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On the use of a split Hopkinson pressure bar in structural geology: High strain rate deformation of Seeberger sandstone and Carrara marble under uniaxial compression

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ABSTRACT

There is increasing evidence that seismogenic fractures can propagate faster than the shear wave velocity of the surrounding rocks. Strain rates within the tip region of such super-shear earthquake ruptures can reach deformation conditions similar to impact processes, resulting in rock pulverization. The physical response of brittle rocks at high strain rates changes dramatically with respect to quasi-static conditions. Rocks become stiffer and their strength increases. A measure for the dynamic behavior of a rock and its strain dependency is the dynamic increase factor (*DIF*) which is the ratio of the dynamic compressive strength to the quasi-static uniaxial compressive strength. To investigate deformation in the high strain rate regime experimentally, we introduce the split Hopkinson pressure bar technology to the structural geology community, a method that is frequently used by rock and impact engineers. We measure the stress-strain response of homogeneous, fine-grained Seeberger sandstone and Carrara marble in uniaxial compression at strain rates ranging from 10^{+1} to 10^{+2} s^{-1} with respect to tangent modulus and dynamic uniaxial compressive strength. We present full stress-strain response curves of Seeberger sandstone and Carrara marble at high strain rates and an evaluation method to determine representative rates of deformation. Results indicate a rate-dependent elastic behavior of Carrara marble where an average increase of ~18% could be observed at high strain rates of about 100 s^{-1}. *DIF* reaches a factor of 2.2–2.4. Seeberger sandstone does not have a rate-dependent linear stress-strain response at high strain rates. Its *DIF* was found to be about 1.6–1.7 at rates of 100 s^{-1}. The onset of dynamic behavior is accompanied with changes in the fracture pattern from single to multiple fractures to pervasive pulverization for increasing rates of deformation. Seismogenic shear zones and their associated fragment-size spectra should be carefully revisited in the light of dynamic deformation.

1. Introduction

Rocks can be exposed to high loading rates and fast strain rates by a number of sudden geo-hazards such as meteorite impact, earthquake faulting, explosive volcanism, gravitational mass movements, and lightening strike. The final product of such events are strongly fractured, brecciated and even pulverized rocks (Davies and McSaveney, 2009; Kenkmann et al., 2014; Fondriest et al., 2015). Heating by friction or adiabatic pressure release can even melt these rocks (e.g., Spray, 2010; Di Toro et al., 2011). High rates of loading induce changes in the mechanical properties and the fracture behavior (e.g., Ramesh et al., 2015) that may strongly deviate from behaviors for quasi-static conditions. Deformation behavior and rock failure for quasi-static conditions including fracture initiation and propagation are rather well understood (e.g., Zang et al., 2000; Scholz, 2002). Brittle deformation under quasi-static conditions is insensitive to the loading rate, but responds sensitively to confinement and pore pressure.

The critical strain rate above which a rate dependency on strength occurs in rocks varies between 10^{+0} and 10^{+2} s^{-1} (Zhang

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and Zhao, 2014) and represents the onset of the so-called high strain rate regime (HSR) (Zhang and Zhao, 2014). Obviously, deformation during hypervelocity meteorite impact events occurs in the high strain rate regime, for positions close to the point of impact (Melosh, 1989; Kenkmann et al., 2014). However, evidence is increasing that seismogenic fractures propagate fast and likely deform rocks in the high strain rate regime. The majority of earthquake ruptures tend to propagate with an average velocity that is about 80% of the shear wave velocity (Heaton, 1990). Yet, super-shear earthquake ruptures even propagate faster than the shear wave velocity (Passelèque et al., 2013) of the surrounding rocks. Strain rates within the tip region of such super-shear ruptures are comparable to deformation conditions that develop during impact processes. For instance, the 2001 Kunlunshan earthquake produced a 400-km-long surface rupture. Bouchon and Vallée (2003) determined that the rupture propagated at an average speed of 3.7–3.9 km/s, which exceeds the shear velocity of the brittle part of the crust. Mode II fracturing started at sub–Rayleigh wave velocity and became super-shear, probably approaching 5 km/s, after about 100 km of propagation.

Super-shear rupture events during earthquakes can produce pervasively pulverized rocks up to several hundred meters from the fault core, indicating high strain rates. Doan and Gary (2009) reported such intensively fragmented fault rocks up to 400 m from the fault core at San Andreas Fault, exhibiting textures of low total strain. Similar observations by Fondriest et al. (2015) found highly shattered to pulverized dolostones within the exhumed seismogenic Foiana Fault zone in the Southern Italian Alps, generated in absence of significant shear strain.

Using the split Hopkinson pressure bar (SHPB) technique for testing intact samples, Doan and Gary (2009) showed that high strain rates are necessary to reproduce the fracture pattern of these natural examples and experiments showed a related increase of rock strength at dynamic conditions. Similarly, Yuan et al. (2011) experimented on Westerly granite to ascertain the critical-stress wave loading conditions required for the change in fracturing behavior from discrete fracturing to pervasive pulverization. Reches and Dewers (2005) compared examples of pulverized rocks of fault gouges from different settings according to their grain size distribution. They attributed the formation of these gouges to fast-propagating earthquake ruptures and calculated models for the surrounding rock deformation history of a dynamic shear fracture propagating at speeds close to the Rayleigh wave velocity. They concluded that for strain rates of up to 10^{+5} s^{-1}, occurring close to the fracture tip, extreme rates of subsequent volumetric expansion and contraction produced the pervasively pulverized fault rocks. To summarize, slip rates and the crack propagation along tectonic shear zones can reach conditions during displacement where the dynamic mechanical behavior becomes important. Knowledge about the changing properties of rocks at high strain rates obtained by SHPB methodology is required and can provide new insights into the propagation of faults and earthquakes. This can significantly improve our understanding of the deformation inventory of faults in the field, and is the focus of the contribution of this paper.

Meteorite impacts are the natural processes with the greatest loading and strain rates. Depending on the kinetic energy of the impacting body, initial shock pressures are in the order of several hundred GPa, and strain rates reach 10^{+6} - 10^{+8} s^{-1} (e.g., Melosh, 1989). However, by geometric thinning and attenuation due to irreversible deformation, phase transformations, and heating, shock waves transform into elastic pressure waves. Consequently, wide spectra of pressure, strain, and strain rate are realized within a single impact event (O'Keefe and Ahrens, 1975; Collins et al., 2005; Kenkmann et al., 2014). Buhl et al. (2013) showed that the strain rate in experimentally produced impact craters decays strongly with time and with distance from the impact point. The decrease in strain rate could be correlated with a change from pervasive grain pulverization with a power law exponent >2.4 of the particle size distribution to discrete fracturing with power law exponents distinctly below 2. The great fracture densities at high strain rates and low bulk strain were explained by the activation of abundant micro-flaws simultaneously with abundant crack branching. To understand the fragmentation behavior of rocks in the high strain rate regime, the dynamic strength properties of rocks in this regime have to be measured, and we will do so, utilizing SHPB methods (Millon et al., 2016; Ramesh et al., 2015).

Rocks deformed in the high strain rate regime are sensitive to strain rate in terms of their stress-strain response as well as in their mode of failure and strength during both compression and tension. In general, increasing tangent moduli and either increasing or decreasing critical strain have been observed for a diversity of rocks (Zhang and Zhao, 2014, and references therein). Failure mechanisms change from single to multiple fracturing, and ultimately lead to rock pulverization accompanied by increasing energy absorbance, as shown experimentally by Hakalehto (1970), Li et al. (1993) and Hong et al. (2009). More inherent flaws are activated at high strain rates to accommodate strain (Grady and Kipp, 1993).

Kimberley et al. (2013) presented scaling laws for the rate dependent strength in uni-axial compressive and tensile regimes in brittle materials. These scaling laws correlate the pre-existing flaw densities and their size and spacing to the changing fracture pattern and energy degradation during failure. The propagation speed of mechanical information, given by the P-wave velocity and the limited propagation velocity of wing cracks (typically a fraction of the Rayleigh wave speed) represent key factors of the dynamic behavior. At high loading rates beyond a critical material-dependent threshold, the weakest flaws are not capable of causing macroscopic failure before other, increasingly stronger flaws are activated. Hence, according to the statistical theory of Hild et al. (2003), the onset of multiple fracturing is linked to an intrinsic increase in material strength, since more energy is required for the propagation of numerous fractures. Furthermore, properties like pore space, fluids, grain-size distribution, presence of twin lamellae and the interplay of different mineral phases influence the bulk dynamic behavior of rocks.

The current study is aimed at comparing the dynamic behavior of sandstone and marble, while familiarizing the structural geology community with the SHPB technology, a powerful technique of dynamic mechanical testing. We deliberately selected this journal for publication of this work because we are convinced that rate-dependent brittle deformation is of great importance for understanding the deformation inventory of seismogenic shear zones in the field. The time is ripe to bridge the gap between impact engineering and rock dynamics on the one side and structural geology on the other side.

2. Methodology of the split Hopkinson pressure bar technique: setup and theory

The experiments were performed with a 5 cm diameter split Hopkinson pressure bar (SHPB), characterizing the dynamic response of Seeberger sandstone and Carrara marble at dynamic conditions. The loading technique represents a precise tool that enables the experimentalist to induce diverse stress histories in cylindrical samples. The experiments cause one-dimensional states of stress for controlled conditions including longitudinal stress equilibrium and constant strain rates. Additionally, a uniaxial loading frame was used to obtain reference values of compressive strength and the Young's modulus at quasi-static conditions.