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Incipient interface waves used to monitor rock failure

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ABSTRACT: We show that shear waves are especially sensitive to crack formation when the wave particle motion is perpendicular to the fracture plane, because these shear waves couple into interface waves that propagate along a fracture. Long before catastrophic failure, when a macroscopic fracture is formed, the energy in shear wave signals shows a dramatic frequency shift. This frequency shift is a signature of the partitioning of energy out of a bulk wave and into interface waves. 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.

1 INTRODUCTION

Seismic wave propagation through rock masses approaching failure is affected by the formation of micro-cracks, and appears as a modification in the modulus of the rock which affects seismic velocities and introduces anisotropy (Rothman, 1975; O'Connell & Budianski, 1974; Jaeger & Cook, 1979; Crampin, 1981; Zheng, 1989; Sayers, 1990; Hudson, 1991). However, more specific information about the approach to failure can be obtained by taking advantage of the tendency for microcracks to predominantly orient along the plane of principal stress. Seismic waves propagating along the plane of failure would lead to the inception of interface waves that would propagate along the plane of weakness and that would be sensitive to changes in the network of oriented but discontinuous micro-cracks.

The characteristics of interface waves that propagate along fractures are now well established (Pyrak-Nolte & Cook, 1987; Nagy, 1991; Pyrak-Nolte et al., 1992; Gu, 1994; Ekern et al., 1995). It has also been shown that these fractures are sensitive to fracture properties, making them sensitive probes of the physical condition of the fracture (Pyrak-Nolte et al., 1992; Roy & Pyrak-Nolte, 1995; Ekern et al., 1995). For instance, the velocity of interface waves depends on the specific stiffness of the fracture. One signature of interface wave propagation is that the frequency content of the signal is affected by the fracture stiffness, specifically, the dominant seismic energy shifts to lower frequencies as the fracture stiffness decreases. For a rock undergoing failure, where the micro-cracks are orient

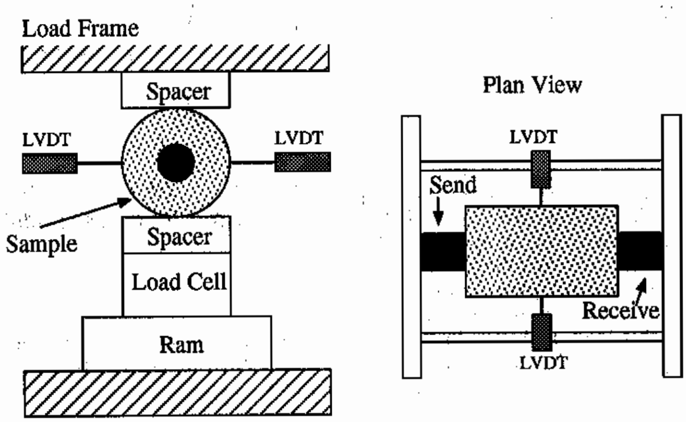

Figure 1. Sketch of experimental set-up .

along a plane, the stiffness of this plane would decrease as failure is approached, and the frequency content of an interface wave would be expected to shift to lower frequencies. In this paper, we investigate the seismic signature of the inception of interface waves during the growth of microcracks from Brazil-mode failure.

2 EXPERIMENTAL SET-UP

Several cores of Berea sandstone were used to ascertain the seismic precursor to failure. Table 1 gives the dimensions of the cores, BS15 and BS16, presented in this paper. A sketch of the experimental set-up is shown in Figure 1. The sample is placed in a load frame which applies a line load parallel to the long axis of the core, similar to Brazil testing (Jaeger & Cook, 1979) or split cylinder testing. Piezoelectric transducers for sending and receiving seismic waves are attached to the core by a small frame and are coupled to the core with honey. Two polarizations of shear wave ($S_\perp$ & $S_{||}$) transducers, with a central frequency of 1.0 MHz, were used to monitor the failure process during Brazil-mode fracturing of the cores. $S_{||}$ polarization was taken parallel to the line of loading and $S_\perp$ polarization was taken perpendicular to the line of loading. $S_\perp$ was measured on sample BS15 and $S_{||}$ was measured on BS16. Linear displacement transducers (LVDTs) with sub-micron resolution were used to measured the diametrical expansion of the core during loading and were mounted diametrically opposed using the same frame that held the piezoelectric transducers (Figure 1). A load cell was used to measure the load on the sample. The waveform, displacement, and load were collected concurrently with a four-channel digital oscilloscope to allow exact temporal correlation.

Table 1. Sample dimensions

Sample	Length (cm)	Diameter (cm)
BS15	4.52	5.05
BS16	4.31	5.05

3 RESULTS

Figures 2 & 3 show the received $S_\perp$ and $S_{||}$ -waveforms as a function of load for sample BS15 and BS16, respectively. As failure is approach, the $S_\perp$-wave is delayed, attenuated, and the phase of the signal is altered. The arrows in Figure 2 indicate the emergence of an interface wave starting at an applied load of 17.9 kN. At this load, a change in slope is observed corresponding to the inception of an interface wave. The displacement as a function of load for sample BS15 is shown in Figure 6. The change in slope around 14 kN represents the increase in displacement caused by crack growth, with failure occurring at 19 kN. The observation of the emergence of an interface wave at load of 17.9 kN suggests that enough cracks have formed to weaken the plane of failure. For the $S_{||}$-wave which is known not to couple into interface waves, the velocity increased but no attenuation and no phase changes of the wave is observed until post-failure (Figure 3). Sample BS16 therefore performs as a control experiment. From theoretical analysis and experimental measurements (Pyrak-Nolte & Cook, 1987; Pyrak-Nolte et al., 1992; Gu, 1994), it has been shown that $S_{||}$ excitation on a fracture will not generate interface waves. We can therefore use $S_{||}$ waves as a control experiment to show that the signatures that we see for $S_\perp$ are absent.

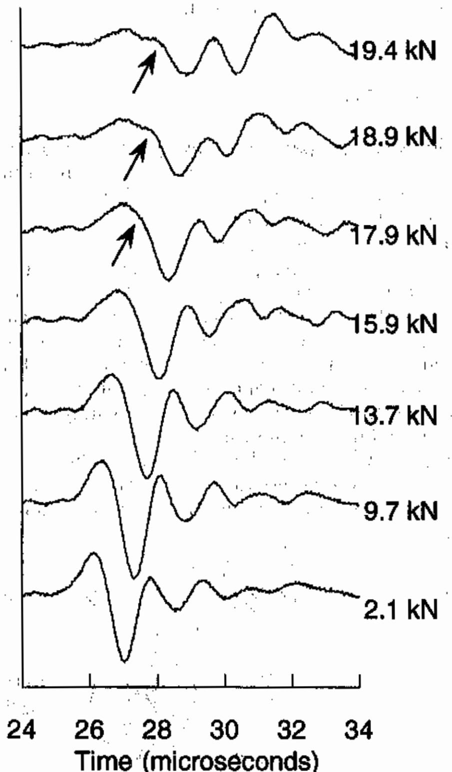

Figure 2. Received $S_\perp$ waveforms for a range of loads. Arrows indicate the inception of an interface wave.

4 DISCUSSION

The frequency content of an interface wave depends on the specific stiffness of the fracture. Roy & Pyrak-Nolte (1995) have shown that on pre-existing fractures, as fracture specific stiffness increases, the dominant energy in an interface wave shifts to higher frequencies. During the Brazil-mode failure process, a plane of weakness is induced as the load on the sample is increased. This plane of weakness consists of a distribution of microcracks that reduce the stiffness of this plane. If the observed waves are interface waves, a reduction in the frequency content of the signal would be expected. A wavelet analysis (Combes et al., 1989; Pyrak-Nolte & Nolte, 1995) of the received waveforms was performed to examine the energy partitioning during failure. The wavelet analysis provides a direct quantitative measure of spectral content as a function of arrival time, and is used to look for the signature of an interface wave, namely the spectral shift with change in stiffness.

Figures 4 & 5 show the group wavelet transformation for samples BS15 and the control BS16 for several loads. The contour represents lines of constant amplitude. For $S_{\perp}$ -waveforms from sample BS15, as the load on the sample increased from 13.7 kN to 17.9 kN, there is a large shift of the dominant energy from 0.58 MHz to 0.21 MHz. This shift in frequency content is consistent with the generation and existence of interface waves (Nagy , 1991; Pyrak-Nolte et al., 1992; Gu, 1994; Pyrak-Nolte and Nolte, 1995; Roy and Pyrak-Nolte, 1995), and is a signature of the partitioning of energy out of a bulk wave and into interface waves. 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 discontinuous micro-cracks that form during loading.

For $S_{||}$ -waveforms from sample BS16, the dominant energy exhibits a small shift to higher frequencies prior to failure (Figure 5). The spectral peak was observed to shift from 0.58 MHz at a load of 2.7 kN to 0.62 MHz for loads greater than 4.0 kN, and after failure the dominant energy occurred at 1.1 MHz. This increasing frequency behavior is opposite that expected for interface waves.

For samples BS15 and BS16, the energy partitioning between low and high frequency components of the signal is examined for two frequencies. Figure 6 shows the change in amplitude as a function of load for frequencies of 0.21 MHz and 0.54 MHz for sample BS15. The displacement as a function of load is also shown in Figure 6 for comparison. Initially, both the low and the high frequency energy increase with increasing load. A decrease in high frequency energy begins approximately at the same load when cracks begin to grow around 14 kN, and decreases by 65% just prior to failure. However, the low frequency energy component gains strength with increasing load and increases in amplitude by 120% between the initiation of crack growth and failure. As cracks grow along the plane of failure, the stiffness of this plane decreases which leads to the inception of interface waves. The growth of cracks is also indicated by a change in group velocity of the energy traveling at these two frequencies. As the sample deforms, the low and high frequency components of the energy are both delayed.

Examination of the spectral content for the $S_{||}$-waveforms show a spectral shift to higher frequencies as the sample is loaded to failure (Figure 5). For a frequency of 0.66 MHz and 1.18 MHz, the

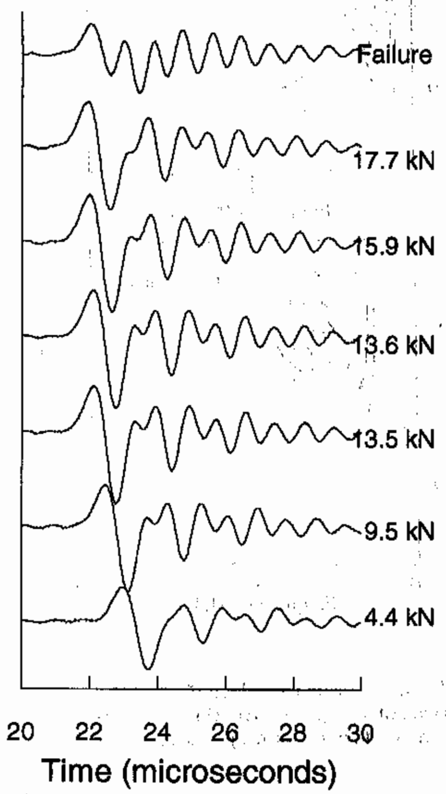

Figure 3. Received $S_{||}$ waveforms for a range of loads.

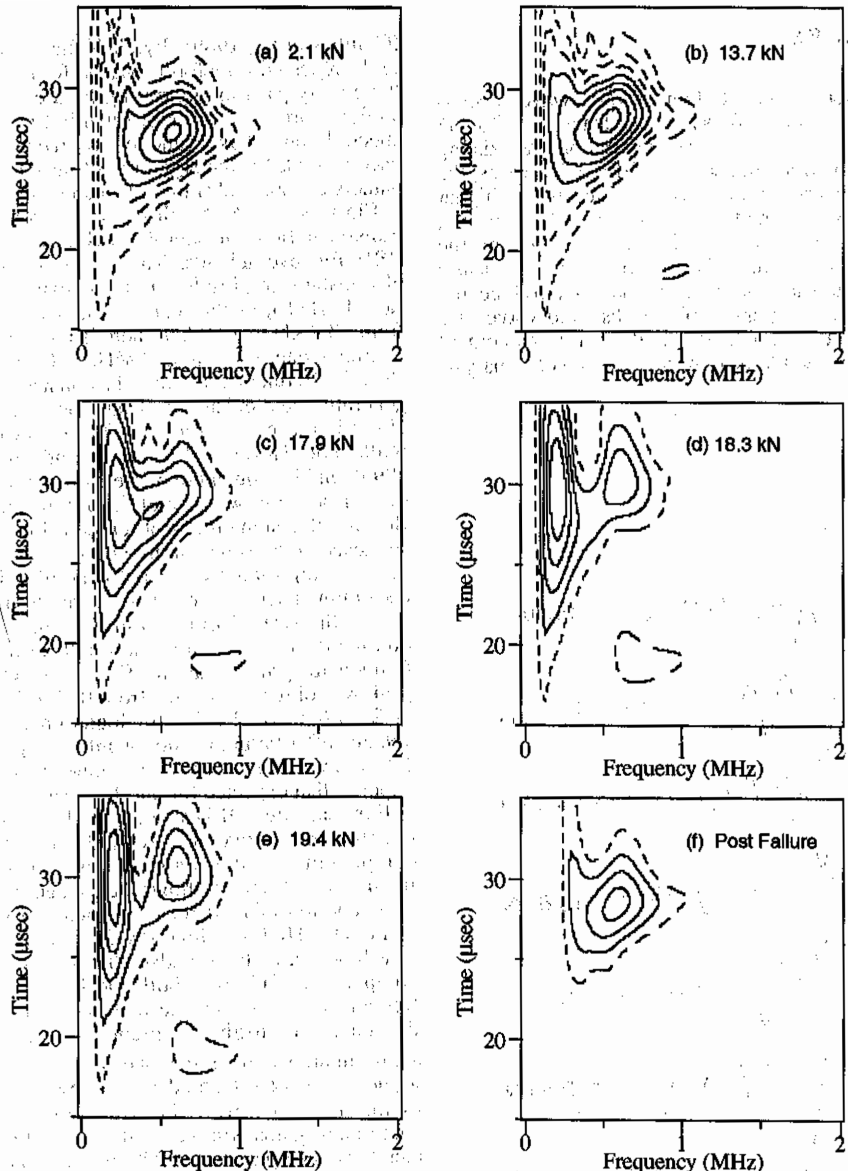

Figure 4. Group wavelet transformation of received $S_{\perp}$ waveforms for selected stresses. Contour ranges and intervals are (a)-(b) 10-80 in intervals of 10; (c)-(e) 10-50 in intervals of 10; (f) 10-40 in intervals of 10. Units of contours are Volts per root Megahertz.

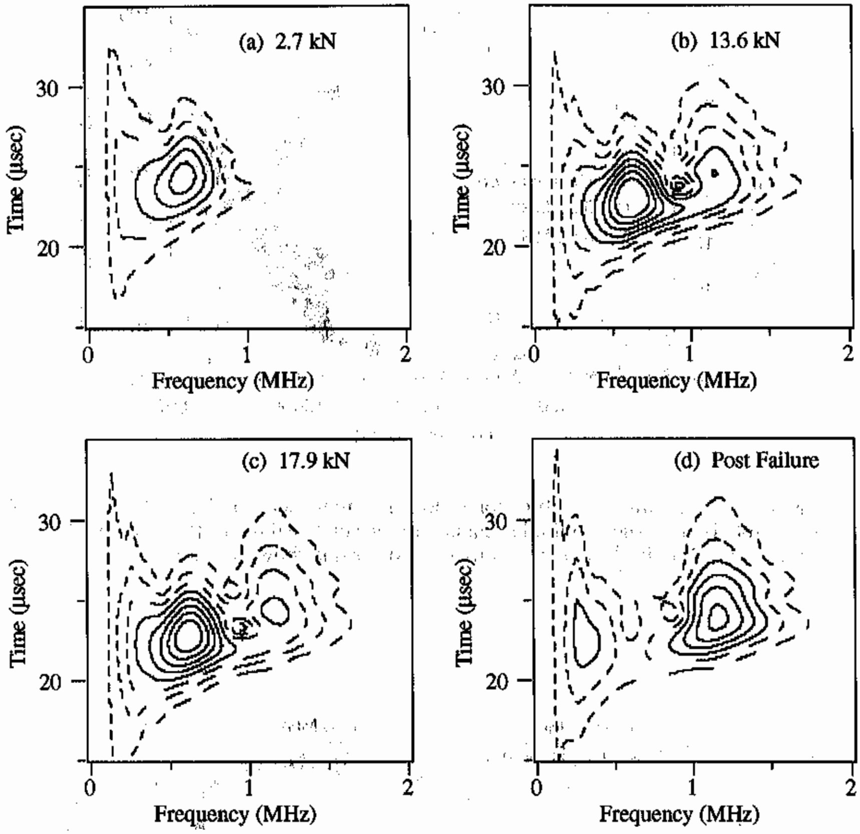

Figure 5. Group wavelet transformation of received $S_{||}$ waveforms for selected stresses. Contour ranges and intervals are (a) 25-125 in intervals of 25; (b)-(c) 25-200 in intervals of 25; (e) 25-150 in intervals of 25. Units of contours are Volts per root Megahertz.

energy at both these frequencies decreased only 10%-15% between a load of 15 kN (when crack growth begins) and failure. As observed in the received waveforms (Figure 4), the velocity of the $S_{||}$-wave increased with increasing load until crack initiation occurred. After crack initiation, the velocity at both frequency components plateaued. For this shear wave polarization, i.e. parallel to loading, the shear wave is sampling grain contacts that increase in stiffness with increasing load. From theoretical modeling of a single non-welded contact (Pyrak-Nolte et al., 1990; Nihei, 1992), an increase in stiffness of a non-welded contact increases the amplitude and velocity of the transmitted wave, and shifts the spectral content to higher frequencies.

5 SUMMARY

The seismic signature of the initial formation of a failure plane is the generation of incipient interface waves. These waves show a distinct shift in wave energy to lower frequencies as failure is approached. Furthermore, because the incipient interface wave is strongly sensitive to fracture properties, this provides a sensitive technique for monitoring the growth of microcracks during rock failure.

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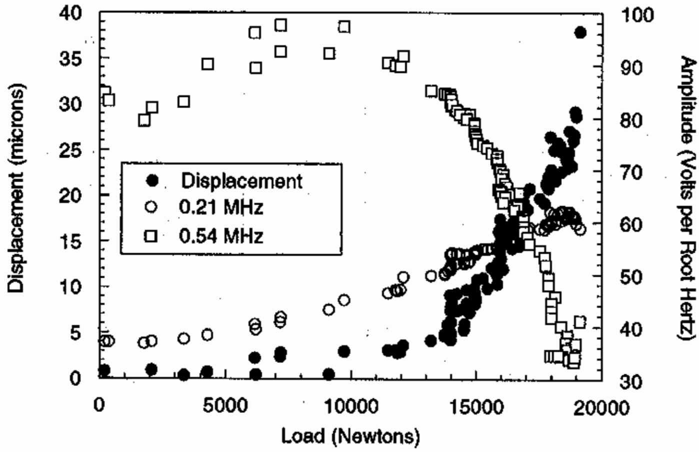

Figure 6. S⊥ amplitude as a function of load for frequencies of 0.21 MHz and 0.54 MHz for sample BS15. The amplitude data is form wavelet analysis of the received S⊥ waveforms. The displacement as a function of load is shown for comparison.

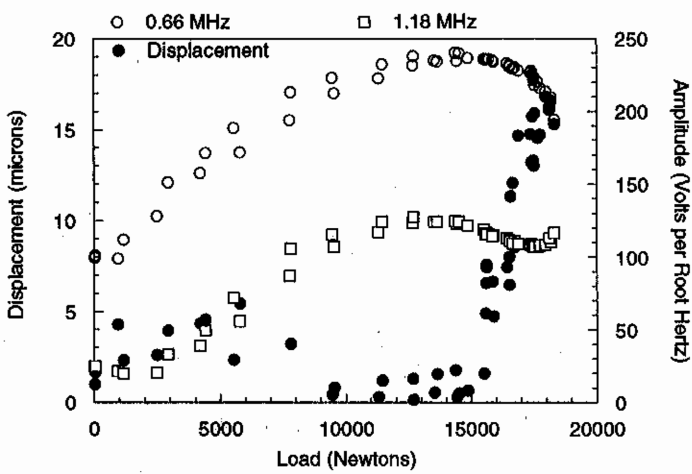

Figure 7. S|| amplitude as a function of load for frequencies of 0.66 MHz and 1.18 MHz for sample BS16. The amplitude data is form wavelet analysis of the received S|| waveforms. The displacement as a function of load is shown for comparison.

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