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Influence of Source Frequency on Shear Wave Splitting - An Experimental Approach

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SUMMARY

Elastic anisotropy due to aligned cracks has been the subject of many seismic physical modeling experiments. Different experimental approaches related to sizes, shapes and density of cracks has been taken into account in earlier investigations. In this paper we present a physical study of shear-wave splitting in anisotropy induced aligned cracked media. In this experiment, rubber discs were used as inclusions in a solid epoxy resin matrix. Pulse transmission measurements were carried out on a reference model (without inclusions) and two other models with different aperture of cracks and dissimilar crack densities. The seismic records were measured using three different S-wave source transducers with dominant frequency of 0.1 MHz (low frequency), 0.5 MHz (intermediate frequency) and 1 MHz (high frequency). Crack apertures to seismic wavelength ratio were varied from 1.3 to 13.3 in one model and 2.3 to 23.5 in the second cracked model. Our results show that effects associated with acoustic scattering, attenuation and velocity dispersion interfere directly in shear wave splitting, which in turn is a function of crack aperture and source frequency.
Introduction

Elastic anisotropy due to aligned cracks has been the subject of many seismic physical modeling experiments. Previous experiments by Assa’d et al. (1993) established an experimental relationship between crack density and anisotropic parameters. In this paper, we extend this approach to a more specific case where thickness of layers in the models is at least 2 times lower in magnitude compared to seismic wavelength (low frequency source). Experiments were carried out on a reference model (without inclusions) and two other models with different sizes of inclusion and so different crack densities using the same penny-shaped rubber inclusions. The seismic sections were measured using three different shear wave transducers with dominant frequency ranging from 0.1 MHz (low frequency) and 0.5 MHz (intermediate frequency) to 1 MHz (high frequency). Crack aperture to seismic wavelength ratio was varied from 1.3 to 13.3 in one model and 2.3 to 23.5 in the second model. Shear wave splitting was observed in different magnitude as a function of frequency. Our result shows that effect associated with scattering and apparent attenuation interfere directly with shear wave splitting, which in turn is related to crack density. Results also show that anisotropic parameter $\gamma$ (Thomsen, 1981) varies with frequency and size of crack.

Experimental setup

The constructions of the cracked models as well as the ultrasonic measurements were carried out at the Allied Laboratories of Geophysics (AGL) at University of Houston. The rubber chips were cut using hole punchers which helped in creating uniformly sized chips. The same epoxy resin was used as matrix material for all models (both cracked and uncracked). Epoxy resin has P-wave velocity of 2700 m/s and S-wave velocity of 1260 m/s. Three models were analyzed in this paper. Model M1 was constructed without any inclusions under vacuum and is used as a reference model. Models M2 and M3 contain rubber inclusions as cracks. The sizes of the included rubber cracks in each model are displayed in Table 1. The same distance between layers (0.5 cm for M1 and 0.25 cm for M2) was ensured by using the same volume of epoxy resin poured for each layer. Included crack material for M2 was neoprene rubber with P-wave velocity ($V_p$) 1650 m/s, and included cracks for M3 was silicone rubber with $V_p$=1100 m/s. The crack density $\varepsilon$ in the cracked models was determined using the following equation,

$$\varepsilon = \frac{N \pi r^2 h}{V},$$

(1)

where $N$ is total number, $r$ is radius, $h$ is thickness of inclusions (aperture of cracks), and $V$ is volume of model. Equation 1 is a modification of Hudson’s relation (1981) for crack density computation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Crack density (%)</th>
<th>Measured distance (cm)</th>
<th>Density (g/cc) of model</th>
<th>Number of layers</th>
<th>Aperture of cracks (cm)</th>
<th>Diameter of cracks (cm)</th>
<th>Number of cracks per layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0 (Isotropic)</td>
<td>7.31 ± 0.02</td>
<td>1.18</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M2</td>
<td>4.5</td>
<td>7.29 ± 0.02</td>
<td>1.18</td>
<td>10</td>
<td>0.091</td>
<td>0.7</td>
<td>36</td>
</tr>
<tr>
<td>M3</td>
<td>3.8</td>
<td>7.32 ± 0.02</td>
<td>1.20</td>
<td>17</td>
<td>0.051</td>
<td>0.4</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 1: Physical parameters of the isotropic and anisotropic models M1, M2 and M3.

All S-wave seismograms displayed in this paper were recorded using a pulse transmission method. The source and receiver transducers were arranged on opposing sides of the model with initial shear wave polarization parallel to cracks. Changes in polarization was achieved by rotating both transducers every 10 degrees until polarization was again parallel (i.e. 0 to 180 degrees). In total, 19 traces were recorded in each section. The polarizations equivalent to 0 and 180 degrees correspond to the fast S-wave ($S_1$) but to 90 degree correspond to slow S-wave ($S_2$). All measurements were executed using the same configuration and experimental apparatus with three kinds of S-wave transducers. The delay time for all of them was 0.27 $\mu$s. Analog ultrasonic signal was digitalized into seismic signal using scale factor 1:10000. For velocity computation, each scaled delay time was
subtracted from observed arrival time. The accuracy of picking time was ± 0.02 µs that allow estimate velocity with error ± 0.1%. The pictures of the models M1, M2 and M3 as well as experimental sketch are visualized in the Figure 1.

![Fig 1](image_url)

**Figure 1:** (a) Cracked models M1, M2 and M3. All measurements were done in Y direction. (b) Experimental sketch setup used for seismogram records. (c) Both source and receiver transducers are rotated from 0 to 180 degrees for each seismogram.

**Results and analysis**

Figure 2 shows seismogram display of all models with three different frequencies. Model M1 (isotropic model) shows uniform first arrivals with S1 (0° and 180°) and S2 (90°) for all kind of transducer used. However small differences in first arrivals could occur in a purely isotropic model as a result of velocity dispersion due to attenuation (Stewart et al., 1984).

Shear wave splitting that can be observed in both models M2 and M3 in all frequencies shown. The magnitude of this birefringence also appears to depend on the frequency of source. In model M2, for low and intermediate frequencies, (0.1 MHz and 0.5 MHz), the delay between fast and slow shear wave is 70 ms and 56 ms respectively. In model M3 the values are 40 ms and 33 ms for low and intermediate frequencies respectively. In the case of high frequency transducer model M2 (Figure 3(a)) shows inconsistent fast and slow shear wave arrivals. This is expected because the wavelength of the pulse is almost equal (1 to 1.3) to the aperture of cracks in the model which leads to acoustic scattering. However, on applying a band pass filter of 1-5-35-40 to remove high frequency acoustic scattering, it is possible to see a shear-wave splitting magnitude of 18 ms (Figure 3(b)).

The frequency spectra were obtained for all S-wave seismograms shown in Figure 2. For seismograms 2(a) - M2 as well as Figure 2(a) - M3, two frequency peaks were observed. However in model M2 (f1=19 Hz and f2=75 Hz) the separation between peaks was more evident than in model M3 (f1=30 Hz and f2= 45 Hz). On the other hand, the seismic section associated with the second peak (75 Hz) can be observed in the Figure 3(c).

A band-pass filter was also applied to model M3 (Figure 2(a)) but no significant difference in shear wave splitting was noted. However the values of time arrivals for both fast and slow shear wave appear to depend on the slope of the band pass filter used. To avoid inconsistencies in time arrival picking which in turn leads to discrepancies in velocity and anisotropic parameter calculations, we used splitting values without applying filter. Observed delay between shear waves for model M3 is 30ms (see Figure 2(a)-M3). In model M3, pulse wavelength to crack aperture ratio is 1 to 2.3. This explains why there is less acoustic scattering and consistent time arrivals as compared to model M2.
The relationship between velocities $V_{S1}$ and $V_{S2}$ and source transducer frequency are shown in Figure 4(a)-M1, Figure 4(b)-M2 and Figure 4(c) - M3. Figure 4(d) shows anisotropy parameter $\gamma$ as function of source frequency. We can infer from these figures that magnitude of shear wave splitting appear to depend on frequency and apparent attenuation due to acoustic scattering. This splitting is more pronounced at low-frequency (0.1 MHz) for all cracked models. We can infer from Figure 4(d) the relationship between seismic frequency (and wavelength) and crack aperture. At high wavelength (low frequency) this anisotropy percentage is higher. This is because pulse wavelength is higher than crack aperture which leads to an effective response. In essence, there is no response or acoustic scattering from individual layers or cracks but rather the whole model behaves as an effective medium in low frequency.
Figure 4: Velocity plots for models M1 (a), M2 (b) and M3 (c) as a function of frequency (error ± 3 m/s). (d) Anisotropic parameter $\gamma = \frac{1}{2} \left( \frac{V_{S1}}{V_{S2}} \right)^2 - 1$ in models M2 and M3 as a function of frequency.

Conclusions

This experimental study has investigated the influence of source frequency on velocity measurements in anisotropic media containing aligned cracks. The results demonstrate that S-wave splitting has direct dependence on frequency of source. In low frequency limit, this splitting is more conspicuous. However, a decrease in birefringence is noted when the frequency is increased, this is evidence of high frequency scattering. This scattering effect is more pronounced when crack aperture is of the same magnitude as the source wavelength.

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References


