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Observation of a distinct compressional-mode interface wave on a single fracture

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Abstract. A compressional-mode interface wave propagating along a fracture has been observed in a fracture in limestone. This compressional-mode interface wave co-propagates with the bulk compressional wave, is localized to the region surrounding the fracture, and has particle motions containing both transverse and longitudinal displacements. As stress across the fracture increases, the wave energy shifts to earlier arrival times, and is accompanied by a decrease in the transverse displacement and an increase in the longitudinal displacement of the particle motion.

Introduction

Analytical studies as well as laboratory experiments have established the existence of "Rayleigh-type" interface waves that propagate along fractures in rock at velocities between the bulk shear-wave and the Rayleigh velocities (Pyrak-Nolte & Cook, 1987; Nagy, 1991; Pyrak-Nolte et al., 1992; Gu, 1994; Roy & Pyrak-Nolte, 1995; Ekern et al, 1995, Gu et al., 1996; Fan et al, 1996). These interface waves are dispersive, depend on the mechanical properties of the fracture and depend on the frequency content of the source signal. One of the most important signatures of these interface waves is the simultaneous expression of both shear and longitudinal particle displacement. As an alternative, Gu (1994) predicted numerically the existence of a distinct "compressional-type" interface wave using a point-source solution which propagates with a velocity near the velocity of the bulk compressional wave. This compressional-mode interface wave was predicted to be dispersive, to depend on the specific stiffness of the fracture, and also to contain both longitudinal and transverse particle displacements. However, this compressional-mode interface wave depends simultaneously on both shear and normal specific stiffnesses, while the two Rayleigh-type interface waves each depend on only one stiffness or the other.

In this letter, we present the first experimental observation of a compressional-type interface wave that co-propagates with the bulk compressional-wave. What distinguishes this new interface wave from the bulk compressional wave is the simultaneous expression of both transverse and longitudinal particle displacements, which are prominent close to the fracture plane but are absent farther away. This compressional mode wave has a frequency content that is strongly stress-dependent (unlike bulk compressional waves), and the wave is sensitive to fracture properties. All these features establish that this propagating wave is a distinct interface wave. This interface wave may be important for field measurements of fracture properties because this wave co-propagates with the bulk compressional-wave, and is not obscured by mode conversions or by other late-arriving signals.

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Experimental Method

Interface wave measurements were performed on an induced tensile fracture in a solid cylinder of limestone. The dimensions of the fractured sample and a companion intact sample are listed in Table 1. Measurements of compressional wave amplitude and velocity were performed as a function of stress (0 to 3.09 MPa) on an intact sample and on an fractured sample. The compressional waves were propagated along the axis of the cylindrical samples while stress was applied to the sample as shown in Figure 1.

Compressional-wave transducers (Panametrics Inc.) containing piezoelectric elements with a resonant frequency of 1 MHz were mounted straddling the center line of the cores (Figure 1b). The input pulse to the transducers (for both the intact and fractured samples) consisted of a 250 V square pulse with a 0.4 μs duration and a repetition rate of 100 Hz (Velonex Model 350). The received waveforms were digitized (Phillips Model 3375) and stored on a computer for analysis. Arrival times were read to within 0.02 μs.

The fractured sample was created by inducing a tensile fracture in an intact sample using a technique similar to Brazilian testing (Jaeger and Cook, 1979). The induced fracture spanned the diameter of the core, and ran parallel to the long axis. With the seismic transducers placed straddling the fracture, measurements of compressional and shear wave amplitudes and velocities were made as a function of normal stress on the fracture. Particle motions of the interface wave were measured using a compressional wave source, and receiving with a compressional (P) and a shear wave (Sv) transducer. The received waveforms from these two experiments were plotted against each other to give the particle motion. Multiscaling wavelet analysis was used to observe the time-frequency behavior of the wave (Pyrak-Nolte and Nolte, 1995). Measurements of compressional and shear wave amplitudes and velocities as well as particle motion were made for a companion intact sample.

Experimental Results

For the intact sample, the arrival time, amplitude and frequency content of the bulk compressional wave were stress independent. Figure 2a shows the waveforms received through

Table 1. Dimensions and density of fractured and intact samples.

Sample	Fractured	Intact
Diameter (cm)	5.05	5.05
Length (cm)	7.19	7.18
Density (kg/m^3)	2325	2348

the intact sample for three different stresses. From the measurement of first arrivals, the velocity of the bulk compressional wave was determined to be 4698 (±6.5) m/sec. In contrast, for the fractured sample, there was a significant change in the received waveform as the stress across the fracture was increased, as shown in Figure 2b. As the stress increased, the two positive peaks in the waveform that occur at 17.1 μs and 18.1 μs (at low stress) merge and interfere destructively. The waveform also appears to broaden, which corresponds to a decrease in the frequency content of the signal.

Wavelet Analysis

To extract specific time-frequency information from the received waveforms, a wavelet analysis was performed on both the intact and fractured waveforms. Wavelet analysis is a powerful technique that can isolate spectral energy from several coincident waves in a single waveform. Wavelets are therefore indispensable to this analysis in which the compressional-type interface wave co-propagates with the bulk compressional wave. Using wavelet analysis, we are able to show that the compressional-type interface wave is distinctly different from the bulk wave, and information about the interface wave can be extracted independently of the bulk wave.

A wavelet analysis (Morlet et al., 1982; Combes, 1989; Pyrak-Nolte & Nolte, 1995) was performed on the compressional waveform measured for the intact sample, and is shown in Figure 3a. The mother function for the wavelet analysis consisted of a first derivative of gaussian (1DOG) in quadature with a second derivative of gaussian (2DOG) wavelet. A DOG wavelet produces better time resolution than a Morlet wavelet analysis but sacrifices frequency resolution. Because of this trade-off in resolution, no conclusions on the frequency dependence of compressional-mode interface wave is made. Figure 3a shows the wavelet transformation for the intact sample at a stress of 3.09 MPa. The dashed line in Figure 3 indicates the distribution of energy in the positive anti-node at 16.8 μs observed in Figure 2a. At this arrival time, the dominant frequency of the signal occurs at 0.7 MHz. Applied stress had no measurable effect on the wavelet transformation for the intact sample.

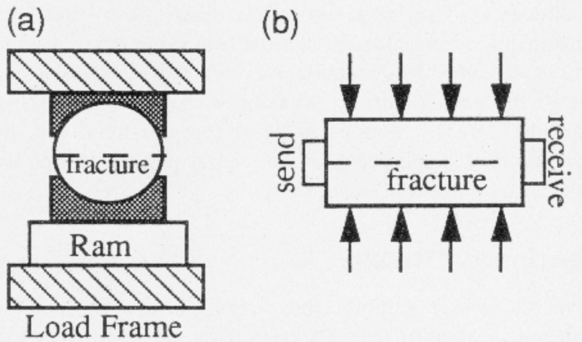

Figure 1. Sketch of experimental set-up to measure interface waves. (a) Loading configuration; (b) Transducer location.

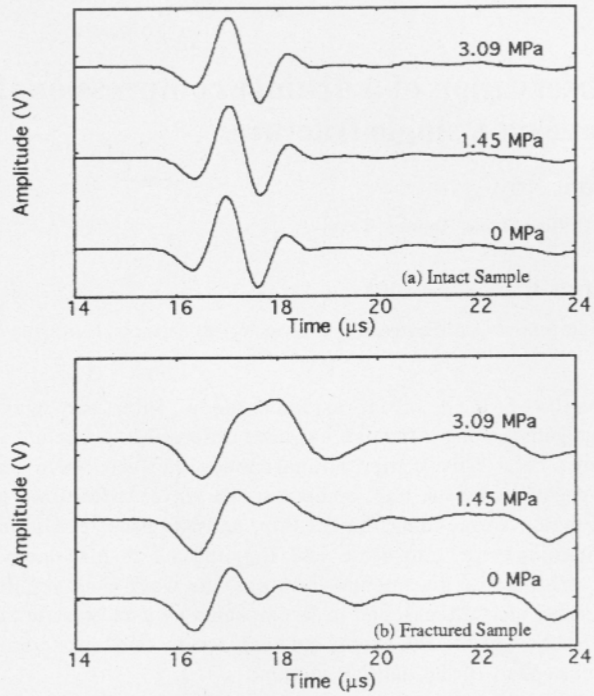

Figure 2. The effect of stress on received compressional waveforms for (a) intact sample and (b) fractured sample.

A wavelet analysis was then performed on the waveforms for the fractured sample. The wavelet spectra are shown in Figures 3(b), (c) and (d) for three different normal stresses. Both the bulk compressional wave (indicated by the dashed line) and the compressional-mode interface wave (labeled as PIW in the figure) are evident in the wavelet transformation. The solid line passing through Figure 3 b, c, and d is given to show the decrease in arrival time of the compressional-mode interface wave with increasing stress. For no applied stress on the fractured sample, the bulk compressional wave arrives at 16.8 μs with a dominant frequency of 0.7 MHz. The compressional-mode interface wave arrives at 19.1 μs with a dominant frequency of 0.3 MHz. As stress across the fracture is increased from 0 to 3.09 MPa, the compressional-mode interface wave shifts to earlier arrival times (18.4 μs). This behavior of the compressional-mode interface wave is similar to the Rayleigh-type interface waves (Pyrak-Nolte & Cook, 1987; Nagy, 1991; Pyrak-Nolte et al; 1992; Gu, 1994; Roy & Pyrak-Nolte, 1995), in which the peak of the spectral content shifts towards earlier arrival times as the stress across a fracture is increased. This aspect of stress-dependent arrival times provide strong evidence for the compressional-type interface wave. However, the strongest evidence for an interface wave is simultaneous transverse and longitudinal particle displacement.

Particle Motion

The particle motion of the compressional-mode interface wave was measured as a function of normal stress on the fracture. While the bulk compressional-wave has only longitudinal motion, interface waves contain both longitudinal and transverse particle displacements (Pyrak-Nolte & Cook, 1987; Gu, 1994; Gu et al, 1995; Fan et al., 1996). The particle motion of the arriving compressional energy is shown as a function of normal stress in Figure 4 for

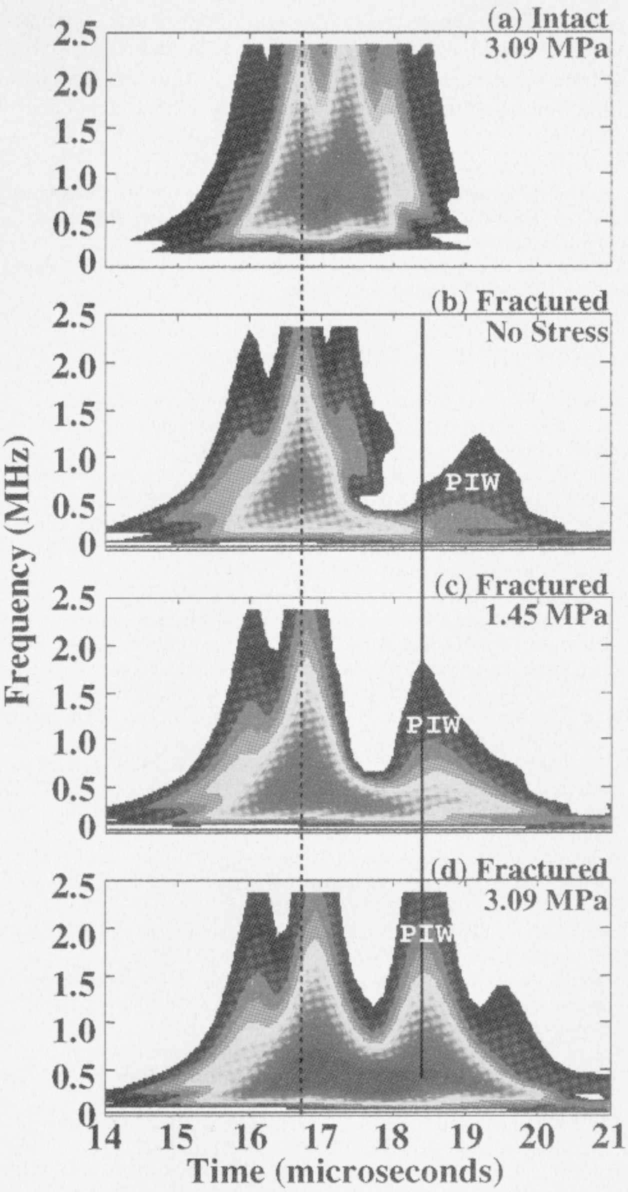

Figure 3. Group wavelet transforms of compressional wave through (a) intact sample, and (b) fractured sample for no stress, (c) fractured sample under 1.45 MPa, and (d) fractured sample under 3.09 MPa. The color represents the strength of the transform. The dashed line in (a) gives the location of positive anti-mode of the bulk compressional-wave from the intact sample. The dashed line is continued through (b)-(d) to compare the arrival time of the bulk compressional wave in the fractured sample under different stresses. The solid line is used to compare the arrival time of the compressional-mode interface wave (PIW) for different stresses on the fractured sample.

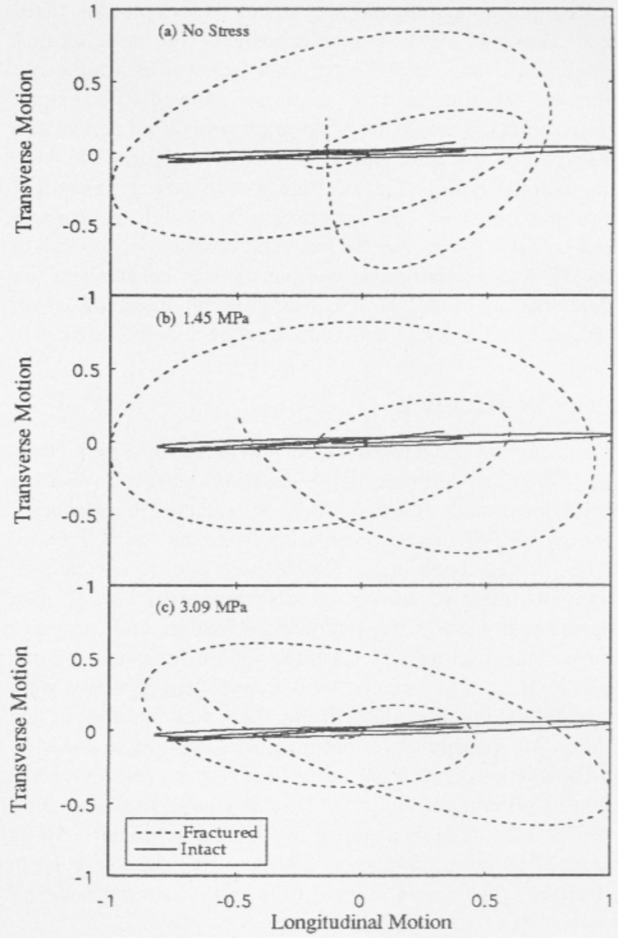

Figure 4. Particle motion as a function of stress (a) No Stress, (b) 1.45 MPa and (c) 3.09 MPa for an intact sample (solid line) and a fractured sample (dashed line). As stress on the fractured sample is increased, the amount of transverse displacement decreases and a phase shift is observed.

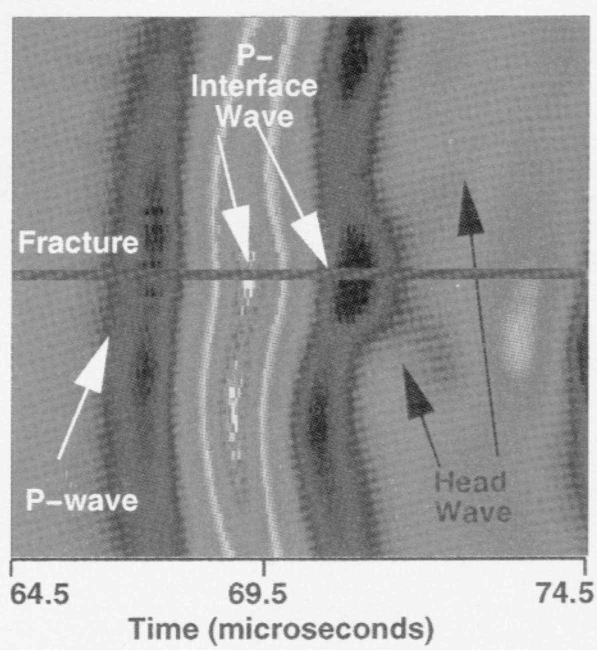

Figure 5. Sixty received waveforms along a 60 mm line perpendicular to a fracture. The location of the fracture is indicated by the blue line. Color represents the nodes and antinodes of the received waveforms. A high concentration of energy localized on the fracture is observed at 68.5 μs and is indicated by the red and yellow region. A head wave arrives at 71.7 μs and is indicated by the blue wings of energy on either side of the fracture.

both the intact sample and the fractured sample for three normal stresses. The x-axis represents the longitudinal displacement, and the y-axis represents the transverse component of the particle motion. The displacements measured from the amplitude of the waveforms were normalized with respect to the peak amplitude of the waveform. For the intact sample (solid line in Figure 4), only longitudinal motion was observed, and no effect of stress on the particle motion was observed. For the fractured sample (dashed line in Figure 4), a large transverse component was observed in the particle motion of the compressional-mode interface wave, which decreased as stress across the fracture was increased.

Energy Distribution

We examined the data obtained previously by Pyrak-Nolte et al. (1996) to determine if the observed wave is a distinct compressional-mode interface wave or is caused by scattering of energy or P-S mode conversions from the rough fracture surface. Pyrak-Nolte et al. (1996) used acoustic wavefront imaging to quantify the spatial distribution of energy in a compressional wave propagated along a fracture and compared it to the data from an intact sample. On a limestone sample measuring 9.1 cm in diameter by 9.3 cm in length, waves were propagated along the axis of the core and parallel to the fracture. An acoustic wavefront imaging technique was used to map the spatial distribution of the arriving wavefront over a 60 mm by 60 mm portion of the core in 1 mm increments for a 50 μs window. The data shown in Figure 5 represent a 10 μs window of 60 waveforms along a 60 mm line perpendicular to the fracture. The colors represent the nodes and anti-nodes of the waveform.

In Figure 5, the first arriving wave is the bulk compressional wave (P-wave) followed by the compressional-mode interface wave (P-interface wave). The compressional-mode interface wave is delayed by the fracture as indicated by the notch in the contours. Note in Figure 5, the high concentration of energy at the interface (black line) represented by the red-yellow region at an arrival time of 68 μs. The high concentration of energy localized on the fracture provides evidence that the compressional-mode interface wave is not caused by scattering of energy off of the interface because scattering and mode-conversion would be associated with a deficit of energy localized on the interface.

Therefore, based on the shifts in arrival time observed in the wavelet analysis, on the clear demonstration of simultaneous transverse and longitudinal displacements for the interface wave, and on the concentration of energy observed on the interface, we conclude that the evidence reported here supports the existence of a distinct form of a compressional-type interface wave that propagates along fractures.

Summary

An interface wave, associated with the compressional wave, but depending explicitly on the presence of a fracture, was observed to propagate along a tensile fracture in limestone. This wave travels close to the compressional wave velocity is found to be confined close to the fracture, and has particle motion containing both transverse and longitudinal displacements. As fracture stiffness increases with increasing stress, the transverse component of the particle motion decreases, with a corresponding increase in the longitudinal component.

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