

Chapter 25

NIST Mini-Kolsky Bar: Historical Review

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Abstract The Society for Experimental Mechanics (SEM) has sponsored a series of technical paper sessions titled “Novel Testing Techniques” at their annual meetings. These sessions were organized by the Dynamic Behavior of Materials Technical Division of SEM and started in 2008. One of the novel techniques that we first learned about by attending SEM was the use of a small-size Kolsky bar system especially designed for the testing of polymer-single fibers. The Mini-Kolsky Bar was added to the National Institute of Standards and Technology (NIST) Kolsky Bar Laboratory based, in part, on the work presented at SEM conferences. A number of informal discussions at the annual SEM conferences added to the understanding and design details as we constructed our first small tension Kolsky bar. Subsequent developments of the NIST Mini-Kolsky bar, including improved gripping techniques were presented and discussed at SEM conferences. This paper reviews some of the work presented in the SEM’s Novel Testing Techniques sessions and discusses the history of additional follow-on work precipitated by the original papers.

Keywords Kolsky bar • Hopkinson bar • Dynamic fiber testing • Kolsky bar history • Experimental mechanics history

25.1 Introduction

We have developed a tension Kolsky bar for the dynamic testing of single fibers in our laboratory at the National Institute of Standards and Technology (NIST). We refer to this apparatus as the “Mini-Kolsky Bar”. Our approach, and the design of this system, did not originate at NIST—it is based on work by a number of researchers from several different labs. Professor Wayne Chen and his colleagues at Purdue University have been particularly helpful in our design effort [1]. This NIST Mini-Kolsky bar has been very successfully used in performing hundreds of tests on several different types of single polymer fibers [2, 3].

The purpose of this current paper is to review the history of developing the NIST Mini-Kolsky Bar. In particular, we highlight contributions to our work resulting from our involvement in the Society for Experimental Mechanics (SEM). The conference papers from the SEM annual meetings, in particular the Dynamic Behavior of Materials Technical Division and a series of sessions from 2008 to 2015 called “Novel Testing Techniques”, have played a role in our application of the Mini-Kolsky bar. Also, the informal interactions facilitated by the SEM meetings have influenced our development and research approaches, including our development of a new fiber gripping technique. Our work at NIST has both benefitted from the SEM meetings and it has been a venue for us to report some of our contributions.

There are two reasons that reviewing the history of the NIST Mini-Kolsky bar are important. First, reviewing the ideas and designs can guide us in our future work: What approaches have worked and what questions remain? Where are the gaps in our understanding? We summarize some of these thoughts in Sect. 25.5.

Second, a historical review can contribute to our ongoing effort to quantify the uncertainties of Kolsky Bar measurements. For example, we know that alignment is important, but can we estimate an uncertainty in our results based on an assessment of our bar alignment? An approach to communicating uncertainties of the Kolsky Bar is presented in Sect. 25.6. The building of an uncertainty budget, filling in all the numbers in this outline, is beyond the scope of this paper; as a matter of fact, we suggest that this will be an ongoing cooperative effort with input from many different research

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institutions. Improved uncertainty assessments will assist in establishing broadly accepted standards for Kolsky bar dynamic material testing.

In preparing this conference paper we have reviewed our Mini-Kolsky bar project from the standpoint of where the pertinent ideas came from—or at least where we learned of the basics for a specialized dynamic polymer fiber testing system. We do not claim any unique inventions on our part, and we apologize if we have not given proper credit to all those who have made special contributions to the techniques of using a small Kolsky bar for single-fiber dynamic testing. An evolutionary scenario seems best to describe the history of the Kolsky bar work—small, but important, developments. These developments have come over many years to bring the state-of-the-art to the point where we started building the Mini-Kolsky Bar at NIST.

25.2 Background: Dynamic Material Properties

There has always been a practical need to understand how materials behave under load: “How much does the object deform when you push on it?” or, “Will this beam break when you drop a rock on it?” Robert Hooke (1635–1703) is credited with the idea that there is a mathematical relationship between the load on a component and its deformation, now referred to as Hooke’s law. Thomas Young (1773–1829) contributed the idea that there was a material property—the modulus of elasticity often referred to as Young’s modulus—that relates the stress (load per area) in the component to its strain (change in length per unit length). (Young is given credit for the idea, although it can probably be traced to a paper by Leonard Euler in 1727.) In Young’s own words [4]:

[W]e may express the elasticity of any substance by the weight of a certain column of the same substance, which may be denominated the modulus of its elasticity, and of which the weight is such, that any addition to it would increase it in the same proportion, as the weight added would shorten, by its pressure, a portion of the substance of equal diameter.

Even though Young’s wording is difficult to understand, the idea is correct. Applying new mathematical approaches and the principles of classical mechanics scientists developed the ideas of Hooke and Young, and others, into what we now call “Solid Mechanics”. It seems a safe bet that many practical scientists understood that when applying loads rapidly that materials behave differently than when slowly loaded, and experiments to measure dynamic properties were needed. John Hopkinson, a professor at Cambridge University in the nineteenth century, is often cited for early scientific experiments to measure dynamic properties. In 1872 he published results documenting a considerably higher strength for an iron wire—up to a factor of two—when the load was applied by impact. John Hopkinson’s son Bertram followed on with dynamic experiments in the early part of the twentieth century. This interesting history of the Hopkinson’s work is summarized by both Kolsky [5] and Rhinehart [6] in books written in the early 1950s.

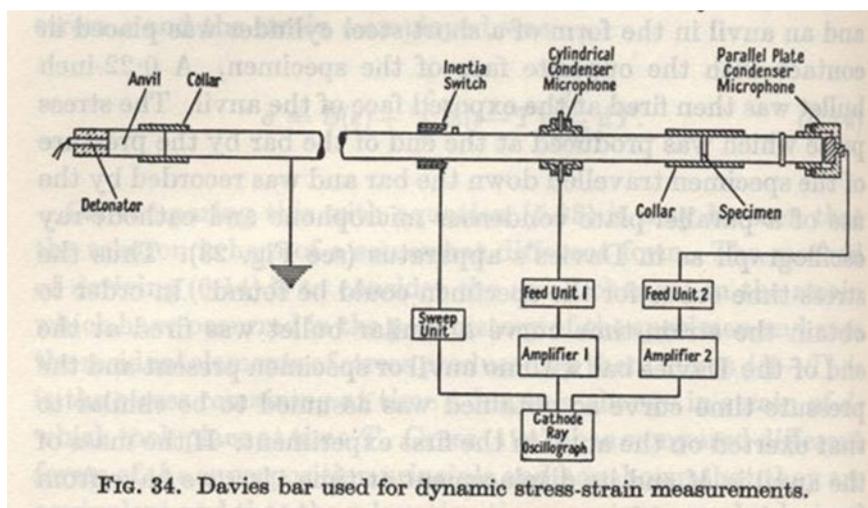
The description of the relationship between stress and strain, now referred to as the constitutive equation for a material, relies on experiments involving challenging measurements. An excellent and concise description of the measurement problem we are discussing here was presented by Professor James F. Bell in the 1960s [7]:

On a cylindrical solid the simultaneous measurement of an axial force and the axial deformation it produces is conceptually one of the simplest experiments in experimental physics. That a vast literature has been written during the last two centuries to describe the functional relation between load and deformation in such experiments attests to the complexity of nature.

For slow rates—quasi-static type loading—the simultaneous measurement of load and displacement might appear as a straight forward experimental problem. This is the traditional material testing where a load frame applies a force to a specimen. The magnitude of the force is measured with a load cell. The extension or compression of the sample is measured by a transducer on the specimen or motion of the frame, and the results are a load-displacement curve. A great deal of research work has led to new techniques and specialized equipment for determining load-displacement curves. The load frames and associated instrumentation, such as modern servo-hydraulic testing machines, have become very sophisticated instruments. However, testing under high rates is still beyond the load-frame approach. Historically dynamic testing has developed from impact experiments with some now common approaches evolving from the Hopkinson work. In these approaches stress waves in elastic bars provide the dynamic loading. In recent decades there have been efforts to bridge, or combine, aspects of the traditional load frame testing approaches and the dynamic stress-wave techniques. The goal of the different methods is aimed at answering Bell’s statement of the problem quoted above.

Much of Bell’s research work in the 1950s and 1960s was directed at measuring the deformation—or strain—directly on the sample under dynamic loads. By producing a fine grating on a small cylindrical specimen and using an optical diffraction technique, an accurate time history of the specimen strain could be recorded. Bell’s approach has high resolution, both in

Fig. 25.1 Schematic drawing of the historic “Davies bar” used by H. Kolsky [8]



strain and time, and can measure large plastic strains, but it does appear that it would be difficult and time consuming to make the specimens.

In the same era as Bell’s diffraction grating work, techniques related to Hopkinson’s impact experiments were being developed. In particular, the approach of using two long bars with a small sample held between the bars became popular. Historically the approach appears to be two Hopkinson pressure bars sandwiching the short specimen, and hence the name “split Hopkinson pressure bar” is used. Also, the basic theory of the split bar was developed and clearly presented by H. Kolsky; hence, the name “Kolsky bar” has also become common. The basic concept of this now widely used apparatus is illustrated in Fig. 25.1 [8]. This apparatus looks much like our modern apparatus except the “condenser microphones” have been replaced with common metal foil strain gages, and the impact is usually applied by an air gun launching a projectile rather than an explosive charge at the end. This drawing is copied from Kolsky’s book where he labeled it a “Davies bar”. There has been some debate over the years which name should be used—“split Hopkinson pressure bar” or “Kolsky bar”—but maybe we should be calling it a “Davies bar.” At NIST, in about 2000, we started developing our new dynamic materials measurement laboratory and decided to use the name “Kolsky bar” because it seemed to be a more general term (pressure bar might imply a compression bar).

The specimens are easy to make for the Kolsky bar compared to Bell’s approach, but the strain is not measured directly in the specimen as stated as a requirement in his description of the problem. In the Kolsky bar the strain in the specimen is calculated from elastic strain measurements on the bar. The experimental problem is how to accurately measure the elastic strain as a function of time and relate this strain measurement to the motion of the end of the bar; and then, specify the resulting deformation of the specimen. Much of the practical work related to Kolsky bar research in the past 50 years has been in determining the plastic-strain time-history in the specimen as related to the strain-time recorded signal from a strain gage on the bar some distance from the specimen location.

Historically, metal resistance strain gages—originally thin wire gages that evolved into the now common metal foil gages—were used in impact experiments. In the early 1950s there was a considerable effort in developing the wire strain gages, including work at NIST (then called National Bureau of Standards (NBS)). A special conference was held as part of the 50th anniversary of NBS in 1951 highlighting progress in strain gages. The NBS Director, A.V. Astin, wrote in the introduction to the book publishing the papers of the conference: “Work is in progress on strain gages consisting of a conducting coating applied by an evaporation technique” [9]. The development of the Kolsky bar as a tool for dynamic material property measurements appears to be in parallel to the development of the metal foil strain gages.

However, there were concerns that the gages, calibrated in a quasi-static fixture, would not respond with the same sensitivity in dynamic applications and high strains. In 1970, Professor William Sharpe published a very important paper which we have referred to in answering questions related to strain gages: “Dynamic Plastic Response of Foil Gages” [10]. In this paper, Professor Sharpe compares the metal foil gages with output from an interferometric strain measuring technique in impact experiments. There was reasonable agreement between the metal foil gages and interferometric gage up to about 8 % strain.

Applying strain gages directly to metal and ceramic specimens have been used by some researchers, but it is impossible with the size of the single fiber. It is worth noting that the modern high-speed video recording capability coupled with advances in the relatively new field of digital image correlation (DIC), when applied to Kolsky bar experiments, may provide

the direct strain measurements in the specimen as advocated by Professor Bell; however, the small size fibers prevent the use of this technique.

The adaptation of the Kolsky bar approach to tension would appear to be straight forward—apply a tension impact pulse rather than a compression pulse. However, there are a number of practical problems associated with tension testing such as gripping the specimen. By 2008 the NIST Kolsky lab had established the capabilities and gained experience in high rate testing of metals, including a unique pulse-heating capability; however, we did not have the equipment or experience in tension testing of polymers. So, to answer a need for a capability to test single polymer fibers we turned to others for the necessary specialized techniques. About the same time, there was an increased interest at the Society for Experimental Mechanics (SEM) meetings regarding applying the traditional dynamic methods to novel material testing techniques. Therefore we have benefitted from participating in the SEM conferences.

25.3 Background: Novel Testing Techniques Sessions at SEM Annual Meetings

For more than half a century the Society for Experimental Mechanics (SEM) has been a technical community where researchers developing the Kolsky bar techniques have presented and discussed their work. (Note: we have chosen to use the name “Kolsky bar” in this paper to apply to a variety of dynamic test systems including several variations of the “Hopkinson bar”, such as the split-Hopkinson pressure bar.) The society started in the 1940s and was originally called the Society for Experimental Stress Analysis (SESA) and evolved into our current technical society called SEM. SESA/SEM played an important role in the development, and applications, of variable resistance strain gages, such as the famous SR-4 gage (described in an interesting article in the historic Handbook of Experimental Stress Analysis [11].) Also, from the beginning the society has been a home for the development of dynamic measurement techniques, using strain gages and other transducers. So, with the advantage of hindsight, it seems natural that the SEM was the society to highlight Kolsky bar system design and development.

There are significant SEM papers related to Kolsky bar development from the 1960s through 2000, but from a quick review there appears to be an increase in the reports on measuring dynamic properties for materials other than metals, especially using Kolsky bars, in the past two decades. With the establishment of the Dynamic Behavior of Materials Technical Division, and in particular a series of sessions called “Novel Testing Techniques”, the SEM annual meetings became an excellent forum for researchers interested in applying dynamic tests to new materials. Therefore, for those of us building new dynamic test apparatuses the Novel Testing Techniques sessions provided a place to learn about recent developments, interact with researchers currently active in the field, and to present our ideas for rapid feedback.

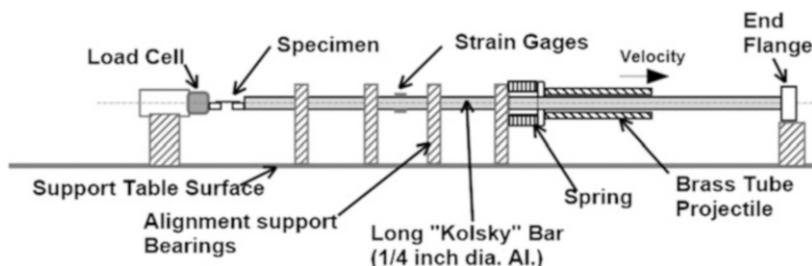
In reviewing the technical program for the SEM annual meetings from 2008 to 2015, there have been 23 sessions called “Novel Testing Techniques.” (In 2013 three of these sessions were actually called “Novel Techniques” and in 2014 three sessions were called “Novel Testing.”) In the 23 sessions there were 103 papers listed with authors from many different universities and institutions, international as well as many locations in the USA. About a third of the papers were from three institutions (Purdue University, Army Research Laboratory, and Sandia National Laboratory).

It appears that all the papers addressed dynamic measurements, and a majority of the reported research involved an apparatus of the Kolsky or split-Hopkinson type. Of the 103 papers, 15 titles included the word “Hopkinson” (or a related acronym) and 24 titles included the word “Kolsky”.

In terms of our work at NIST, we were particularly interested in these sessions because of our effort to perform dynamic tests on polymer fibers. Dynamic tension testing seems like an obvious extension of traditional tension tests—just make the test machine move faster. The challenges of increasing the speed in conventional test machines were introduced in the first paper in 2008 Novel Testing Techniques I: “Analysis of Dynamic Tensile Testing” by X. Xiao of General Motors Corporation [12]. This paper discusses the dynamic stress equilibrium issue. It is interesting to note that this is a key issue for many dynamic tests and is often mentioned in related work. Several papers refer to pulse shaping techniques in regard to achieving force equilibrium in testing soft materials and other new applications. In our work two papers that provided a valuable background in pulse shaping and understanding the force equilibrium condition were published in *Experimental Mechanics* by Chen [13] and by Song [14].

Discussions of the uncertainty of the measurement results (addressing the question “How good are these measurements?”) is an underlying theme of much of the work presented in the Novel Testing Techniques. All researchers have an interest in this question, but we are particularly interested at NIST because it is part of our mission to characterize uncertainty of measurement processes. In the last session of the 2015 SEM meeting (Novel Testing Techniques II) one of the papers addressed this directly: “Data Reduction Uncertainties in Kolsky Bar Experiments on Metals”, E.E. Nishida, B. Song, E. Corona, Sandia National Laboratories [15]. This paper presentation was valuable. Also, the discussion following this paper was significant—there were a number of questions and comments concerning other uncertainties that have not yet

Fig. 25.2 Schematic drawing of NIST tension mini-Kolsky bar for fiber testing



been addressed such as the effect of bar straightness. The need for additional work in the ongoing efforts to understand the uncertainty of dynamic testing results may indicate a need for continuing the novel testing technique sessions in the future!

25.4 NIST's Mini-Kolsky Bar

The fiber-testing Kolsky bar that we built at NIST, starting in 2009, is shown schematically in Fig. 25.2. The drawing labels the major components. The idea and basic configuration of our system are based on the apparatus we observed in a visit to Dr. Wayne Chen's laboratory at Purdue University. The long bar with a strain gage is an obvious connection to the traditional Kolsky bar. The use of the load cell to replace the transmitted bar is a reminder of the traditional load frame approach: the mini-Kolsky bar shown could be thought of as a traditional testing machine with simply the moving frame being replaced with a high velocity ram. The end velocity of the bar, often referred to as the particle velocity, is caused by the impact of the hollow tube on the end flange producing a stress wave to propagate down the bar. The required rapid loading is achieved, but the extension of the specimen is limited by the length of the striker tube.

We were familiar with Kolsky bar testing of metals from several years of work with our larger (15 mm diameter) bar system; however, the mini-Kolsky bar presented some new challenges. We had the experience and necessary equipment to apply and record strain gage and load cell data at the high rates required. However, as we started our work on the Mini-Kolsky bar we had questions about the fiber attachment methods, the use of the piezoelectric load cell, details about the pulse shaping needed for testing single polymer fibers, and gripping techniques for the small fibers (approximately 10 μm diameter). Interactions with other researchers were valuable in addressing these concerns.

The pulse length in our Mini-Kolsky Bar design is limited by the length of bar that can be used unsupported by bearings. And, the velocity of impact is limited by the force of the spring and it was difficult to add a stiffer spring because of the limits of hand compression and release of the spring. To address a desire for a longer pulse and higher impact velocity, a project to update the Mini-Kolsky Bar was undertaken by one of the authors (Jae Hyun Kim). This system uses an air gun to fire a projectile down a long barrel that becomes part of the incident bar. This new system was modeled after the large tension Kolsky bar in the NIST laboratory. The design of this tension system is presented in a paper on the tension testing of a special steel alloy by Mates [16]. There will be future discussion papers about the updated Mini-Kolsky Bar.

25.5 Unanswered Questions

In reviewing our work with the Mini-Kolsky Bar, we have recognized that we still have some unanswered questions, or gaps in our understanding. These questions may provide topics for papers and discussions at future "Novel testing techniques" sessions. Some of our questions are summarized below:

1. Do we have an accurate measure of the change in the fiber length during a test? By using the strain gage signal of the "return pulse" we calculate the end motion of the bar. We have compared the end motion calculated from the strain gage signal with a DIC measurement of the end motion, and there is agreement within the measurement uncertainties. We have installed a laser displacement gage on the NIST Mini-Kolsky Bar (adapted from the system presented by Lim [17]). All three methods agree on the displacement time history of the end of the bar; however, we have yet to verify that there is no relative motion of the force transducer end. How can the stability of the force transducer be verified? Can a laser displacement gage be adapted to measure the actual motions at each end of the specimen?

2. Is the frequency response of the piezoelectric force transducer adequate? The manufacturer of the force gage provides a natural frequency of the unit. However, when we install a gripping system to hold on to the fiber end, the added mass will lower the natural frequency of the force transducer. Can we model, or perform a test experiment, to determine the effect of the grip mass on the natural frequency and how this might affect the force-time history? We use the manufacturer's sensitivity value for the load cell; is there a way of performing a dynamic calibration of the cell?
3. What is a reasonable way to determine the effective gage length of the specimen? With either the direct clamping type grip, or a fiber gluing system, there is a question about how much slip may occur inside the grip. Assuming that the gage length is right at the end of the clamp, or at the end of the glue blob, may produce some uncertainty of the gage length number used in calculating the strain-time history. Is there a modeling or experimental techniques that will provide a quantitative uncertainty estimate of the effective gage length?
4. What method should be used to calculate the stress in the specimen? To calculate stress from the force measurement we need the cross sectional area of the specimen. How should the area be determined? We have used scanning electron microscope measurements of the diameters of several fibers and then calculated an average area. Is there a better way of determining a cross sectional area for calculating stress?
5. What is the effect of pre-tension on the results from the Mini-Kolsky Bar? In a traditional load frame type test a fiber can be loaded with a slight amount of slack and the load—displacement data can be adjusted to take into effect the removal of any slack in the specimen. This does not work in a dynamic test. To ensure that there is no slack, it may be necessary to pre-load slightly. How does this preload affect the measurement results?

25.6 Outline for Uncertainty Budget

Before a technique like testing of single polymer fibers can become a standard test, there needs to be an assessment of the instrument's measurement results uncertainty. One method of summarizing and communicating the overall performance of a measuring technique is referred to as an "uncertainty budget". This approach involves analyzing each aspect of a technique including an estimate of the uncertainty of each error component. Then all of the individual uncertainties are combined into an overall uncertainty of the final measurement results.

Researchers usually look at their data with some sort of statistical approach. The "scatter" in the data can be expressed in terms of a standard deviation. The "expanded uncertainty" can be expressed in terms of the standard deviation times a coverage factor. The variation or scatter when testing different samples can be a result of material property variations; however, it can also be a result of inconsistencies, or unknowns, in the test apparatus or test technique. Our long-term goal is to be able to quantify variables in the test equipment and procedure; that is, to determine uncertainties in our results related to the test technique so we can evaluate variations in the material properties of the specimen. Test results variations cannot all be attributed to variations in material properties of the specimens.

A proposed approach for preparing an uncertainty budget for the Mini-Kolsky Bar apparatus is to analyze the causes of the uncertainties by separation into four components:

1. the uncertainty estimate for the measured strain gage signal as related to the time history of the end motion of the input bar
 - (a) gage factor and sensitivity calibration uncertainties
 - (b) gage bonding effects
 - (c) dynamic response of metal foil gages
 - (d) gage length effects on the strain gage signal (mechanical filtering)
 - (e) effect of gage in the center of the bar related to end motion
 - straightness of bar and alignment effects
 - bearing drag effects
2. Uncertainty estimate for the force-time signal recorded from the piezoelectric load cell
 - (a) sensitivity calibration uncertainty
 - (b) frequency response effects
 - (c) alignment of the load cell effect
3. Uncertainty of the force-displacement history of the specimen

- (a) force non-equilibrium effects
 - (b) pulse shaping effects and repeatability
 - (c) slack or pre-tension effect
 - (d) effect of slipping of fiber in grip
4. Uncertainty of the stress-strain response of the specimen material
- (a) uncertainty of sample size (diameter and area calculation) for calculating stress
 - (b) uncertainties in calculating strain from displacement

We have only begun the rather lengthy task of filling in numbers for this outline. This project will need the input of many researchers and the support of several different research organizations. That is why we see the value of discussing this effort as part of the SEM technical paper sessions such as the Novel Testing Techniques.

The approach of combining individual uncertainties into the four major groups; and then, combining the groups into an overall uncertainty is an effort beyond the scope of this paper. We propose that the approach used for estimating the strain gage measurement uncertainty in Rhorer [18] is a starting point for the more complete uncertainty analysis outlined here.

25.7 Conclusions and Future Work

The Mini-Kolsky Bar has been an effective research tool at NIST. The design and construction of the system has been impacted by our participation in SEM conferences. The background for the Kolsky bar has a long history, building on dynamic testing research conducted over the past century. This historical review has highlighted several areas where additional work could be beneficial to achieve the ultimate in “simultaneously measuring the axial force and the axial deformation” of the single polymer fibers.

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