Effects of a Fracture on Ultrasonic Wave Velocity and Attenuation in a Homogeneous Medium.

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Abstract: Nondestructive acoustic testing is used to assess damage in infrastructure as a function of elastic wave velocity and attenuation variations. This study focuses on understanding the effects of a thin fracture on ultrasonic elastic wave velocity and attenuation. Experiments were performed on the effects of a thin interface fracture within polymethylmethacrylate (PMMA) specimens. Wave velocity and attenuation were measured across the width of the homogeneous specimen using the ultrasonic pulse velocity (UPV) method. Seventeen specimens (12.5 mm and 25.4 mm thick) were tested under three conditions. First, the intact annealed interface between two PMMA blocks was tested; then, specimens with a small hole perpendicular to the interface and milled ends were tested; and finally specimens with the center hole and an induced fracture at the annealed interface were tested. Four extra specimens, two with annealed (but weak) interfaces between blocks and two solid blocks, were tested during the fracture growth process under uniaxial strain-controlled test conditions. Wave velocity results show a marginal reduction up to 4% when damage in the form of a thin fracture is present; whereas there is a reduction of up to 60% in attenuation readings. The findings confirmed the reliability of using wave attenuation to identify the presence of thin fractures with the UPV condition assessment method in a homogenous medium.

CE Database subject headings: Ultrasonic Pulse velocity, fracture, attenuation, PMMA.

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Introduction:

Fracture propagation is studied to better understand material failure from crack nucleation, growth, and coalescence. Macroscale physical simulations have been carried out in various homogenous and heterogeneous materials, such as concrete, metals and ceramics, and, to a lesser extent, plastics (Ayatollahi et al. 2015; Haeri et al. 2013; Jiefan et al. 1990; Yang 2011). Standard procedures, such as the three-point test for concrete, exist to characterize fracture toughness (Gerstle, 2010; Tattersall and Tappin 1966). In the four-point test, two symmetrically vertical loads replace the single load (Gerstle, W., 2010), (ASTM 2010). In metals, the tear test is a standard procedure to measure fracture toughness (ASME 2001), and the Charpy test is also widely used (Tattersall and Tappin 1966). In the three-point and the impact test, the fracture initiation point is dictated by where the point load is applied or where a notch is placed. Tearing test and four-point tests let the fracture initiate in a flaw within a specified portion of the specimen, and this is regarded as an improvement, but unstable fracture growth remains a major limitation of these test procedures.

These methods are standardized because analysis is straightforward and can be easily compared. The tearing and multi-point tests involve loading, whereas impact tests involve a dynamic fracture initiation and propagation. In all these methods applied to materials, it is difficult to measure fracture growth in real time; once a threshold has been crossed, propagation is uncontrollably unstable, and only the peak load measurement has meaning.

Compressive loading to generate local tensile stresses and evaluate stable fracture toughness has a long history in rock mechanics: the Brazilian Test is widely used and standardized (Ulusay, 2015). Yang (2011), and Haeri et al. (2013) tested sandstone and rock-like specimens in a cylindrical mold (Fig.2a) containing two artificially created flaws to study fracture coalescence
under uniaxial compressive load. Ayatollahi et al. (2015) used PMMA to study fracture development in brittle material with V-notch as a stress concentrator within a specimen under compression; a fracture developed from the tip of the notch and eventually reached the other end of the specimen. All these are attempts to quantitatively observe fracture propagation under quasi-static conditions.

A stable and controllable fracture propagation test method is developed (Gomez Rodriguez et al. 2016), to evaluate fracture behavior of a weak, planar annealed interface between polymethylmethacrylate (PMMA) blocks. External compression forces are applied to a prepared incremental compression load, and is therefore stable. Any material exhibits Mode I fracture propagation, such as polycrystalline rocks and ceramic materials, concrete and mortar, can be tested with this configuration.

The material chosen for the study is PMMA because it is a transparent, permitting visual fracture growth tracking in real time along the weakly bonded interface being tested, and because it exhibits elastic and plastic deformation in a brittle manner. It is widely used and well understood material for basic studies of fracture (Ayatollahi et al., 2015), and has served previously as an analogue material to study rock (Rubin, 1983). PMMA can anneal itself through thermal bonding when subjected to high pressure and temperatures for a given period of time (Yang, 2011), providing the possibility of creating specimens under conditions or scenarios that produce a specific bond strength of an interface.

Specimens were created using two identical solid PMMA rectangular prisms, 101.6 mm × 152.4 mm and 25.4 or 12.7 mm thick (Fig. 1b, 1c), annealed along the long and narrow edges by heating under stress for a set time. A hole is drilled normal to the interface as a controlled stress
concentrator. Fig. 1(c) illustrates the growth of a fracture along the partially annealed interface as the axial compressive load is increased.

Elastic wave propagation methods are commonly used in nondestructive testing (NDT) of materials such as rock, soil, and concrete because, at low strains, wave propagation parameters depend on the elastic material properties (Santamarina et al., 2001; Breysse, 2012; Slawinski, 2010). Among the NDT methods, the ultrasonic pulse velocity (UPV) method is most commonly used in practice (Bungey et al., 2006), used in medicine, chemistry, physics, biology, and engineering.

Ultrasonic pulse velocity (UPV) method is used in the study to monitor thin stable fracture growth in PMMA under controlled laboratory conditions, envisioning future application to common processes in geotechnical, geological, petroleum and mining engineering. The UPV technique is used in accordance with the American Concrete Institute standard ACI 228.2R-13 to assess the quality of natural rocks and concrete elements (Hertlein, 2013; Malek and Kaouther, 2014), to quantify environmental impacts on geomaterials and concrete (Chen et al., 2015; Duan et al., 2011), and to determine material elastic properties (Ensminger and Bond, 2011).

Although velocity can be reliably used under certain conditions, UPV is not well-suited to identify heterogeneities such as cracks generated from loading conditions or environmental factors. In the case of such small-scale internal damage, wave attenuation from UPV test results is a more reliable measure (Chai et al., 2011; Kirlangic, 2013). Attenuation is sensitive to heterogeneities at many scales, and is used to characterize defects and heterogeneities in different materials (Aggelis et al. 2009; Chai et al. 2011; Yim et al. 2012). As a further development, Gaydecki et al. (1992) proposed frequency-dependent attenuation studies to assess aggregate particle distribution in a concrete specimen, so attenuation and frequency dependent approaches
might be used to assess an array of inhomogeneities such as several rocks. The relationship between the wave amplitude and mechanical damage is studied by Nogueria and Willam (2001) to estimate microcracks evolution in concrete. Moreover, Philippidis and Aggelis (2005) reported a significant effect of aggregate quantity on the wave velocity, whereas the attenuation was more influenced by the aggregate geometry. Chaix et al. (2003) evaluated thermal damage (microcracking) in concrete from wave attenuation data. Cerrillo et al. (2014) used both ultrasonic P- and S-wave data, on granite specimens to investigate the feasibility of wave attenuation to quantify the physical-mechanical properties of the medium. They pointed out the reliability of wave attenuation to assess properties such as apparent density, compressive strength, and dynamic elastic parameters.

Detection of a change in a medium using UPV depends primarily on the arrival time of the signal, not always a straightforward and practical measure. For instance, increasing the signal amplitude by a factor of 10 can lead to a different arrival time pick (Fig. 2), a particular issue if algorithmic arrival time detection is used. Despite a reasonable UPV history of several decades (Hertlein, 2013), there are no data on wave amplitude attenuation analysis to monitor change such as stable fracture growth in PMMA or similar material. We decided to study the interaction between thin fracture growth and changes in pulse velocity and wave attenuation to better understanding of fracture growth mechanisms along the weakly bonded interfaces created in PMMA specimens.

Theoretical Background

Ultrasonic wave parameters

Ultrasonic waves may be generated by different sources including piezoelectric, laser, electromagnetic, and mechanical transducers (Ensminger and Bond 2011). We used two
piezoelectric transducers with a frequency range of 20-100 kHz, placed on opposite sides of the element/specimen being tested, using silicone grease for consistent coupling (Krautkrämer and Krautkrämer, 2013). An ultrasonic wave pulse is emitted passes through the specimen and recorded; calculations using this data yield both velocity and attenuation.

In a homogenous solid, the pulse velocity $V_p$ is calculated as (ASTM C 597-02, 2003):

$$V_p = \frac{L}{T}$$  \hspace{1cm} (1)

Here:

$L$ is distance between the centers of the transducer faces and $T$ is the pulse travel time.

The wavelength $\lambda$ and frequency $f$ are related to the wave velocity as

$$V_p = f \cdot \lambda$$  \hspace{1cm} (2)

The selection of transducer frequency range in UPV can influence the evaluation process, and it is essential that the defect size be at least on the order of the wavelength to establish a practical chance of being recognized (Krautkrämer and Krautkrämer, 2013).

Attenuation arises from different mechanisms such as wave spreading, scattering, absorption and mode conversion (Santamarina and Fratta, 1998; Hellier 2001). It is commonly expressed as (Ensminger and Bond, 2011):

$$A_z = A_o e^{-z\alpha}$$  \hspace{1cm} (3)

$A_z$ and $A_o$ are the wave amplitudes at the beginning and after propagating a distance $z$ in a medium, and $\alpha$ is the attenuation coefficient. We used the area under the waveform spectra to approximate the attenuation of signal energy similar to Eq (3) by comparing the spectra area of the corresponding amplitudes to estimate attenuation as the interface fracture propagated.
Attenuation arises from different mechanisms such as wave spreading, scattering, absorption and mode conversion (Santamarina and Fratta, 1998; Hellier 2001). Wave spreading is simply geometrical attenuation as a wave propagates out from a source, spreading outward in all available directions. Scattering is the reflection of waves at acoustic impedance oriented differently than the original direction of propagation. The conversion of wave energy to other forms of energy such as heat is known as absorption. Mode conversion occurs when an acoustic wave encounters an interface between materials of different acoustic impedance, and a part of the energy is transformed into different waveforms and are reflected or refracted along different ray paths.

Experimental program

**PMMA specimen fabrication and characterization**

Seventeen PMMA specimens with lightly bonded (annealed) interfaces and two intact specimens were made. The seventeen interface specimens were subjected to different pressure, temperature and time conditions (TABLE 1) to produce different levels of annealing. Seven of the annealed specimens were 12.7 mm (1/2 in) thick, ten were 25.4 mm (1 in) thick.

To create an annealed interface, two flat-milled PMMA prisms are placed in a steel jig that restrains out-of-plane movement and allows normal compressive stresses to be applied. The jig is placed in an oven, a steel bar is used to distribute the load evenly, and a dead weight load applied to the steel bar. This set up is heated to a temperature of 150° C (Gomez Rodriguez, et al., 2016). After a prescribed time set by the desired degree of interface annealing, the specimen cools in the oven under the applied load.

The specimens are then milled to final dimensions of 150 × 100 × 12.7 or 25.4 mm. A 6.3 mm hole is drilled symmetrically through the annealed interface (Fig. 2b) to serve as a stress
concentrator. At this point, a second ultrasonic test is performed on each specimen to assess the impact of milling and the creation of hole on the acoustic signals.

Once preparation is complete, a specimen is placed in a MTS (322) frame set on displacement control at 0.1 mm/min (Fig. 3.a), then the displacement and corresponding load recorded continuously. Four specimens ultrasonically tested during fracture propagation had piezoelectric transducers glued on the thin edges after the centre hole was drilled, but prior to loading. These transducers remained during loading and unloading stages until the maximum load was reached.

**Ultrasonic testing setup**

The UPV setup consists of two transducers, a function generator, an oscilloscope, and a laptop computer (Fig. 4). Transducers of nominal frequency 54 kHz and 50 mm diameter were used for emitting and capturing the ultrasonic pulse. Plastic transducer holders were created using a 3D printer and connected by two elastic cords to sustain a constant contact pressure on both transducers. Coupling grease was applied between the transducers and PMMA surfaces to reduce signal losses caused by air voids. Excitation consisted of a square waveform from the function generator, with a centre frequency of 60 kHz and amplitude of 10 volt peak to peak.

To minimize the effect of random noise and enhance signal quality, 16 readings were averaged during each UPV measurements, giving a good standard deviation less than 0.0001 [V]. The time signal is then converted to a frequency spectrum using the fast Fourier transform [FFT] technique, and the area under this spectrum used as a parameter to quantify signal attenuation in a comparative manner during fracture growth.

Figs. 4a and 4b show the means of the sixteen signals obtained for each test in both time and frequency domains, with standard deviations of $5.7 \times 10^{-4}$ and $4.37 \times 10^{-6}$ [V], respectively. The
delay time was determined in two ways: by a face-to-face test, and with standard test specimens such as aluminum and steel billets of various lengths. This delay time $2 \times 10^{-6}$ s was subtracted from the signal arrival time to calculate the wave velocity.

For signals acquired during testing of the PMMA specimens under stress in the load frame, time window processing was used to reduce noise and improve spectrum peak identification. Fig. 4c and 4d show the improvements that occurred when various time windows (called Tukey windows) are used.

**Testing procedure**

The seventeen specimens were tested under three configurations. First, the intact annealed interface was tested (case A); then, specimens with a small hole perpendicular to the interface and milled ends were tested (case B); and finally specimens containing a centre hole and an induced interface fracture of some length were tested (case C). Four extra specimens, two annealed and two solid, were tested during the fracture growth process under uniaxial strain-controlled conditions. All specimens showed fracture initiation in the interface at the contact with the starter hole, and continued to propagate toward both ends of the symmetric specimen with increased uniaxial displacement (Fig. 2c).

Table 2 summarizes the testing procedures of PMMA specimens. As specified loads were reached, the fracture length was recorded and a UPV reading taken. A final UPV reading was taken for all specimens once the maximum fracture length was reached and the specimens were retrieved from the loading frame. The signal was sampled at every microsecond for 4000 $\mu$s. The signals were processed using Mathcad 14 to determine the arrival times and velocities of the ultrasonic pulses.
Results and discussion

In this investigation, the effect of propagating a thin-aperture crack along a weak interface on ultrasonic UPV signals acquired in both time and frequency domain is studied under different conditions.

Load-displacement response of PMMA specimens.

During the fracture propagation test, the applied load and displacement of the actuator are measured constantly. Although stress and strain are not homogeneously distributed across the entire specimen because of the hole and the fracture propagation, we decided to use the nominal intact cross-sectional area and the nominal length to calculate an “equivalent” stress and strain for the plots and analysis.

Fig. 6 shows stress-strain plots from four PMMA specimens (PA-1, PA-2, PS-1, PS-2) obtained from the load tests. An equivalent stiffness, Young’s modulus ($E$), was calculated from the curves. Two distinct zones (initial and final) are identified (Fig. 7 shows the details): the initial part of the curve with a steeper average slope (zone A in Fig. 7), and the terminal part of the curve with a flatter average slope (zone B in Fig. 7). Two equivalent moduli, $E_a$ and $E_b$, are calculated from the plots (Fig. 7), and $E_b$ is taken to represent the overall specimen stiffness once the fracture has propagated to some distance along the interface. $E_a$ and $E_b$ for four PMMA specimens are summarized in Table 3, and we note that $E_b \approx 0.55 E_a$. Values of $E_a$ obtained from this study were found to be close to the values for PMMA found in the literature (1.8 – 31 GPa); the effects of the small circular hole and the fracture propagation at the initial stages do not have a significant impact on the load-displacement response of the PMMA specimens. The dynamic Young’s modulus determined from the UPV measurements was found to be 4.96 GPa for annealed specimens and 4.66 GPa for solid specimens, values about three times greater than $E_a$. 
The controlled fracture propagation approach allows fracture length to grow stably as a function of a greater compressive load on the specimen. Fig. 8 shows the plots of load versus observed fracture length of four PMMA specimens. The relationship for the annealed specimens demonstrates approximately linear fracture growth until 90 kN load; thereafter, fracture lengths increased at higher rates with added loads. The solid specimens exhibited a linear trend until a load of 90 kN, and 120 kN, for specimens SP-1 and SP-2, respectively, at which point macroscopic fractures formed in the solid specimens and propagated, but at a lower rate than in the annealed specimens, this is expected behavior because of the low fracture toughness of the annealed interface.

Different specimens exhibited a similar fracture propagation growth rate. The fracture lengths observed in annealed specimens are greater than those of the solid specimens. The maximum fracture length observed in the annealed specimens is 7.1 cm. In contrast, the maximum fracture length in the solid is 1.5 cm. The presence of weak interface in the annealed specimens results in lower loads required for producing fracture - i.e. lower fracture toughness. It is worth mentioning here that the fracture orientations in all PMMA specimens were found to be normal to the loading direction. Thus, the fabrication method used to produce the annealed PMMA specimens provides an effective procedure for monitoring fracture growth.

**Fracture interaction with wave velocity**

The UPV measurements of PMMA specimens tested at three configurations (A, B, and C) were analyzed to determine the arrival times and P-wave velocities. Fig. 9 shows the ultrasonic pulse velocities of PMMA specimens with different thicknesses (12.7 mm and 25.4 mm) versus the specimen number for all cases. The main values of UPVs of the thin PMMA specimens are determined as 2720 m/s ± 12 (case A), 2718 m/s ± 10 (case B), and 2630 m/s ± 10 (case C).
UPVs of thick PMMA specimens are found to be 2803 m/s for (A) intact specimens and (B) specimens with holes, respectively. While for (C) damage case the UPV was 2709 m/s.

The wave velocities of the intact and hole configurations are almost identical with small variations. There were average only minor differences of 2% and 3.6% between the values of UPVs corresponding to the initial (case A) and final (case C) conditions, respectively. Thus, the difference between the reference initial cases and damaged cases cannot be considered a strong indicator to quantify the fracture propagation. Moreover, the variability observed in the results of the thin thickness can be attributed to the testing conditions and the narrow surface area used to take UPV measurements. In which, the amount of signal energy emitted from the transducer through the thin PMMA specimen is less than the energy in the case of thick specimens.

Fig. 10 shows the variations of the UPV determined after testing two PMMA specimens, annealed and solid, as example behaviours. In Fig. 10(a), the wave velocity was slightly decreased because of the influence of fracture within the annealed zone when the load exceeds 70 kN. After 125 kN, the wave velocity decreased linearly which may be attributed to the travel path of wave becoming longer than the reference case because of the existence of fracture that occupied by air. It is well known that the speed of wave in air around 340 (m/s), which means practically the wave spends longer time in travelling. Unlike the annealed specimens, the wave velocities of solid specimens do not show any kind of variation because the wave was not influenced by the fracture growth, which is lower than the annealed one. The results of wave velocities have demonstrated that a single measurement cannot be sufficient to characterize the existence of fracture in the PMMA specimens.

Fracture interaction with wave attenuation in time domain
Fig. 11 shows time domain signals obtained for PMMA specimens 12.7 mm. In this figure, the time signals of cases A and B exhibit a slight reduction in maximum amplitude (13%); while in C, waveforms experienced a noticeable reduction because of the fracture existence (62%). The reduction of signal amplitude can be related to the absorption and scattering mechanisms (Krautkrämer and Krautkrämer 2013) because of the presence of the fracture at the annealed zone. Similar findings were obtained for the other PMMA specimens that fabricated and tested under same conditions.

Fig. 12 shows typical variations in waveform amplitudes with respect to the configurations adopted, the differences between intact and the other two cases were found to be around 13% for hole, and 45% for the damage case. This provides another example of using signal attenuation as a complementary tool to study the interaction between the ultrasonic waves and internal condition of a homogenous material such as the PMMA specimens.

UPV measurements were obtained during the fracture propagation of the PMMA specimens within the loading frame to monitor the impact of fracture growth over the ultrasonic wave energy in the annealed and solid conditions. Fig. 13 shows waveforms corresponding to three selected load steps at the beginning of loading (no load applied), loading corresponding to 10 mm fracture, and loading corresponding to the end of the tests for both annealed and solid PMMA specimens. The observed reductions in maximum amplitudes between waveforms with respect to the initial measurement are 36% and 68% for the annealed PMMA specimens, 50% and 76% for the solid PMMA specimens.

**Fracture interaction with wave attenuation in frequency domain**

Figs. 14 and 15 show the corresponding frequency spectra (magnitudes) of the signals obtained of PMMA specimens tested at three cases (A, B, and C). To quantify the attenuation of waveforms during the fracture propagation, areas under frequency spectra of signals are calculated.
The relationship between frequency and the presence of fracture existence is investigated by defining distinct zones under the frequency spectrum as low band zone (LB) comprising of the range 20-40 kHz, and high band zone (HB) comprising of the range 40-70 kHz (Fig. 14). This is beneficial to assess the sensitivity of frequency to the fracture at the interface zone A comparison was made considering the results of three criteria: area under low band, area under high band, and total area.

The frequency spectra of (Figs. 14 and 15) confirm the results obtained in the time domain of the testing signals that revealed the reduction of wave amplitudes because of the fracture existence. There were slight variations in spectra between cases A and B. The existence of holes was not enough to cause attenuation in signals. While the comparison of the frequency spectra between the intact and damage cases had revealed a noticeable influence of the fracture on the signal spectrum. It is worth to mentioning, that all the spectra obtained from the PMMA specimens tested at the three configurations exhibit similar patterns.

To evaluate the fracture influence, areas under the low and high band frequencies are examined. Fig. 14 shows the difference in the total area of the intact case versus the hole and damage cases of a typical PMMA specimen which are found to be 15% and 52%, respectively. In the case of low and high frequency bands for the annealed specimen, the low bands do not exhibit any variation whereas reduction percentages for high bands were 15% and 57%, respectively. Similar observations were found in other PMMA specimens. Figs. 14 and 15 illustrate the dependence observed between the high frequency and the fracture growth in PMMA material.

Monitoring stable fracture propagation during strain controlled test provides a reliable procedure to examine the interaction between the fracture and waveforms. In which, the transducers were glued to the PMMA surfaces to help provide a constant bond to obtain identical
waveforms during the tests. During the test of PMMA specimens under strain controlled loading, ultrasonic signals were acquired. The frequency spectra of these signals were used to evaluate the potential effect of fracture induced under the applied load.

The peaks of signal spectra that were recorded from testing PMMA specimens under the strain controlled loading were not easily identifiable. In which, the signal spectra showed more peaks so require to apply a time window technique to obtain clear peaks for the main frequency components of the spectra. To do so, a time window with factor 0.1 was used to enhance the peaks by smoothing the spectra and reduce the peaks number. Fig. 16 shows the window signals corresponding to selected load steps of a typical annealed specimen. It can be seen that frequency spectra become easily identifiable after applying the window. In the case of annealed configuration, the wave velocity exhibits a slight variation until the test reaches the load of 130 kN, beyond which the reduction in velocity was pronounced (Fig. 10). In contrast, the attenuation of signal spectrum reveals more sensitivity to the fracture at earlier load steps, (Fig. 16).

At the end of the test, the reduction observed in signal attenuation was significant. It is important to note that all PMMA specimens exhibit similar results. Close examination of the spectrum corresponding to case where there is no load applied, reveals three peaks can be identified which are correspond to frequencies $f_1 = 54$ kHz, $f_2 = 30$ kHz, and $f_3 = 16$ kHz. When the load increased, the peaks in spectra experienced a slight shifting which can be attributed to the fracture conditions in the annealed specimens.

Another interesting outcome is the peak under $f_1 = 54$ kHz was the most susceptible to fracture than the other two peaks. The corresponding wavelengths for the aforementioned frequencies ($f_1 = 54$ kHz, $f_2 = 30$ kHz, and $f_3 = 16$ kHz) $\lambda_1 = 5$ cm, $\lambda_2 = 9$ cm, and $\lambda_3 = 16.7$ cm for wave velocity of 2715 m/s. The wavelengths determined for the end test results were $\lambda_1 = 4.8$ cm,
\[ \lambda_2 = 8.9 \text{ cm}, \quad \lambda_3 = 17.8 \text{ cm} \] for wave velocity of 2004 m/s. The variations in wavelengths were attributed to the reduction that occurs to the wave velocity.

Fig. 17 shows the results obtained from the signals of a typical solid specimen during fracture propagation. The findings were identical to that observed in annealed specimen with the exception that peaks exhibit slight variations. For the cases of initial upon loading measurements and at 10 mm of fracture propagation, the peaks observed correspond to frequencies \( f_1 = 56 \text{ kHz} \) \( (\lambda_1 = 4.8 \text{ cm}) \), \( f_2 = 30 \text{ kHz} \) \( (\lambda_2 = 8.9 \text{ cm}) \), and \( f_2 = 15 \text{ kHz} \) \( (\lambda_3 = 17.8 \text{ cm}) \), respectively. While the values of end test waveform were found to be \( f_1 = 56 \text{ kHz} \) \( (\lambda_1 = 4.8 \text{ cm}) \), \( f_2 = 30 \text{ kHz} \) \( (\lambda_2 = 8.9 \text{ cm}) \), and \( f_2 = 16.5 \text{ kHz} \) \( (\lambda_3 = 16.2 \text{ cm}) \), respectively. Thus, like annealed specimen, the peak under high frequency band \( (f_1 = 56 \text{ kHz}) \) was more susceptible to fracture in comparison to other peaks.

To investigate the interaction between the fracture and wave attenuation, the same procedure was followed after testing 15 PMMA specimens under the aforementioned three cases. The relation between the fracture with respect of wave energy was quantified by determining the total, low band and high band areas of wave spectrum.

In Fig. 18, the relationship between fracture, spectra areas and load steps are shown and the gradual reduction of the wave energy in two cases, annealed and solid, can be observed. This was accompanied by a noticeable propagation of fracture at the centre lines of both cases. Furthermore, the high band was more sensitive to the fracture propagation than the low band as it was noticed in previous discussion in this article. The sensitivity of wave attenuation to fracture induced by loading can be a potential indicator for quantifying damage in PMMA specimens.

The new fabrication method used to produce the annealed PMMA specimens provides an effective procedure to monitor the stable fracture growth under quasi-static loading. Furthermore,
the nondestructive testing of the PMMA specimens pointed out that a single measurement of the pulse velocity may not be sufficient to detect internal damage in homogenous medium. In which, the determination of wave arrival times need to be achieved with precaution, otherwise may lead to incorrect values of wave speeds. The sensitivity of high frequency ($f > 50$ kHz) to fracture highlighted the reliability to use the wave attenuation as a complementary tool to characterize the fracture growth in PMMA specimens.

Conclusions

The ultrasonic pulse velocity test was performed on 19 PMMA specimens of two different thicknesses under three cases; intact, hole, and hole with fracture. While four PMMA specimens of annealed and solid conditions were tested under strain controlled test during fracture propagation. In this article, new fabrication technique was used to produce stable fracture growth at the annealed interface of bonded PMMA blocks under quasi-static loading. Furthermore, the combination of ultrasonic pulse velocity and signal attenuation was used to characterize the stable fracture growth in PMMA specimens.

The UPV results show the questionable relationship between wave velocities and fracture (velocity variation$\approx 4\%$). Nevertheless, the observations of signal amplitudes and corresponding frequency spectra obtained from the ultrasonic measurements indicated that a change occurred in the condition of the specimens ($\approx 60\%$). Moreover, the comparison of frequency spectra confirms the increase of wave attenuation because of fracture growth. The readability of frequency spectrum peaks obtained from strain controlled test was improved by using a time window technique. The spectra of damaged PMMA specimen shown that high frequencies ($f > 50$ kHz) were more susceptible to the fracture propagation than lower frequencies ($f < 40$ kHz). While the dynamic
modulus of elasticity of the PMMA specimen calculated based on UPV was three times greater than static modulus.

The new fabrication method of annealed PMMA specimens provides an effective procedure for monitoring fracture growth. Also, the nondestructive testing of the PMMA specimens pointed out that a single measurement of the pulse velocity may not be sufficient to detect internal damage in homogenous medium. The study reveals the determination of arrival time requires a careful selection to avoid obtaining incorrect values of wave velocities. Furthermore, it is recommended to explore the use of attenuation to overcome the aforementioned concerns of the pulse velocity measurements to assess the fracture conditions in PMMA material. The most interested finding of this study is the sensitivity of wave amplitude to characterize the discontinuous (fractures) in PMMA material.
**Notation**

The following symbols are used in this paper:

- $A_o$ = wave amplitude at a distance $z$ in a medium;
- $A_z$ = wave amplitude at the beginning in a medium;
- $f$ = frequency;
- $L$ = distance between centres of the ultrasonic transducers;
- $T$ = arrival time of the ultrasonic wave;
- $V_p$ = longitudinal wave velocity;
- $z$ = distance; and
- $\alpha$ = coefficient of attenuation.
Acknowledgment

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References


### TABLE 1. List of PMMA specimens tested and their corresponding bonding conditions

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Type</th>
<th>Thick. (mm)</th>
<th>No.</th>
<th>Temperature (°C)</th>
<th>Duration (Hrs)</th>
<th>Pressure (KPa)</th>
<th>Pressure (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA-(1-4)</td>
<td>Annealed</td>
<td>25.4</td>
<td>4</td>
<td>150</td>
<td>6</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>PA-(5-8)</td>
<td>Annealed</td>
<td>25.4</td>
<td>4</td>
<td>150</td>
<td>6</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>PA-(9-10)</td>
<td>Annealed</td>
<td>25.4</td>
<td>2</td>
<td>150</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>PA-(11-13)</td>
<td>Annealed</td>
<td>12.7</td>
<td>3</td>
<td>150</td>
<td>6</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>PA-(14-16)</td>
<td>Annealed</td>
<td>12.7</td>
<td>3</td>
<td>177</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>PA-17</td>
<td>Annealed</td>
<td>12.7</td>
<td>1</td>
<td>177</td>
<td>6</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>PS-(1-2)</td>
<td>Solid</td>
<td>25.4</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### TABLE 2. Outline of testing procedure of PMMA specimens

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Type</th>
<th>Testing configuration</th>
<th>Testing method</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA-(1-4)</td>
<td>Annealed</td>
<td>A,B,C</td>
<td>UPV</td>
</tr>
<tr>
<td>PA-(5-8)</td>
<td>Annealed</td>
<td>A,B,C</td>
<td>UPV</td>
</tr>
<tr>
<td>PA-(9-10)</td>
<td>Annealed</td>
<td>A,B,C</td>
<td>UPV</td>
</tr>
<tr>
<td>PA-(11-13)</td>
<td>Annealed</td>
<td>A,B,C</td>
<td>UPV</td>
</tr>
<tr>
<td>PA-(14-16)</td>
<td>Annealed</td>
<td>A,B,C</td>
<td>UPV</td>
</tr>
<tr>
<td>PA-17</td>
<td>Annealed</td>
<td>A,B,C</td>
<td>UPV</td>
</tr>
<tr>
<td>PS-(1-2)</td>
<td>Solid</td>
<td>D</td>
<td>UPV</td>
</tr>
</tbody>
</table>

A, B, and C are intact case, with hole case, and with fracture case, respectively, D is the testing configuration under strain controlled.

### TABLE 3. Elastic moduli of specimens tested under strain controlled test.

<table>
<thead>
<tr>
<th>Zone #</th>
<th>Static elastic modulus, $E$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PA-1</td>
</tr>
<tr>
<td>A</td>
<td>1.69</td>
</tr>
<tr>
<td>B</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Figure 1. (a) Schematic of a general fracture in a specimen during a compressional test, (Haeri et al., 2013) (b) schematic of PMMA specimen, and (c) perspective view of PMMA specimen with hole and fracture.

Figure 2. Typical arrival times of PMMA specimen signals, (a) fracture signal, (c) fracture signal magnified by a factor of 10.
Figure 3. (a) Prepared specimen of dimensions 152 mm by 100 mm (6 in by 4 in), milled short ends and hole in the centre ready to be tested, (b) fully fractured specimen loaded in compressive displacement mode at 0.01mm/min. It exhibits buckling at the ultimate load.
Figure 4. The ultrasonic pulse velocity instrumentation setup using fabricated plastic transducer holder.
Figure 5. Typical measurements, (a) sixteen averages in time series, (b) corresponding sixteen averages spectrum, (c) signal with applied time widows, (d) signal and windows spectra. where (a) original time signal and (b,c) time window factors $0.1$ and $0.3$, respectively.
Figure 6. Typical average stress – average strain curves for annealed and solid PMMA specimens.

Figure 7. Typical defined zones in stress-strain curve of PMMA specimen. where A and B are initial and final zones, respectively.
Figure 8. Fracture propagation of four PMMA specimens, annealed (PA) and solid (PS), tested under strain controlled test.
Figure 9. Average ultrasonic wave velocity of PMMA specimens (a) 12.7 mm thick. (b) 25.4 mm thick.
Figure 10. Typical effect of fracture propagation with respect to ultrasonic wave velocity of PMMA specimens (a) annealed condition (b) solid condition.
Figure 11. Typical signals in time domain of PMMA specimen (12.7mm) tested at three configurations.

Figure 12. Typical time signals of PMMA specimen (25.4mm) tested at three configurations.
Figure 13. Time signals of two PMMA specimens (25.4mm) measured at three different loading steps (10 mm fracture): a. annealed specimen. b. solid specimen. $P$ is the load and $L$ is the fracture length.
Figure 14. Typical average spectra of two PMMA specimens (12.7mm) tested at three cases.

Figure 15. Typical frequency spectra of PMMA specimens (25.4 mm) tested under three configurations.
Figure 16. Application of Tukey window on signals acquired during testing a typical annealed specimen under strain test in frequency domain. \( A_{sp} \) is total area percentage with respect reference spectrum, and \( R_F \) is fracture percentage with respect maximum fracture length.

\[ f_1 = 54 \text{ kHz} \]
\[ f_2 = 30 \text{ kHz} \]
\[ f_3 = 16 \text{ kHz} \]
\[ A_{sp} = 1.00, R_F = 0.0 \]
\[ A_{sp} = 0.76, R_F = 0.14 \]
\[ A_{sp} = 0.27, R_F = 1.00 \]

Figure 17. Application of Tukey window on signals acquired during testing solid specimen under strain controlled machine in frequency domain. where \( A_{sp} \) is total area percentage with respect reference spectrum, and \( R_F \) is fracture percentage with respect maximum fracture length.

\[ f_1 = 56 \text{ kHz} \]
\[ f_2 = 30 \text{ kHz} \]
\[ f_3 = 15 \text{ kHz} \]
\[ A_{sp} = 1.00, R_F = 0.0 \]
\[ A_{sp} = 0.73, R_F = 0.47 \]
\[ A_{sp} = 0.39, R_F = 1.00 \]
Figure 18. Typical effect of fracture propagation on spectra areas of PMMA specimens tested under strain controlled machine (a) annealed specimen and (b) solid specimen.