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# A modified Kolsky bar system for testing ultra-soft materials under intermediate strain rates

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**Abstract:** A 25 mm Kolsky bar made of 7075 Aluminum is modified to test ultra-soft materials under intermediate strain rates (10 to 100/s). In the modified system, an ultra-long loading pulse (5 ~ 50 ms) is generated using an 800 mm steel striker with a pulse shaper made of soft rubber. The slope of the long incident pulse thus produced is small enough to ensure both the dynamic force balance of the sample and the intermediate strain rate deformation of the sample. For such long loading pulses, the traditional data reduction scheme that is based on the strain gauge measurements is not possible. We use a laser gap gauge to measure the deformation of the sample directly and monitored the low amplitude dynamic loading forces on the sample with a pair of piezoelectric force transducers that are embedded in the bars. A commercial foam rubber is tested to demonstrate the feasibility of our modified system. Annular-shaped specimen is adopted to minimize the dynamically induce axial stress in the specimen. Experimental results show that the foam rubber is strongly rate dependent in the intermediate strain rate range.

## INTRODUCTION

Strain rate dependency is one of the most important properties of ultra-soft materials such as foam rubbers. To determine material response at low strain rates (< $10^1$ $s^{-1}$), one can use servo-hydraulic loading frame.[1] For measurements under strain rates higher than $10^1$ $s^{-1}$, the diagnostic systems (load cell and linear variable differential transducer) used in loading frames can not provide sufficient frequency response for accurate force and displacement measurements. On the other hand, for intermediate to high strain rate measurement where the strain rate is larger than $10^2$ $s^{-1}$, conventional Kolsky bar system is extensively used.[2-4] However, to test materials the intermediate strain rate range ($10^1$ to $10^2$ $s^{-1}$) is very changeling, especially for ultra-soft materials. It is thus the objective of this paper to develop an experimental system that can be used to carry out accurate measurements of ultra-soft materials in this strain rate range.

Some attempts have been done to addresses the gap in strain rates. A long loading pulse (in the order of milliseconds) is needed to achieve the desired strain rate and to ensure dynamic force balance[5, 6]. Zhao and Gray developed the “slow bar” technique which can generate a long loading pulse without a duration limitation[7]. Shim et al. use a high-impedance striker to generate long pulses[8]. The data reduction in the conventional Kolsky bar test requires a clear separation between the incident pulse and the reflected pulse. The duration of the loading pulse is thus constrained by the length of the incident bar. Zhao and Gray use the 2-point strain measurements technique to separate the overlapped strain gauge signal[7]. To use a long incident bar is another way to get clear separation between the incident and reflected pulses for long loading. For example, Song et al. developed a long bar system for the intermediate strain rate characterization of soft materials[9]. However, it is not always realistic to increase the length of the incident bar. For a loading pulse with 2 ms duration, the incident and reflected pulses will unavoidably overlap if the incident bar length is shorter than 10 m assuming the strain gauge is mounted at the center of incident bar made of aluminum. Song et al. employed a high-speed digital camera to take sequential images of specimen deformation in a Kolsky bar system[10] to obtain the intermediate strain rate property. But only few points of strain can be given due to the speed limit. When testing ultra-soft materials using Kolsky bar, the tiny transmitted signal will lead to significant error if one measures the transmitted load using the traditional

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strain gauges. The X-cut quartz has been shown to be much more sensitive in detecting forces in its X-direction than the strain gauge in Kolsky bar tests, with three orders of magnitude increase of sensitivity.[11]

To address the deficiencies of conventional Kolsky bar system for testing ultra-soft materials, we develop a modified Kolsky bar system in this work. To achieve the desired intermediate strain rate, a long striker and a special pulse shaper are employed to substantially extend the duration of the loading pulse, which features a slow rising front. The strain gauge measurements are abandoned in our modified system. The dynamic loading forces on both side of the specimen are monitored by a pair of piezoelectric force transducers that are buried in the incident bar and transmitted bar,[11] and the strain is monitored directly using a recently developed laser gap gauge.[12] This system is then used to test a commercially available foam rubber from McMaster-Carr at strain rate from 20 to 200 $s^{-1}$.

## MODIFIED KOLSKY BAR SYSTEM

In this research, we modified a 25 mm Kolsky bar system to investigate the response of ultra-soft materials under intermediate strain rates. The bars are made of 7075 Aluminum alloy, with the yield strength of 455 MPa. The incident bar is 1500 mm long and the transmitted bar is 1000 mm long. The way to achieve intermediate strain rate loading is to have a long loading pulse with a slow rising front (Fig. 1).

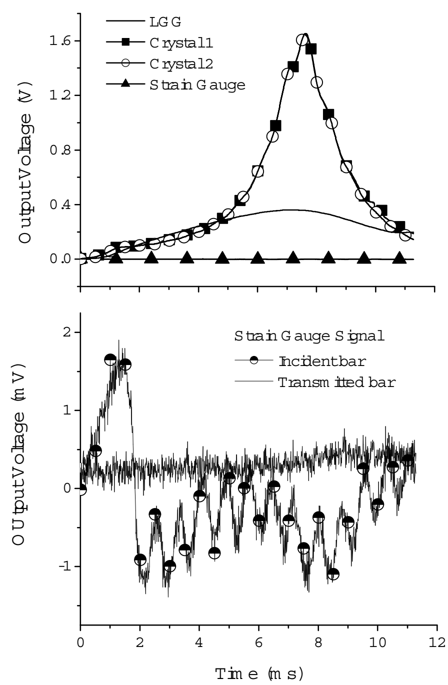



Fig. 1. Typical output signals of the modified SHPB system. (a) All outputs and (b) The enlarged strain gauge outputs.

To generate a longer loading pulse, we use an 800 mm long, 25 mm diameter maraging steel bar as the striker and a 12.5 mm diameter pulse shaper made of 2.5 mm thick rubber. When the striker impact the pulse shaper and the incident bar with a velocity of 1 m/s, an incident pulse with duration about 1 ms is generated. At the incident bar-sample interface, most of the incident pulse will be reflected as tension due to the huge mismatch between acoustic impedance of the bar and that of the specimen. The reflected pulse will be reflected one more time at the impact end of the incident bar, inducing second compression on the specimen. In our design, the incident bar is 1500 mm long, the second compression will arrive at the specimen 0.6 ms latter after the first pulse. In this way, there will be third compression, forth compression and so on due to reflection at the impact end of the incident bar. These compressive pulses add up and lead to a loading pulse with duration in the range of 5 ~ 50 ms depending on the striker velocity.

As shown in Fig1.b, the amplitudes of both strain gauge signals are very small for a typical test. The strain record from the strain gauge on the transmitted bar is essentially the white noise of the oscilloscope. The strain record from the strain gauge on the incident bar features a linear portion in the beginning, which is followed by steep decrease. This decrease of the strain is due to the superposition of the incident (compressive) pulse by the reflected wave (tensile). The initial slope of the incident wave is only about 866 MPa/s. For a typical incident wave in Kolsy bar experiments, the amplitude is around 25 MPa and the duration of the rising front is around 25 μs, this leads to a slope of 1000 GPa/s, which is about 1000 time of the slope achieved in our tests. The small slope of the incident pulse ensures the intermediate strain rates deformation of the sample as will be shown later.

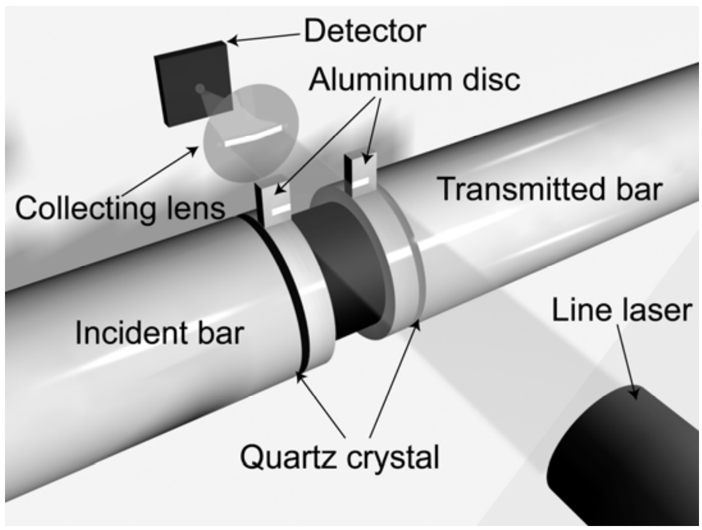


Fig. 2. Schematics of modified SPPB system.

In a conventional Kolsky bar system, two strain gauges mounted on the incident bar and transmitted bar are used to measure the stress wave profiles. A clear separation of incident and reflected waves is required for obtain the strain using the reflected strain for 1-wave analysis, or other operations for 2- and 3-wave analyses.[4] At intermediate strain rate, the loading pulse needs to be extended to as long as a few milliseconds.[6] This will lead to an overlap of incident and reflected wave (Fig. 1b). As a result of this overlap, one can not measure the deformation of the specimen with strain gauge signals. To overcome this obstacle, we used a laser gap gauge (LGG) to measure the deformation of the specimen directly (Fig. 2). The idea of using optical techniques in Kolsky bar testing was first proposed by Griffith and Martin,[13] who used a white light to monitor the displacements at the end faces of a cylindrical specimen. Ramesh and Kelkar adopted a line laser to measure the velocity history of flyer in planer impacts.[14] Later, this technique was used to measure the radial expansion of specimens in Kolsky bar tests.[15, 16] Details of our LGG system was reported elsewhere.[12]

The LGG measures the distance between the two bar-specimen interfaces, i.e., the length of the specimen. The output of the LGG is voltage (Fig. 1) and it is calibrated to obtain the sample length measurements[11]. The strain is then calculated by dividing the change of the sample length by the initial sample length.

When testing ultra-soft materials using Kolsky bar, the transmitted signal is too small due the mismatch between the acoustic impedance of the bar and that of the materials, as the strain gauge signals shown in Fig. 1b. We use two piezoelectric force transducers that are sandwiched between the specimen and two bars respectively to directly measure the dynamic loading forces. As shown in Fig.2, the quartz crystal is calibrated by the strain gauge signal. When the striker hits the incident bar without a pulse shaper, a square wave will be generated in the incident bar, which can be monitored by both the strain gauge and the quartz crystal. The stress amplitude 6.54MPa is obtained by the strain gauge. We can calculate the parameter of the crystal gauge (3.57MP/V), where as the average amplitude of the crystal signal is 1.83V. We can see that the signal to noise ratio of the quartz crystal measurements is substantially better than that of the strain gauge signal.

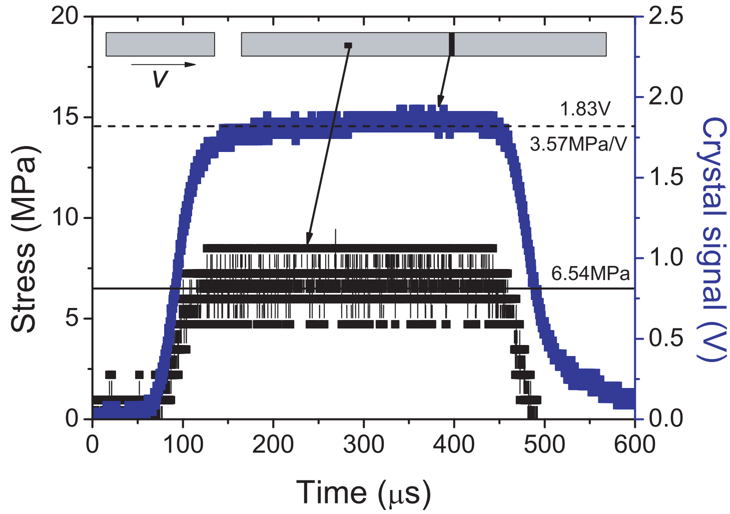



Fig. 3. The quartz crystal is calibrated by the strain gauge signal.

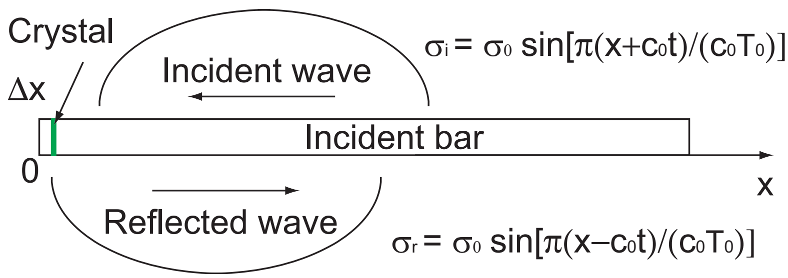



Fig. 4. Schematics of the error induced by embedding.

In our experimental design, the positive pole of the crystal is glued to the bars, and the negative pole of the crystal is glued to the aluminum disc, with the distance of Δx away from the specimen (FIG. 4). This distance could be ignored for the quasi-static test where the wave propagation effects need not to be considered. However, in the dynamic tests, the measured stress by the imbedded crystal may be different from that at the end of the incident bar. As shown in Fig.3, we assume that the incident wave has the sinusoidal form $\sigma_i = \sigma_0 \sin[\pi(c_0 t - x)/c_0 T_0]$, where $\sigma_0$ is the maximum stress of the incident wave, $T_0$ is the duration, $c_0$ is the wave velocity of the bar. The origin is chosen at the incident bar-specimen interface and the incident pulse arrives at the bar-specimen interface at time 0. We used the conversion that the compression is positive hereafter. The loading wave will be mostly reflected at the bar-specimen interface due to the huge mismatch of the acoustic impedance. Let us examine an extreme case, where 100% of the wave is reflected. The reflected wave is $\sigma_r = -\sigma_0 \sin[\pi(c_0 t + x)/c_0 T_0]$. The summation of the incident wave and the reflected wave gives:

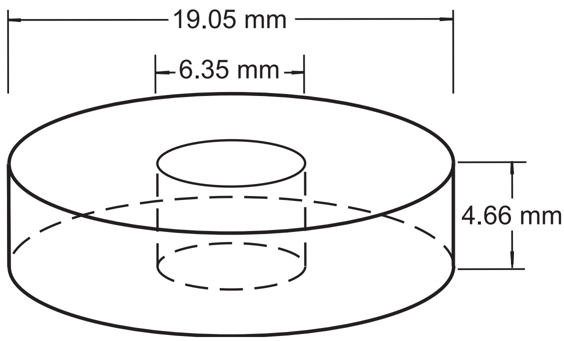
$$\sigma = -2\sigma_0 \sin(\frac{\pi x}{c_0 T_0})\cos(\frac{\pi t}{T_0}) \tag{1}$$

From Eq. (1), the dynamic stress on the incident bar-specimen end, where $x$ = 0, is always 0. However, the maximum stress measured by the imbedded crystal, which is located at $x = \Delta x$ is:

$$\Delta\sigma = 2\sigma_0 \sin(\frac{\pi \Delta x}{c_0 T_0}) \tag{2}$$

The elastic wave velocity of the bars is $c_0$ = 5000 m/s. In a typical Kolsky bar test, assuming the loading duration $T_0$ = 200 μs, and the amplitude of the incident wave $\sigma_0$ = 25 MPa, the stress error is around be 0.5 MPa if $\Delta x$ =3 mm. This value is in the same order of the strength of ultra-soft materials (~0.1 MPa). In our design, a 1 mm thick aluminum shim of the same diameter as the quartz crystal is used as the negative pole between quartz crystal and specimen, the loading duration is longer than 5 ms, and the loading amplitude is around 2 MPa. Using Eq. (1), we find that the error induced by embedding is within 0.5 kPa, which is negligible even for low strength ultra-soft materials.

**RESULTS AND DISSCUSTION**




(a)


(b)

Fig. 5. Schematic and photograph of a specimen used in this study.

A commercially available closed cell silicone foam rubber (from McMaster-Carr) is selected in this research. The black foam rubber with the density of 96 kg/m$^3$ is manufactured follow the ASTM specification (E84 25/50). It is available in the form of a tube with outer diameter of 19.05 mm and inner diameter of 6.35 mm. The tube is sliced into an annular disc with thickness of 4.66 mm. A schematic of the specimen is shown in FIG. 5a and FIG. 5b shows a photograph of an untested specimen.
The radial inertia effect in specimen in Kolsky bar experiment has been studied since it was invented [17], and was further discussed recently by Forrestal [18] and Song [19, 20]. The radial inertia in specimen leads to an extra axial stress in the cylindrical specimen. The distribution of the inertia induced axial stress $\sigma_z^I$, along the radial direction was found to be parabolic, with its maximum value reached at the center of the specimen and zero value on outer surface of the cylindrical specimen.[18] The additional axial stress averaged over the specimen cross-section is:[19]

$$\bar{\sigma}_z^I = \frac{a^2 \rho_s}{8} \ddot{\varepsilon} \tag{3}$$

where $a$ is the radius of the specimen, $\rho_s$ is the density of the specimen material, and $\ddot{\varepsilon}$ is the specimen's axial strain acceleration. In a typical Kolsky bar experiment, the strain acceleration at the beginning of loading is of the order of $10^8$ s$^{-2}$. The additional stress in a specimen with a diameter of 6 mm and density of 96 kg/m$^3$ is estimated to be of the order of 50 kPa. This additional axial stress may be negligible when testing regular engineering materials, such as metals, rocks and glasses. However, it is in the same order of magnitude of the flow stress of foam-rubbers (~100 kPa) and will thus lead to significant error in the experimental results. The inertia-induced stress can be minimized by using an annular specimen that help decrease the axial strain acceleration in the specimen.[19, 20] A parametric study shows that the inertia-induced stress in an annular specimen decreases rapidly as the inner radius reaches about 30% of the outer radius.[19] We can also see from Eq. (3) that long loading pulses with slow rising front help decrease the dynamically induced additional axial stress.

For the typical test, the outputs are shown in Fig. 1. We can see that the dynamic forces on both sides of the sample are recorded and dynamic stress equilibrium is achieved (Fig. 6). There is a regime of approximately linear variation of strain with time for times between 1.5 ms and 5 ms in the curve of strain history in Fig. 6. The slope of this region was determined from a least squares fit as strain rate, shown as a dashed line in the figure.

Figure 7-(a) shows a typical stress-strain curve of foam rubber. Compared to the result of high speed camera,[5] our method can give detailed strain measurements and thus complete stress strain curve. The results show that the loading of the diagrams is non-linear especially at higher stresses within the range of strain rates used. At low strains, the stress-strain curve of the foam rubber features a straight line of linear elastic deformation, which is

followed by a plateau of deformation at almost constant stress indicating collapsing of cells. The last deformation of the foam rubber is the plastic deformation of the densified material.[21] Figure 7-(b) shows the strain rate effect of the foam rubber from low to intermediate strain rates. The yielding strength of foam rubber increases with the strain rate. The quasi-static result obtained by an MTS machine with $10^{-2}$ strain rate is also shown as reference.

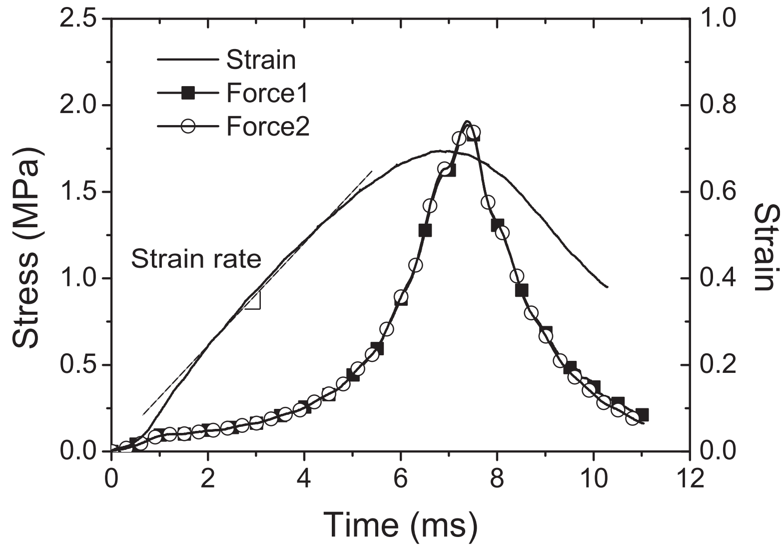



Fig. 6. Stress balance of the specimen, and the determination of strain rate.

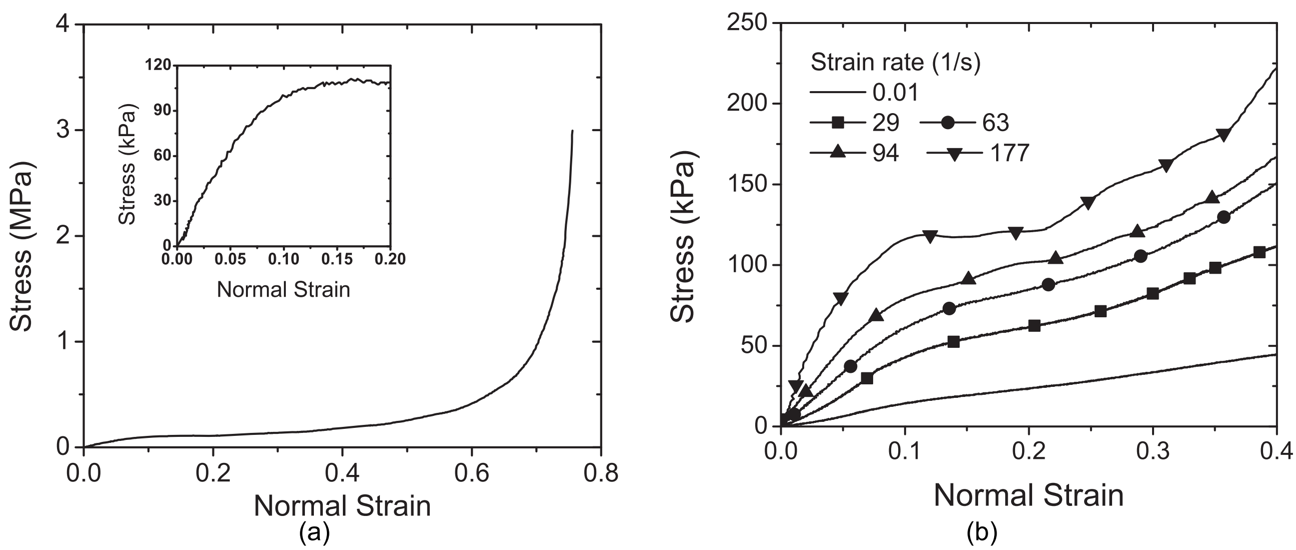



Fig. 7. (a)Typical stress-strain curve of foam rubber.(b) Strain rate effect of foam rubber.

## CONCLUSIONS

In this work, we modified a 25 mm Kolsky bar made of 7075 Aluminum to test ultra-soft materials under intermediate strain rates. To achieve the desired strain rate range, we used an 800 mm steel striker with a pulse shaper made of soft rubber. The slope of the resulting ultra-long loading pulse (5 ~ 50 ms) is small enough to ensure both the dynamic force balance of the sample and the intermediate strain rate of the sample deformation. A laser gap gauge is employed to measure the deformation of the sample directly, and the low amplitude dynamic loading forces on the sample are monitored by a pair of piezoelectric force transducers that are buried in the incident and transmitted bars at ends close to the specimen. A commercial foam rubber is tested to demonstrate the feasibility of our modified system. Experimental results show that this new method is effective and reliable for determining the dynamic compressive stress-strain responses of materials with low mechanical impedance and low compressive strength.

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