Miniature Beryllium Split-Hopkinson Pressure Bars for Extending the Range of Achievable Strain-Rates

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Abstract: Conventional Split Hopkinson Pressure Bars (SHPB) or “Kolsky” bars are often used for determining the high-rate compressive yield and failure strength of materials. However, for experiments generating very high strain-rates (>10^3/s) miniaturization of the setup is often required for minimizing the effects of elastic wave dispersion in order to enable the inference of decreasingly short loading events from the data. Miniature aluminum and steel bars are often sufficient for meeting these requirements. However, for high enough strain-rates, miniaturization of steel or aluminum Kolsky bars may require prohibitively small diameter bars and test specimens that could become inappropriate for inferring representative properties of materials with large grain size relative to the test specimen size. The use of a beryllium Kolsky bar setup is expected to enable high rates to be accessible with larger diameter bars/specimen combinations due to the inherent physical properties of beryllium, which are expected to minimize the effects of elastic wave dispersion. For this reason, a series of beryllium Kolsky bars have been developed, and, in this paper, the dispersion characteristics of these bars are measured and compare the data with those of similarly sized 7075-T6 aluminum and C350 maraging steel. The results, which agree well with the theory, show no appreciable frequency dependence of the elastic wavespeed in the data from the beryllium bars, demonstrating its advantage over aluminum and steel in application to Kolsky bars.

Keywords: Kolsky bar; beryllium; dispersion; high strain-rate; metals

1. Introduction

The Conventional Split Hopkinson Pressure Bars (SHPB) or “Kolsky” bars are often used for determining the high-rate compressive yield and failure strength of materials. However, for experiments generating very high strain-rates (>10^3/s) miniaturization of the setup is often required for minimizing the effect of elastic wave dispersion in cylindrical bars in order to appropriately infer decreasingly short loading events from the data [1–6]. The limit on the maximum measurable strain-rate for a Kolsky bar experiment can be taken to have two major requirements [4]: (1) The deformation in the test specimen must be approximately homogeneous (i.e., dynamic equilibrium must be achieved) and (2) the measured stress pulses must undergo minimal dispersion (i.e., the signals must be corrected for dispersion) for the SHPB analysis to maintain a high temporal resolution. A limiting criterion for testing brittle materials stipulates that the time for material failure, \( t_f \), must be greater than a limiting time, \( \tau \), (i.e., \( t_f \geq \tau \)). This limiting time can be taken as the minimum time required for both (1) and (2) to be satisfied (i.e., \( \tau = \max\{ \tau_{\text{eq}}, \tau_{\text{r}} \}\)). The time required for the test specimen to reach stress equilibrium, \( \tau_{\text{eq}} \), is proportional to the transit time in the specimen, i.e., \( \tau = aL/\sqrt{Cs} \), where \( L \) and \( C_s \) are the length and elastic wavespeed in the specimen and \( a \) is some multiple of the transit time (often taken to be \( > 4 \) [4]). The limit on the temporal resolution of the analysis, \( \tau_{\text{r}} \), is related to the transit...
time of discrete wave frequencies that make up the traveling stress pulse within the bar (i.e., $\sim \alpha_2d_{\text{bar}}/C_n$), where $d_{\text{bar}}$ and $C_n$ are the diameter of the bar and the characteristic speed for individual wave frequencies that make up the traveling waves, and $\alpha_2$ represents some multiple of the transit time. The rise time associated with the measured signals are limited by the differences in the wavespeed of these discrete wave frequencies because of the effect of elastic wave dispersion in cylindrical bars, which must be corrected for optimal interpretation of the measured results. The characteristic speed associated with these frequencies has been found to be proportional to the elastic wavespeed of the bar, $C_{\text{bar}}$ and can be expressed as a function of the ratio $d_{\text{bar}}/\lambda$ (i.e., $C_n/C_{\text{bar}} = f(d_{\text{bar}}/\lambda)$) where $\lambda$ is the characteristic wavelength for each particular frequency. For small values of $d_{\text{bar}}/\lambda$, the Raleigh approximation [7] can be used to demonstrate the relationship of the phase velocity to the uniaxial stress wavespeed,

$$f(d_{\text{bar}}/\lambda) = 1 - \frac{\pi^2}{4} \left( \frac{d_{\text{bar}}}{\lambda} \right)^2$$  \hspace{1cm} (1)$$

where $v$ is the Poisson’s ratio of the bar material. The limiting strain-rate can then be written as

$$\dot{\varepsilon}_{\text{max}} = \frac{\varepsilon_f}{\tau}$$  \hspace{1cm} (2)$$

where $\varepsilon_f$ is the desired final strain on a specimen for a particular experiment. Hence, (2) may be expanded as

$$\dot{\varepsilon}_{\text{max}} = \min\left\{ \frac{\varepsilon_f C_b}{\alpha L_s}, \frac{\varepsilon_f C_{\text{bar}} f(d_{\text{bar}}/\lambda)}{\alpha_2 d_{\text{bar}}} \right\}$$  \hspace{1cm} (3)$$

Equation (3) shows that both the specimen length and bar diameter size (often both) can be decreased for accessing higher strain-rates, which serves as one main motivator for miniaturization of Kolsky bars. Miniaturization of aluminum and steel bars are often sufficient for meeting these requirements, which enables Kolsky bar experiments to extend to higher strain-rates. However, for very high strain-rates, miniaturization of steel or aluminum (Al) Kolsky bars may require prohibitively small diameter bars and test specimens that may become inappropriate for inferring representative properties of materials with large grain size relative to the test specimen size. The larger elastic wavespeed of beryllium (Be) relative to Al and steel (refer to Table 1) enables high strain-rates to be accessible with larger diameter bar/specimen combinations, making it better suited for conducting high-rate experiments that employ materials with large grain sizes. Additionally, the theory (e.g., Equations (1) and (3)) shows that the extremely low Poisson’s Ratio of Be relative to Al and steel is expected to minimize the effect of elastic wave dispersion [8], which further extends the maximum measurable strain-rate in Kolsky bars.

Table 1. A few pertinent physical properties of commercial purity beryllium, 7075-T6 aluminum, C350 maraging steel, and Ti6Al4V.

| Material       | Density (kg/m³) | Elastic Modulus (GPa) | Elastic Wavespeed (m/s) | Poisson’s Ratio | Yield Strength (GPa) |
|----------------|-----------------|-----------------------|-------------------------|-----------------|----------------------|
| 7075 T-6 *     | 2810            | 71.7                  | 5051                    | 0.33            | 0.5                  |
| Aluminum *     | 2800            | 71.0                  | 5051                    | 0.33            | 0.5                  |
| C350 Steel *   | 8080            | 200                   | 4975                    | 0.3             | 2.4                  |
| Ti6Al4V *      | 4430            | 114                   | 5073                    | 0.33            | 0.83                 |
| S200F Beryllium * | 1844          | 303                   | 12,820                  | 0.05            | 0.24 **              |

* Physical properties are taken from supplier. ** Taken from [9].

Be Hopkinson pressure bars have been used in the past due to the materials high elastic wavespeed, which allows for shorter rise-times [10] and for measurements to extend to higher frequencies in comparison to other bar materials [11]. However, to the knowledge
of the authors, the experimental determination of the elastic wave dispersion characteristics of these bars and the use of Be in miniature Kolsky bars has never been published until now.

For these reasons, a series of Be Kolsky bars have been developed, and, in this paper, the dispersion characteristics of these bars are experimentally determined using the approach outlined by Bacon [12] and the data is compared with those of similarly sized 7075-T6 Al and maraging steel bars. These measurements, which agree well with the numerical solution of the Pochhammer-Chree equations [13,14], reveal the frequency dependence of the elastic wavespeed of the different Kolsky bar setups. The results show no appreciable frequency dependence of the elastic wavespeed for the range of resolvable frequencies in Be Kolsky bar experiments, demonstrating the significant advantage of the use of Be for Kolsky bars in comparison to Al and steel. The new Be Kolsky bars are expected to extend the range of measurable strain-rates for larger specimen volumes in comparison to miniature Al and steel Kolsky bars. This advantage will be especially usefully for testing representative volume elements (RVE) of low strength brittle materials (e.g., polymer bonded explosives), as required, due to their large grains relative to the finite test specimen size [15,16]. Ascertaining the statistical response of the minimum RVE is important for developing constitutive models that bridge scales [16].

In Section 2, a description of the general layout of the Kolsky bars is provided, and the experimental method is described. In Section 3, the results and discussions are presented. Finally, the main points are summarized in Section 4.

2. Materials and Methods

2.1. General Description of the Kolsky Bar Apparatus and Laser Diagnostics

The Kolsky bar (or Split-Hopkinson Pressure Bar) is a well-established apparatus for determining the mechanical stress–strain response of materials for a wide range of strain-rates. The classic arrangement [2,17,18], which is employed for all setups herein, is shown schematically in Figure 1.

![Figure 1](image)

*Figure 1. A general layout of the Split-Hopkinson Pressure Bar setup.*

The main components of a general Kolsky bar apparatus include a simple firing mechanism and three bars (i.e., the striker, incident, transmitted bars) that are held within a tight tolerance support fixture for maintaining good alignment between the components of the system. The striker bar is accelerated down the steel barrel using the firing mechanisms and is made to impact the incident bar. The impact between the striker and incident bar generates a stress pulse which travels from the incident bar to the transmitted bar. The measurement of the traveling stress pulses at the measurements points (shown as red circles in Figure 1) are required for the interpretation of the experimental data and are typically measured using strain gauges [19]. However, for all of the experiments presented herein, photonic Doppler velocimetry (PDV) with probes inclined relative to the bar axis is used for monitoring the traveling pulses. The schematic of the present PDV system and the placement of the PDV probes relative to the Kolsky bar apparatus is shown schematically in Figure 2.
Accordingly, a series of Kolsky bar setups have been developed each optimized for testing with and without an acousto-optic modulator (AOM), respectively. The source of reference light (boxed by dotted line) light is split from the illuminating source using a single mode 90:10 fused coupler (TW1550R2A1), for probe-to-reference, respectively, and can be frequency upshifted. For the present experiments, frequency modulation did not show any appreciable differences in the measured signal, hence, the PDV is not frequency modulated.

2.2. Kolsky Bar Geometry and Material Specifications

The geometry of the bars (i.e., diameter and length) and bar material are selected based on the desired range of rates and stresses that each setup is expected to achieve. Accordingly, a series of Kolsky bar setups have been developed each optimized for testing materials of different strength and range of loading rates. The specifications of the present bar setups including the bar material, bar diameter, bar length, barrel length are provided in Table 2.
The striker, incident, and transmitted bars are made from centerless grinding, cutting, and polishing tight tolerance bar stock. In all the setups discussed herein, except for Setup #1, the steel bars are made from C350 maraging steel (supplier: Boston Centerless). For Setup #1, commercial gauge pins made from Tool steel with a rockwell hardness of C60 (McMaster Carr 21135A33 and 2162A11) are employed. In all setups, titanium and aluminum bars are made from tight tolerance bar stock of Ti6Al4V and 7075-T6 Al, respectively (McMaster Carr, Al: 1800T513 and 9063K25). Beryllium bars are made from commercial purity beryllium S200F (certified to AMS 7906) and were centerless ground, cut, and polished by Materion. For all materials except for Be, the striker, incident, and transmitted bars are made from the same material, however, for setups employing Be, the striker bars are made from either Ti6Al4V titanium or 7075-T6 aluminum based upon the desired impedance match and projectile velocity range. The substitution of Be for a Ti or Al striker also minimizes the risk of generating Be residues by the friction between the steel barrel and the accelerating projectile, which could pose a health risk if dispersed.

2.3. Experiments for Determining the Elastic Wave Dispersion Characteristics of the Bars

As discussed in Section 1, the limit on the temporal resolution of the analysis, $\tau_r$ of any particular setup is related to the transit time of discrete wave frequencies that make up the stress pulse within the bar. The rise time associated with the measured signals are limited by the differences in the wavespeed of these frequencies. The relationship between the characteristic speed and frequency has been found to be proportional to the elastic wavespeed of the bar and is a function of the ratio $d_{bar}/\lambda$ (i.e., $C_n/C_{bar} = f(d_{bar}/\lambda)$). This dependence has been calculated from theory [14,18] and, corrections must be applied to the data to account for these differences for proper interpretation of the measured data. Most often the characteristic speeds from theory are used for applying the corrections, however, for miniature bars, less than perfect alignment, machining tolerances, and even the heterogeneous material microstructure [1] can limit the characteristic speeds of the bar. In these cases, there is a limit of agreement between the linear elastic wave propagation theory and the actual bar characteristic speeds. For this reason, it is useful to directly measure the phase speed versus frequency for a bar setup. This can be performed using the approach detailed in [12].

Briefly summarized here, a dispersion correction often involves performing a Fourier Transform of the measured signal and then reconstructing the signal after applying a frequency dependent phase correction [27]. For example, take the impact of a single bar of length, $L_2$ by a striker bar of length, $L_1$, the associated T-X diagram for this impact configuration is shown in Figure 3. This impact will result in a traveling wave originating at position, $X = 0$ with the duration of $2L_1/C_{bar}$. At the measurement location, the traveling pulse will arrive at times $L_2/2C_{bar}$, $3L_2/2C_{bar}$, $5L_2/2C_{bar}$, and so on. Let $\tilde{e}(\omega)$ be the

### Table 2. Table of bar specifications for each configuration.

| Setup Number | 1 | 2 | 3.1–3.3 | 4.1–4.3 |
|--------------|---|---|---------|---------|
| Material(s)  | Steel, Steel, Steel | Al, Be, Be | Al, Al, Al | Al, Al, Al |
| Bar Diameter (mm) | 1.1—0.84 | 1.2—0.31 | 2.41 | 4.80 |
| Bar Length (mm) | 12.7–25.4, 50.8, 50.8 | 12.7–25.4, 101.6, 101.6 | 25.4, 203.2, 203.2 | 50.8, 457.2, 457.2 |
| Barrel Length (mm) | 203.2 | 203.2 | 457.2 | 457.2 |

*a* the values provided refer to the striker, incident, and transmitted bars, respectively. *b* Setup 1 is available in two different size combinations denoted 1.1 and 1.2. Setups 3 and 4, are available in three different material combinations denoted 3.1–3.3 and 4.1–4.3. *c* the material used in setup 1 is off-the-shelf gauge pins (60/65 Rc Tool steel) and is different from the C350 maraging steel used in setups 3 and 4.
Fourier transform of the strain pulse $\tilde{\varepsilon}(t)$. In this scenario, it is possible to relate the former pulses to the later pulses, e.g.,

$$
\tilde{\varepsilon}_1(\omega) = \tilde{\varepsilon}_3(\omega)e^{i\phi_3(\omega)}
$$

(4)

where the phase difference between the two pulses, $\phi_3(\omega) = k(\omega)2L_2$, accounts for the distance that the pulse has propagated and contains a frequency dependent wave number, $k(\omega)$ representing the different wave number for each discrete frequency making up the traveling pulse. The wave number can be written as

$$
k(\omega) = \frac{\omega}{C_n(\omega)}
$$

(5)

From determining the frequency dependent wavenumber, it is trivial to also determine the characteristic speed as a function of frequency. The frequency dependent wavenumber can be computed from the measured pulses using

$$
k(\omega) = -\frac{1}{2L_2} IM\left\{\ln\left(\frac{\tilde{\varepsilon}_1(\omega)}{\tilde{\varepsilon}_3(\omega)}\right)\right\}.
$$

(6)

Figure 3. The T-X diagram of a striker bar of length $L_1$ impacting a single bar of length $L_2$. This impact results in a traveling wave originating at $X = 0$ with the duration of $2L_1/C_{bar}$, and arrives at the measurement location, $X_2$ at times $L_2/2C_{bar}$, $3L_2/2C_{bar}$, $5L_2/2C_{bar}$, and so on.

3. Results and Discussion

For experimentally determining the elastic wave dispersion characteristics of the Be, Al and steel bars, a series of “bars-apart” experiments have been performed. In bars-apart experiments, the incident and transmitted bars are separated, and no sample is placed between the bars. A summary of the experimental conditions for each designated experiment in the series is provided in Table 3, which includes the setup #, projectile velocity, bar material, and the pulse travel distance. These experiments are designed to reveal the effects of wave dispersion, for this reason, the largest bar setup (setup 4) has been chosen. A total of three experiments employing setup 4 are conducted, one for each of the material of interest.
Table 3. A summary of the experimental conditions for all Kolsky bar experiments conducted in the present investigation.

| Experiment Number | Setup Number | Bar Material       | Striker Velocity (m/s) | Pulse Travel Distance (mm) |
|-------------------|--------------|--------------------|------------------------|----------------------------|
| 0082102602        | 4.1          | 7075-T6 Al         | 10.9                   | 454.3                      |
| 0085102602        | 4.2          | C350 Steel         | 11.3                   | 457.6                      |
| 00219102          | 4.3          | S200F Beryllium    | 10.8                   | 477.5                      |

Figure 4 shows the velocity versus time after the arrival of the incident pulse at the PDV monitoring locations for all experiments and Fourier decomposition of the velocity history into power amplitude versus frequency. In all experiments, the solid black curve is the pulse measured as it first arrives at the measurement location on the incident bar (incident pulse) and the red dashed curve is the pulse measured after its reflection off the free surface of the incident bar and arrival back at the measurement point (reflected pulse). Here, the pulse travel distance refers to twice the distance of the measurement location from the free surface of the incident bar.

In a typical Kolsky bar experiment, the propagation of a compressive wave along the bar axis results in a radial motion of the bar due to the Poisson’s effect, moreover, the radial inertia of the bars results in a two-dimensional state of stress. These effects manifest in elastic wave dispersion and cause local fluctuations that can be observed on the plateau region of the traveling pulses. These oscillations due to elastic wave dispersion can be readily seen in Figure 4A,B, however, due to the low Poisson’s ratio of beryllium, these effects are virtually eliminated for beryllium bars, which can be observed in Figure 4C. These observations qualitatively show the reduced elastic wave dispersion in beryllium Kolsky bars in comparison to aluminum and steel. It should be noted that the small amplitude low frequency oscillations that are observable in the plateau region of Figure 4C, are believed to be caused by contributions from a small amount of bending, since these oscillations do not appear in the reflected pulse.

To quantitatively assess the differences in the dispersion characteristics of this Kolsky bar setup for different materials, the analysis procedure described in Section 2.3 Equations (4)–(6) is employed. In Equation (6), $L_2$ is the pulse travel distance. In these experiments, the traveling wave pulses generated by the impact of the striker on the incident bar is composed of a spectrum of frequencies. The Fourier decomposition of the velocity time history into power amplitude versus frequency for all experiments (also shown in Figure 4) shows the power amplitude associated with the frequency spectrum. The power amplitude decreases with frequency. It is worth noting, that for all the present experiments, it was found that the frequency components beyond 300–400 KHz were not resolvable. There exists a characteristic speed associated with each of these frequency components. Typically, the higher frequency components have a slower characteristic speed in comparison to lower frequency components, which results in dispersion of the traveling pulses. The characteristic wavespeed versus frequency, and ratio of wavespeed by the speed of the fundamental frequency ($C_n/C_o$) versus the ratio of bar diameter by wavelength ($d/\lambda$) for all experiments is shown in Figure 5. The plots show the frequency dependence of the wavespeed, on the left, and, a comparison between the present experiments and the numerical solution of the Pochhammer-Chree equations on the right. The plots reveal an initial wavespeed equal to the extensional wavespeed (i.e., $\sqrt{E/\rho}$) of the material, however, for (A) and (B) (7075-T6 aluminum and C350 maraging steel, respectively) the wavespeed decreases with increasing frequency for the range of resolvable frequencies (up to 300–400 KHz). Within this range, there is excellent agreement between the present experiments and theory, however, beyond this limit there is an abrupt deviation from the theoretical solution marking the limit of validity of the present analysis due to the inability to resolve higher frequency components. (C) shows the results for beryllium Kolsky bars, which reveals no appreciable dependence of the wavespeed with frequency for the range of resolvable
frequencies. This reveals no noticeable elastic wave dispersion in the measured signals for beryllium kolsky bars. Demonstrating its advantage over aluminum and steel kolsky bars.

Figure 4. The velocity history and Fourier decomposition of the velocity history into power amplitude versus frequency for (A) 7075-T6 aluminum (0082102602), (B) C350 maraging steel (0085102602) and (C) S200F beryllium (00219102) experiments. The velocity history reveals oscillations on the plateau of the traveling pulses that manifest due to the elastic wave dispersion. These effects are minimized in the Beryllium setup in comparison to aluminum and steel. The Fourier decomposition of the velocity history shows the power amplitude versus frequency of the signal. In the present work, it was possible to resolve and analyze frequencies up to 300–400 KHz.
Figure 5. The characteristic wavespeed versus frequency, and ratio of wavespeed by the speed of the fundamental frequency ($C_n/C_o$) versus the ratio of bar diameter by wavelength ($d/\lambda$) for (A) 7075-T6 aluminum (0082102602), (B) C350 maraging steel (0085102602), (C) S200F beryllium (00219102) experiments. The plot shows no frequency dependence of the wavespeed for the range of resolvable frequencies for the beryllium Kolsky bar.

From these results and from the criterion for the maximum measurable strain-rate in Kolsky bars discussed in Section 2, it was concluded that beryllium bars can be used to extend the range of measurable strain-rates. Ultimately, this will enable the use of larger Kolsky bars/specimens for reaching exceedingly high strain-rates, which will be especially useful for testing representative volumes of low strength brittle materials with large grain sizes.
4. Conclusions

In summary, a series of Be Kolsky bars have been developed, and the dispersion characteristics of these bars are experimentally measured using “bars together” experiments. The data from beryllium was compared with those of similarly sized 7075-T6 aluminum and C350 maraging steel bars. The results, which agreed well with the numerical solution of the Pochhammer-Chree equations, revealed the frequency dependence of the elastic wavespeed of the different Kolsky bar setups. The results showed no appreciable frequency dependence of the elastic wavespeed for the range of resolvable frequencies in Be Kolsky bar experiments, demonstrating the significant advantage of the use of Be for Kolsky bars in comparison to Al and steel. From these results, and from the theoretical limit of measurable strain-rate, it was concluded that the new Be Kolsky bars can be used to extend the range of measurable strain-rates for larger specimen volumes in comparison to miniature Al and steel Kolsky bars. This advantage will be especially usefully for testing low strength brittle materials (e.g., polymer binded explosives).

Author Contributions: Conceptualization, investigation, Methodology, formal analysis, Writing—review and editing, B.Z., K.J.R. and C.A.B.; Conceptualization and investigation, C.M.C.; Conceptualization, A.G., C.S.M. and D.T.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by U.S. Department of Energy (USDOE) National Nuclear Security Administration (NNSA) Office of Defense Programs (NA-10).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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