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Monitoring fracture evolution with compressional-mode interface waves

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Abstract. As a tensile fracture was induced in a sandstone core sample under compressional loading, compressional waves were propagated parallel to the plane of tensile stress. Long before catastrophic failure, when a macroscopic fracture was formed, the energy in the compressional wave showed a dramatic shift in spectral frequency from 0.644 MHz to 1 MHz. This frequency shift is a signature of the partitioning of energy from a compressional body wave into a compressional-mode interface wave. The presence of this signature before failure suggests the presence of an incipient interface wave that is supported by a network of oriented but disconnected microcracks.

Introduction

The formation of microcracks in a rock mass approaching failure appears as a modification in the modulus of the rock. The reduction in the modulus of the rock and the induced anisotropy caused by the microcracks affects seismic velocities and introduces seismic anisotropy (Rothman, 1975; O'Connel & Budianski, 1974; Jaeger & Cook, 1979; Crampin, 1981; Zheng, 1989; Sayers, 1990; Hudson, 1991). By taking advantage of the tendency of microcracks to predominantly orient along the plane of principal stress, more specific information about the approach to failure can be obtained from seismic data. Seismic waves propagating along a plane of failure should partially convert to interface waves that propagate along the plane of weakness and that would be sensitive to changes in the network of oriented but discontinuous microcracks.

The properties and characteristics of Rayleigh-mode interface waves are now well established from theoretical, experimental, and numerical investigations (Pyrak-Nolte & Cook, 1987; Nagy, 1991; Pyrak-Nolte et al., 1992; Gu, 1994; Ekern et al., 1995; Roy & Pyrak-Nolte, 1995). Pyrak-Nolte et al. (1996) examined the inception of Rayleigh-mode fracture interfaces from bulk shear-waves as a fracture was induced in a sample. They observed that energy was partitioned from the bulk shear wave into a Rayleigh-mode fracture interface wave as a fracture formed. While this suggests that using Rayleigh-mode fracture interface waves could be used as a diagnostic tool for examining the approach to failure, it requires the measurement of a late arriving signal. Often, measurements of waves traveling at the shear wave velocity or slower are obscured by reflections or refractions or other converted modes. It is important that a diagnostic method for monitoring the approach to failure be based on a clear, easy-to-detect signal, i.e., on the energy in the first arrival.

Gu (1994) and Gu et al. (1996) predicted numerically the existence of a compressional mode interface wave that co-propagates with the bulk compressional wave along a fracture. Fan et al. (1996) and Roy & Pyrak-Nolte (1997) observed experimentally that this compressional mode interface wave depended on the specific stiffness of the fracture, exhibited both longitudinal and transverse particle motion, affected the frequency content of the signal, and appeared as a concentration of energy on the interface. This signal is always observed experimentally to co-propagate with the bulk compressional wave. It is not currently known whether this compressional interface wave is a true eigenmode rather than a radiating mode.

In a pre-existing fracture, the specific stiffness of the fracture depends on the amount and spatial distribution of the points of contacts between the two fracture surfaces (Brown & Scholz, 1985&1986; Hopkins et al., 1987&1992). However, during the formation of a fracture along a plane, the rock in this region is initially very stiff. As failure is induced, the stiffness of this plane is reduced. In this paper, we present experimental evidence for a seismic signature indicating the approach to failure long before a macroscopic fracture is formed in a rock. This seismic signature involves a shift in the frequency content of compressional wave and an interference null in frequency that signals the inception of a compressional mode interface wave propagating along the weakened plane.

Experimental Set-up

Several cores of Berea sandstone were used to ascertain the existence of a compressional wave seismic precursor to failure. In this paper, representative data from sample BS17 are presented. The dimensions of BS17 were 5.08 cm in diameter by 4.83 cm in length. A schematic of the experimental set-up is shown in Figure 1. A small light-weight

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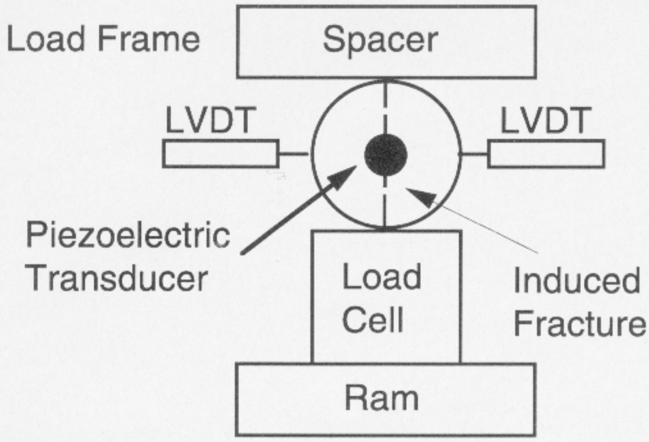

Figure 1. Sketch of the experimental set-up to measure compressional waves propagated parallel to the plane along which a tensile fracture is induced.

aluminum frame was used to hold two Linear Variable Displacement Transducers (LVDTs, with 0.7 micron resolution) which were oriented perpendicular to the axis of the core to measure diametrical expansion of the sample as failure is approached. This frame was also used to attach two compressional wave piezoelectric transducers (central frequency of 1 MHz) to the core for sending and receiving. The transducers are coupled to the core with honey. The sending transducer was excited with a 300 V square pulse with a duration 0.4 microseconds with a repetition rate of 100 Hz.

The cylindrical core with the attached small frame was placed between the platens of a uniaxial hydraulic press. The orientation of the sample relative to the platens produces a line load parallel to the long axis of the core in a manner similar to Brazil testing (Jaeger & Cook, 1979) or split cylinder testing. As the sample is compressed, the rock expands and eventually a tensile fracture is induced across the diameter of the sample parallel to the direction of loading. The load on the core sample was measured using a load cell with a ±667 Newtons resolution.

The LVDTs, load cell, and the received waveforms were recorded on a digital oscilloscope (LeCroy 9314L) every 250 milliseconds to enable exact temporal correlation of the load, seismic response, and expansion of the sample. The received waveforms consisted of 1000 points representing a 20 microsecond window of the transmitted signal containing the compressional wave. After digitization, the data were stored on computer.

Wavelet analysis was performed on all of the received signals to investigate the existence of a compressional wave mode precursor to failure. Wavelet analysis (Morlet et al., 1982, Combes et al., 1989) provides a direct method of extracting the spectral content as a function of arrival time and has been used to extract dispersion in interface waves (Pyrak-Nolte & Nolte, 1995) and to determine the existence of a compressional-mode interface wave (Roy & Pyrak-Nolte, 1997). To examine the frequency content of the received signals as a tensile fracture was induced in the core, a Hilbert wavelet transformation method (Nolte et al., 2000) was used that gives equal accuracy in time and frequency.

Results

Figure 2 shows a 6 microsecond window of 60 of the 310 received compressional waves collected during loading from the initial load to failure with red and blue regions representing positive and negative antinodes, respectively, and green regions representing nodes. The arrival time (15.8 microseconds) of the compressional wave does not change significantly (+0.01 microseconds) with increasing load. The negligible change in velocity suggests that the normal load on the sample does not affect the grain contacts that are probed by the propagating wave. The compressional wave is propagated along the axis of the core but it samples the grain contacts that are orthogonal to the line load. Consequently, as the core sample is loaded, the arrival time of the bulk compressional wave does not change significantly with increasing load. However, starting at a load of 12.5 kN, the emergence of a second wave is clearly observed around an arrival time of 16.8 microseconds. This is observed in Figure 2 as a bifurcation of the first negative antinode (dark blue) by the emergence of a positive antinode (yellow). In addition, the amplitude of the first positive antinode (around 15.9 microseconds - red-yellow) is reduced while the positive antinode at 16.6 microseconds increases in amplitude with increasing load.

Discussion

It is hypothesized that the emerging second wave is a compressional-mode interface wave. Gu et al. (1996) has shown numerically that a compressional-mode interface wave exists and co-propagates with the bulk compressional wave. The characteristics of the compressional-mode interface wave have been examined experimentally (Pyrak-Nolte et al., 1996; Fan et al., 1996; Roy & Pyrak-Nolte, 1997) and have been shown to be sensitive to fracture specific stiffness. The wave exhibits both transverse and longitudinal particle motions, and is observed as a concentration of energy along the interface or fracture. Roy & Pyrak-Nolte (1997) found from wavelet analysis that as the specific stiffness of the fracture increased (by applying a normal load to a pre-existing fracture) the spectral energy shifted from high frequency to low frequency. This suggests that when a fracture is induced in a sample and a plane of weakness forms, i.e. a plane of low stiffness composed of microcracks, a spectral shift in energy from low frequency to high frequency should be observed. A wavelet analysis was performed to examine the frequency content of the signal. Figure 3(a-d) shows a 6 microsecond window of the received compressional wave for selected loads and the associated wavelet transforms for the sample subjected to loads of 2.1 kN, 13.8 kN, 14.5 kN, and 16.9 kN. The color in Figure 3(a-d) represents the strength of the wavelet transformation with the strength increasing from blue to red. As stress on the sample was increased to around 13.8 kN, an interference null appears in the wavelet transform around 16.9 microseconds at frequency of 1.15 Mhz. As the stress is increased to 14.5 kN, the interference null shifts to a frequency of 1 Mhz (an arrival time of 16.7 s) with more of the energy in the signal is shifting to higher frequencies. In addition, the dominant spectral energy shifts from 0.63 MHz for low stresses to 1 MHz when the stress is increased to 16.9 kN. This shift in the dominant spectral energy is consistent with behavior of a compressional mode interface wave, i.e. as fracture stiffness decreases or a plane

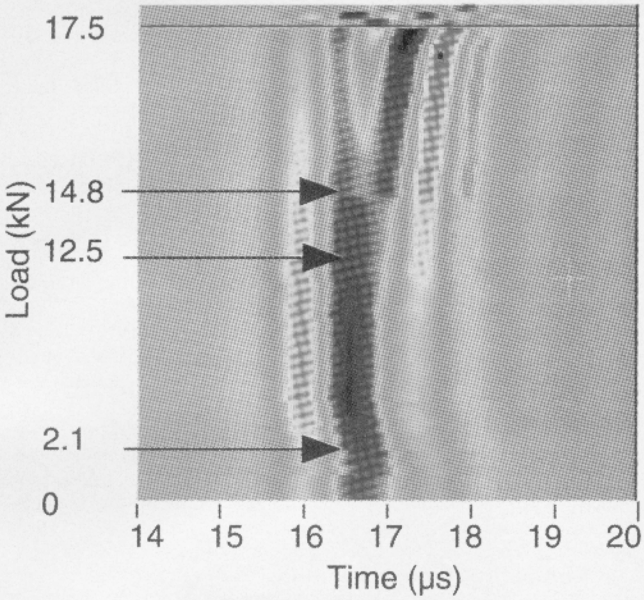

Figure 2. A 6 microsecond window of received compressional wave forms as a function of normal load. The load axis is not linear. Red and blue regions represent positive and negative antinodes, respectively, and green regions represent nodes. Failure occurred at 17.5 kN. Data after failure are shown above the red line.

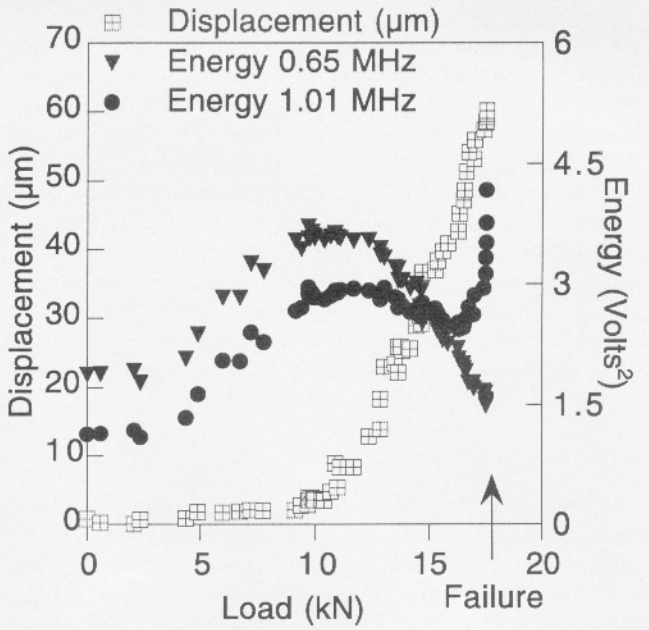

Figure 4. Compressional wave energy as a function of load at frequencies of 0.65 MHz and 1.01 MHz. The energy data are from the wavelet analysis of the received compressional waveforms. The displacement as a function of load is shown for comparison.

of weakness is formed, the dominant spectral energy shifts to high frequencies (Roy & Pyrak-Nolte, 1997).

Figure 4 shows the change in spectral energy at frequencies of 0.65 MHz and 1.01 MHz as a function of load. The displacement as a function of load is also shown in Figure 4 for comparison. Initially, both the low and high frequency energy increases with increasing load. A decrease in low frequency energy begins at a load of approximately 12.5 kN

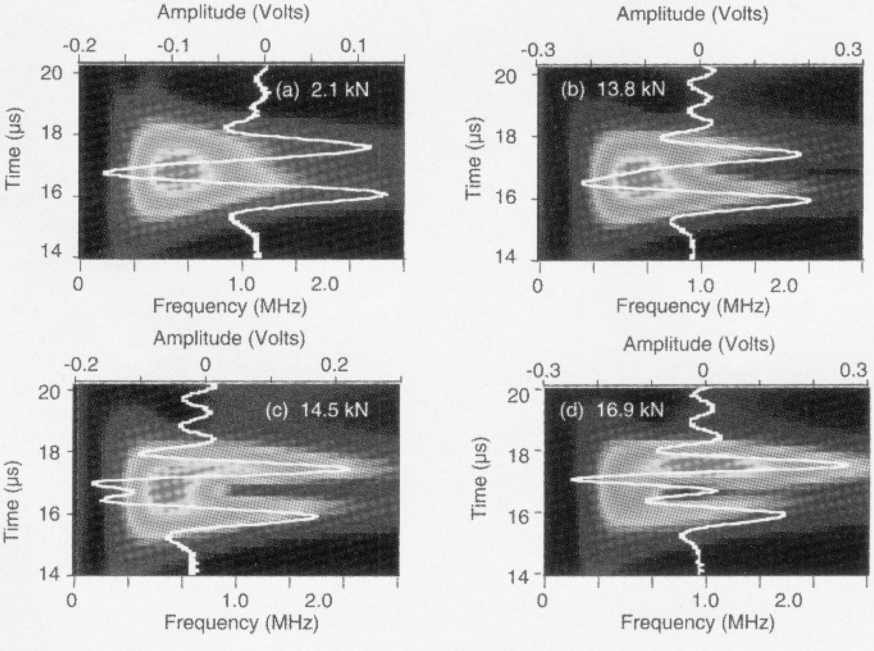

Figure 3. A 6 microsecond window of the received waveform (white curve) and the corresponding group wavelet transform when the sample was subjected to (a) 2.1 (b) 13.8 kN, (c) 14.5 kN, and (d) 16.9 kN. In the wavelet transforms, color indicates the strength of the wavelet with red representing regions of dominant energy.

when crack growth begins to occur, and decreases by 48% just prior to failure. However, the high frequency energy component begins to increase at a load of 16.5 kN and increases in amplitude by 164% just prior to failure. The increase in the high frequency energy and the decrease in the low frequency energy as failure is approached indicates the possible emergence of a compressional mode interface wave as micro-cracks form a plane of weakness, i.e., a plane of reduced stiffness, and is consistent with experimental observations of compressional-mode interface waves under normal loading made by Roy & Pyrak-Nolte (1997). The shift in spectral content observed for the compressional waves in this paper are opposite to the shifts in spectral energy observed for shear waves (Pyrak-Nolte et al.,1996).

Summary

When a fracture forms through the linkage of micro-cracks, this zone of material undergoes a reduction in mechanical strength. This reduction in mechanical strength is confined to a region that is much smaller than a typical seismic wavelength. Therefore, this weakened zone can be represented as a non-welded contact, i.e. by a stiffness. As the stiffness of the zone decreases with increased linkage among the microcracks, seismic waves propagated along this zone will form interface waves that are a function of the stiffness of this zone and are dispersive. From our investigation, distinct phase, amplitude and frequency signatures developed prior to catastrophic failure, i.e. before a macroscopic fracture is formed. The frequency shift of the spectral energy is a signature of the partitioning of energy out of a bulk compressional wave and into a compressional-mode interface wave. Because this signature is observed prior to failure, it suggests the presence of an incipient interface wave that is supported by the network of oriented but disconnected micro-cracks.

Monitoring changes in the spectral content of compressional waves propagated through a rock has the potential for the development of a tool or interpretation method for predicting the potential failure of rocks. However, additional research is needed to determine if the compressional-mode interface wave is a true eigenmode or a radiating mode. If the compressional-mode interface wave is a radiating mode, it may not be observable at larger length scales because the wave will attenuate with increasing propagation distance.

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