory's predictions.

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