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# Stress heterogeneities in earthquake rupture experiments with material contrasts

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ABSTRACT

We investigate significant heterogeneous stresses along bimaterial interfaces in laboratory and numerical experiments. These stresses, partially induced by model or experimental configuration, affect the supershear transition length and rupture speed, mode and directivity in uniaxial compression tests and dynamic rupture experiments with bimaterial interfaces. Using numerical simulations we show that normal and tangential stresses at the fault are distorted by the different stress–strain relationships of the materials. This distortion leads to altered supershear transition lengths, higher rupture potencies and amplifies the preference for rupture in the direction of slip of the slower and more compliant material. We demonstrate how this stress-distortion can be decreased in laboratory experiments by using larger specimen samples and in numerical models by using periodic boundary conditions.

## 1. Introduction

Rupture propagation directly affects the growth and eventual size of earthquakes, the energy radiation patterns and the resulting ground motions that induce tsunamis, landslides and damage to infrastructure. As large earthquakes often occur along faults separating dissimilar materials, dynamic rupture along bimaterial interfaces is extensively studied to improve seismic hazard analysis. Theoretical studies investigate the fundamental physical processes as a starting point to understand rupture propagation along such interfaces (Rayleigh, 1885; Weertman, 1963). However, comparing analytical results with laboratory experiments and numerical models is difficult due to significant effects of apparatus design (loading and confinement methods), numerical procedures and boundary conditions. Due to stress heterogeneities introduced in experiments and models, complex behavior may emerge in even the simplest setups, resulting in rupture characteristics different from those derived theoretically (Anderson, 1972). To better understand the natural phenomena in this work we try to resolve the differences between various experiments and models and evaluate how well they represent in situ processes.

Ruptures propagating along bimaterial faults generate large dynamic changes of the normal stress along the fault. These stress perturbations influence rupture velocities and potencies differently along the positive rupture direction (direction of slip of the more compliant material) and the negative rupture direction (direction of slip of the stiffer material) (Weertman, 1980; Andrews and Ben-Zion, 1997). This so-called 'bimaterial effect' occurs for sub-Rayleigh ruptures and is a result of normal stress change *behind* the rupture tip. Subshear ruptures have higher rupture velocities in the positive direction due to a tensile stress perturbation *behind* the rupture tip which follows the rupture front and promotes rupture

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(Weertman, 1980; Andrews and Ben-Zion, 1997; Rubin and Ampuero, 2007). Subshear ruptures therefore exhibit higher potencies in the positive direction and a preference for this direction in bilateral ruptures (Ben-Zion, 2001; Ampuero and Ben-Zion, 2008; Langer et al., 2010). Conversely, in the negative direction the sign of the normal stress change is reversed (compressive) *behind* the rupture tip leading to dynamic strengthening and lower rupture velocities for subshear rupture.

The possibility of rupture travelling at speeds faster than the Rayleigh wave speed (Rayleigh, 1885) has been shown analytically by Burridge (1973). Andrews (1976) showed numerically that a rupture can transition from sub-Rayleigh to supershear speeds by the occurrence of a daughter crack in front of the crack-tip which then unites with the mother crack and travels at the primary wave speed. Experiments by Xia et al. (2004) showed the existence of this so-called Burridge–Andrews mechanism for transition into supershear. Supershear rupture propagation has also been observed in nature during the 2001 Kunlunshan (Bouchon and Vallée, 2003), the 2002 Denali (Dunham and Archuleta, 2004) and the 2010 Qinghai earthquakes (Wang and Mori, 2012). All three earthquakes started at propagation speeds below the shear wave velocity and then transitioned to supershear speeds. An interesting result of both numerical and analytical studies is that supershear rupture along bimaterial interfaces occurs predominantly (Harris and Day, 1997; Shi and Ben-Zion, 2006; Langer et al., 2012) or exclusively (Ranjith and Rice, 2001; Adams, 2001; Cochard and Rice, 2000) in the negative direction. Our recent numerical simulations showed that the normal stress changes in *front* of the rupture tip influence whether or not a supershear transition will occur (Langer et al., 2012). The supershear transition is enhanced in the negative direction, where normal stress changes ahead of the rupture unclamp the fault, making it easier for the shear wave stress peak to trigger supershear failure of the fault. The opposite applies in the positive direction, such that the transition is delayed or sometimes even suppressed.

In the current work we show that the directivity and supershear transition are influenced by the stress-distortions along the interface and we quantify the extent of these distortions for various experimental and numerical model setups. We also show that increasing the specimen size in laboratory experiments may reduce the stress-distortions and that they can be removed completely by using periodic boundaries in numerical simulations. We add to the growing literature that has studied the influence of finite-size and edge effects and their subsequent stress-distortions which need to be taken into consideration for the interpretation of experimental and numerical results.

Many experimental studies have investigated the above-mentioned earthquake rupture characteristics. An important feature of such laboratory model setups is the finite specimen size that introduces edge effects and influences the outcome of rupture experiments. This shortcoming was addressed in work by Scholz et al. (1972), where in a direct shear test a rock slab was forced to slide between two stationary slabs, producing a large moment, that resulted in a high stress gradient over the sliding surfaces. Thus Scholz et al. (1972) stated that "…frictional results from direct shear experiments cannot be related directly to parameters of interest such as the shear or normal stresses." Lambros and Rosakis (1994) and Rosakis et al. (1998) avoided these loading-induced stress-distortions, as they did not load their specimens prior to rupture nucleation. They subjected an uncompressed specimen to one-point impact-loading near the fault at one boundary of the specimen. Subsequent work decoupled the loading and the initiation of slip along the fault. Xia et al. (2004, 2005) subjected their specimens to uniaxial compression, mimicking slow tectonic loading, where the angle between their fault face and the applied far-field loading did not allow the fault to slip. They then nucleated dynamic rupture by an exploding wire mechanism, implemented in the center of the fault. As in the experiments with impact-loading they were able to prepare a controlled environment with desired conditions for rupture and then decide on the initiation of rupture rather than having to rely on self-nucleation as in Scholz et al. (1972). These experiments were used to document and characterize supershear transition along material interfaces (Xia et al., 2005). In more recent experiments, Ben-David et al. (2010) and Ben-David and Fineberg (2011) studied frictional sliding by pressing together two PMMA blocks (polymethyl-methacrylate blocks) and applying external shear forces to the top and/or bottom block. They observed highly non-uniform normal and shear stresses caused not only by edge effects, but also by the roughness and geometry of the contact area when loading a homogeneous material interface. They also suggest that local static friction significantly depends on loading details. From these previous experiments it can be seen that finite-size effects and stress-distortions may lead to inaccurate interpretation of experimental and numerical results.

In Section 2 we outline the numerical method we use to simulate dynamic rupture along bimaterial interfaces and introduce three commonly used experimental or numerical model configurations used for comparison in this work. Section 3 quantifies the magnitude of stress-distortions due to experimental or model setup present in the three different configurations. This section also shows how to achieve distortion free elastic deformation when periodic boundary conditions are applied in numerical models. It also investigates the influence of stress-distortions due to model setup on sub- and supershear rupture along bimaterial interfaces. In Section 4 we summarize the effects of stress heterogeneities due to model setup on rupture characteristics and the implications for interpretation of laboratory experiments and numerical simulations.

## 2. Comparison of numerical models of dynamic rupture along bimaterial interfaces

### 2.1. Different setups for simulation of laboratory and in situ processes

Uniaxial compression tests consisting of quasi-static loading and subsequent dynamic rupture are simulated using the Finite Element Method implemented in the ESYS.ESCRIPT software (Gross et al., 2007; Langer et al., 2010). Triangular meshes are constructed using Gmsh (Geuzaine and Remacle, 2009) with variable mesh size ranging from 1 mm at the outer boundary to 500 μm along the fault. The models include an absorbing boundary layer and in some simulations we adapt the mesh in order to use periodic boundary conditions.