

The History of Instrumented Impact Testing

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Abstract: Pendulum impact testing is widely known to have a history that extends back to the turn of the last century. To many researchers today, instrumentation of the impact test to acquire a load-time history, and thereby provide important data in addition to absorbed energy, is usually considered to be a relatively recent development. However, our literature review has shown that starting from the earliest test machine development work, researchers have been interested in designing equipment capable of measuring both the energy expended in fracturing the specimen, as well as the force-deflection and energy-deflection curves. This paper recounts the early history of instrumented impact testing, and shows that it also extends back over 100 years. In fact, the earliest known paper on instrumented impact testing predates the first pendulum test machine publication by one year.

Introduction

In the early years of impact testing, researchers evaluated a wide variety of test systems and procedures in their search for both an understanding of the response of a material to impact loading and a method to quantify that response. Some sense of the early developments can be gleaned from papers by famous researchers such as Russell, Charpy, Fremont, Hadfield, Izod, and Martens.¹⁻⁵ Many of the papers by these authors reported results in terms of the absorbed energy, a simple and compelling way to rank the resistance to fracture. It offered a relatively reproducible and inexpensive method of comparing different materials and microstructural conditions.

However, not all researchers agree that the performance of a material for a particular application can be adequately assessed from the absorbed energy alone. Even 100 years ago, some researchers were convinced that the load-time history data are needed to supplement absorbed energy. The earliest of these researchers did not have access to the sophisticated electronics that we use today for capturing the dynamic load history, but were able to develop innovative ways to record both the load and time data. This paper presents a history of some of the early developments from a key technology perspective. Rather than attempt to review all the early research, we have focused on a review of the important technology developments.

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Background

Before reviewing the early instrumented technology history, a brief review of modern instrumented impact data acquisition and analysis will be helpful in understanding the early technical methods. In a typical application today, strain gages are attached to the striker and the voltage-time curve is measured during the impact (Figure 1). The force-time curve is obtained from the voltage-time data using static calibration data. Knowing the mass of the striker, the acceleration-time curve can be numerically integrated to give the velocity-time curve (Figure 2). The velocity-time curve can, in turn, be numerically integrated to give the displacement-time curve. These numerical integrations permit a force-displacement curve to be constructed. Since the work (or energy) of a system is the area under the force-displacement curve, the force-displacement data can be integrated to give the energy absorbed by the specimen in fracturing. The four critical (or characteristic) load points are the general yield load (applicable to metals), peak load, brittle fracture load, and brittle fracture arrest load (Figure 3). The general yield load corresponds to yielding across the entire uncracked ligament. For ferritic materials in the transition region, a small amount of stable crack growth precedes rapid brittle fracture. Rapid brittle fracture is evidenced on the force-displacement curve as a precipitous force drop.

An alternative to the current widely used approach of measuring the force (and integrating to obtain deflection), is the measurement of deflection. In cases where the deflection is measured, differentiation is necessary to obtain the velocity-time and acceleration-time data. This approach is usually less desirable because of issues associated with differentiation of signal data. Nevertheless, early research focused on acquiring deflection data because of the measurement technologies available at that time.

The Earliest Paper - 1897

It is believed that the first technique to measure the incremental forces during impact loading is that reported by B.W. Dunn in 1897.⁶ Korber et. al.⁷ provided a review of instrumented impact test methods in 1926, and these authors also point to Dunn's work as being the first instrumented impact paper. It is interesting to note that Dunn's work was performed on a drop tower and his publication pre-dates that of Russell¹ who introduced the first pendulum impact machine for quantification of the total absorbed energy. In his introduction, Dunn describes how he had been frustrated with the inability to accurately measure the maximum pressure produced by the expansive force of exploded gun powder. At the time of Dunn's work, the common practice was to measure maximum explosive pressures using a "crusher gage", a cylinder of annealed copper that was inserted into the breech block and was compressed by a hard steel piston when the

gunpowder ignited. The compression of the copper cylinder was evaluated after firing the gun by comparison to similar cylinders compressed to a similar deflection in a conventional tension/compression testing machine. Dunn recognized that the use of static data to interpret dynamic compression of the copper cylinder was not correct, and he sought to obtain the equipment needed to measure the incremental strain. After a search for such equipment, he concluded that “no apparatus possessing the required delicacy and accuracy has been available”⁶. Therefore, in 1891, he conceived of a method for compressing copper cylinders dynamically while measuring the resistance to deformation.

His technique for deflection measurement involved mounting a small mirror on a hardened steel piston which rested on the copper cylinder. A weight was dropped on the piston and the mirror revolved about a fixed horizontal axis by linkage between the piston and mirror. As shown in Figure 4, a beam of light was reflected from this mirror and impinged on a rapidly spinning drum covered with photographic film. By proper selection of geometric magnification (beam angles and distances) and rotation speed, he was able to obtain a very high-resolution record of the copper cylinder deflection.

To capture the time data, he modulated a second beam of light by the use of a hole cut through a tuning fork, and also focused this on the drum at a point directly under the beam from the mirror on the specimen. A schematic of the tuning fork arrangement from Dunn’s paper is shown in Figure 5, and the results of the measurements through a small aperture on the tuning fork are shown in Figure 6. Proper selection of the tuning fork geometry permitted a wide range of time resolutions. Thus, the film had two traces, an upper trace that recorded the deformation of the cylinder, and a lower trace with transverse oscillations at the frequency of the tuning fork. As shown in Figure 7, the final system was quite sophisticated with motion actuated introduction of the light beam so that the data record extended only over one third of the cylinder, even when it was spun at 100 revolutions per second. After the test, Dunn differentiated the deflection-time data to obtain the velocity and force data. In retrospect, we can see that one disadvantage of this system was the fact that the loading system for the cylinder started by resting against it. Another disadvantage was that the data analysis was time consuming and cumbersome. Also, the mass (and so the inertia) of the mirror, while slight, still limited the rate of response of the system. In spite of these problems, he was probably the first to plot quantitative force-time data from impact experiments, and the written discussion of his paper in a later issue of the journal included many favorable comments.⁸

Force and Deflection Measurement 1897 - 1926

As previously mentioned, the intent of this review paper is to briefly summarize the significant technological developments in the early history of instrumented impact

testing. Paper length limitations do not permit a review of all of the early literature. If the reader is interested in a more comprehensive review, Korber et. al.⁷ provide a detailed review of the work of several authors over the time period of 1897 to 1926. Many of these early papers are not reviewed here because they were incremental developments of the static comparison method. These authors impacted various steel shapes and compared the deformation with static measurements on the same geometry to estimate the peak load. In some cases, copper cylinders were placed between the test specimen and anvils and permanently deformed during impact. In other experiments, a hardened steel ball was pressed into a soft metal to characterize the peak load. An important limitation of these methods is that the comparison with static data assumes that the deformation is not dependent on the strain rate.

The next major step after Dunn's work seems to have been the development of simultaneous recording of force and deflection data by A. Gagarin as reported in 1912⁹. His paper summarizes the development (begun in 1904) of an apparatus that plotted deflection on one axis versus applied load on the other. His interest was in characterizing the response of the material to a known and controlled impact, instead of Dunn's more indirect interest in measuring the maximum pressure produced in a gun barrel. Therefore, Gagarin built a drop-weight machine equipped with a striker of mass at least 10 kg. Apparently, he was able to test a number of different specimen configurations including dynamic tensile and axial compression specimens (crusher gage copper cylinders). His original approach was to measure the load using a spring under axial compression. He constructed a needle and linkage in which the spring compression produced a vertical displacement of the needle and the extension of the test piece produced a simultaneous horizontal displacement of the needle. The force-deflection trace was etched on the surface of a thin sheet of lead. However, he was not pleased with the vibrations produced by the spring and decided to use low mass crusher cylinders for force measurement. While these cylinders were an improvement from a vibration perspective, the vibrations were not completely eliminated. His final improvement was to attach a mirror to the striker and use photographic film to measure the deflection of the test piece as in Dunn's work. He did not present any final results from these experiments and concludes his paper stating, "At this point my experiments with a non-elastic dynamometer were interrupted".

During this time period, other researchers were focused on measurement of the displacement-time curve from which the force-time curve was calculated by differentiation. In 1904, Hatt¹⁰ reported results from experiments in which he attached a pen to the hammer of a drop tower and marked the surface of a drum spinning at constant speed. As reviewed in Reference 7, several other researchers used similar methods to measure deflection-time data on a variety of specimens and materials. The spinning drum technique was initially applied by Hatt to long tensile rods to avoid the need for signal amplification. However, these tests often led to double necking. Testing of

shorter specimens was accomplished using an optical imaging system. An interesting modification was introduced by Honiger¹¹. He achieved optical magnification by creating a shadow of the back edge of the hammer which was projected onto a light sensitive rotating drum. Using an appropriate lens, a blackened area was created on the film with an edge that provided the displacement-time curve.

Korber et. al.⁷ used a procedure similar to that of Honiger to achieve measurement of the pendulum displacement with minimized vibrations. This was done by machining a 0.1 mm vertical slit at the back edge of the hammer. An objective lens was used to project the light image of the slit to a fast rotating drum which was covered with light sensitive paper (Figure 8). The lens and light source positions were selected to give a 4x magnification of the hammer displacement.

Piezoelectricity and Oscillographs 1927 - 1930

Yamada¹² and Watanabe¹³ performed significant work in Japan during this time period. Yamada was able to optically measure the change in velocity of the pendulum during contact with the test specimen. His work was an improvement over the work of Korber et. al.⁷. As shown in Figure 9, Yamada used a light source and a circular aluminum disk with 128 slits of 1 mm width machined along the circumference to produce a series of lines on a photographic plate attached to the striker. As the hammer slows due to contact with the specimen, the distance between the lines decreases and the change in velocity was measured. These data were then analyzed to give the load-deflection curves.

In 1929, Watanabe reported systematic instrumented impact studies using a C-hammer pendulum machine. As shown in Figure 10, a piezoelectric load cell was constructed by attaching a quartz crystal under one of the test machine anvils. The load cell was calibrated statically and the effect of side loading due to specimens bending between the anvils was considered and shown to be small. A cathode ray oscilloscope was used to record the load-time data. The load-time data were integrated to yield the load-deflection curve. Impact tests on mild steel were performed and Watanabe studied various effects on the instrumented curve including velocity effects, notch radius effects, specimen thickness effects, and uncracked ligament effects.

Strain Gage Technology 1930 - 1961

In 1958, Tanaka¹⁴ reported on an improvement to Watanabe's piezoelectric load cell apparatus. Tanaka attached Rochelle salt crystals to the back of a C-hammer and measured the load-time response. That same year and at the same meeting, Ono¹⁵ reported on the use of a strain gaged specimen support to measure the load-time response during impact on a pendulum machine. Ono used a vacuum tube amplifier to condition the signal for display on an oscilloscope. He used a light beam to trigger the data

acquisition. In 1961, Sakui¹⁶ reported on a similar arrangement, but the strain gages were attached to the C-hammer striker. Sakui studied the effects of annealing on the energy-test temperature and peak load-test temperature curves. Test configurations similar to Sakui are widely used today.

It is interesting to note that strain gage technology was available decades before it was applied in instrumented impact applications. While the true origin of the strain gage transducer is not known, Lord Kelvin reported on strain induced resistance changes in wires in the 1800s. In 1908, St. Lindeck of Germany introduced what may be the first bonded strain gage wire transducer. However, it was not until the 1950s that metallic foil bonded strain gages were introduced, and these rapidly replaced wire gages due to improvements in heat dissipation, creep reduction, better geometry control, and smaller sizes. This appears to have been the key technology improvement to pave the way for instrumented striker applications requiring small spaces for attachment.

Conclusion

The early literature recounts arguments about the relative importance of absorbed energy (in units of work) versus maximum intensity of the load (in units of force). Some of the researchers argued that both are important, and developed techniques to measure the load during successive increments of the fracture process. While the early work was conducted before the time of strain gages and electronic integration of the measured data, the early researchers were able to develop innovative photographic and mechanical methods to record the loads for intervals shorter than one ten thousandth of a second. In most countries, the early study of impact loads was driven by military applications, but the results were eagerly adopted for infrastructure and manufacturing applications. As with the history of conventional (absorbed energy data) impact testing, many researchers from around the world contributed to the developments in the instrumentation of the test machine and in the understanding of the data. The original work was performed in the United States by an Army Lieutenant and then quickly spread to Europe. Significant advances came in the late 1920s in Japan where piezoelectric methods and the use of oscillographs were developed. It was not until the late 1950s that strain gages, which are now widely used, were introduced for instrumented impact testing.

Acknowledgement

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References

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Sample ID
pvr4-15
Comments
NIST PVRC

Impact™ V4.3 Summary Report

Test Parameters	Value
Group ID	DEMO-1
Date	07/12/2002 17:08
Operator	M. P. Manahan
Temperature	68.0 °F
Oscilloscope	MPM Internal Oscilloscope
Striker Name	8mm Metals
Interpolation Method	Point-Point Linear
Encoder Controller	MPM Encoder System
Velocity Determination	Optical Encoder
Material	Metal
Size	Type A
Orientation	Isotropic
Notch Type	V Notch, no Side-Groove
Units Normalization	None
Energy Adjustment	1.0000
Length	2.1654 in
Width	0.3937 in
Thickness	0.3937 in
Span	1.5748 in
Uncracked Ligament	0.3150 in
Notch Radius	0.0098 in
Failure Type	Ductile / Brittle
Post Test Comments	Good Test
Impact Velocity	17.940 ft/s
Striker Energy	139.052 ft lbf
Dial Gage Energy	139.007 ft lbf
Encoder Energy	139.107 ft lbf
Latch Angle	134.17°
Final Angle	77.41°
Potential Energy	302.744 ft lbf
Windage & Friction	1.138 ft lbf
Percent Shear	88.00 %
Lateral Expansion	0.0733 in

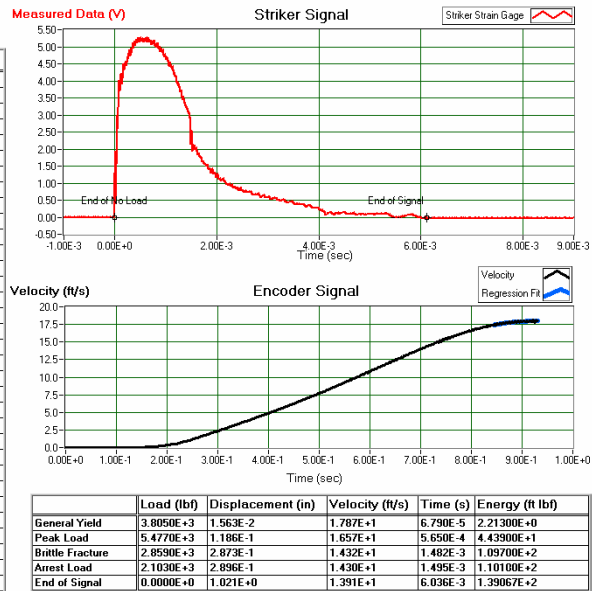


Figure 1 Strain gage voltage-time signal obtained with a modern instrumented striker system. The lower plot shows the striker velocity from release up to impact.

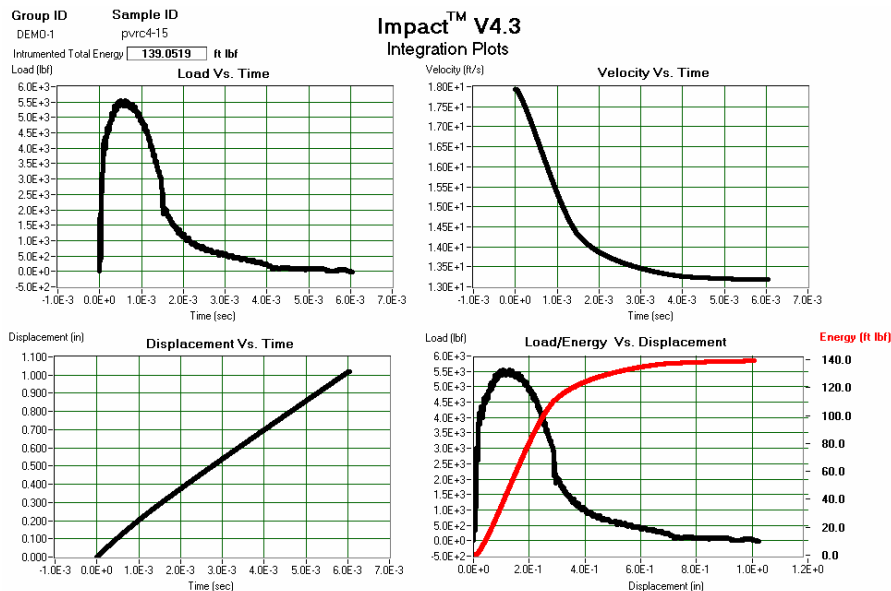


Figure 2 The raw voltage-time signal has been converted to the force-time signal through the striker calibration. The force-time curve is integrated to give the velocity-time curve. The velocity-time curve is integrated to give the striker displacement-time curve. Finally, the force-displacement curve is integrated to give the energy absorbed by the test specimen.

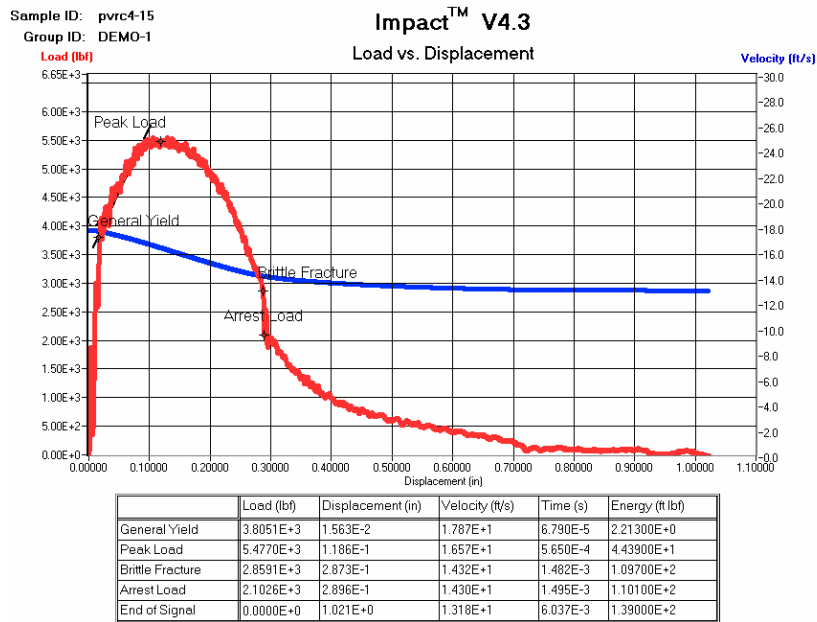


Figure 3 This plot displays the force-displacement plot and the velocity-displacement plot. The characteristic loads, displacements, and energies are automatically determined.

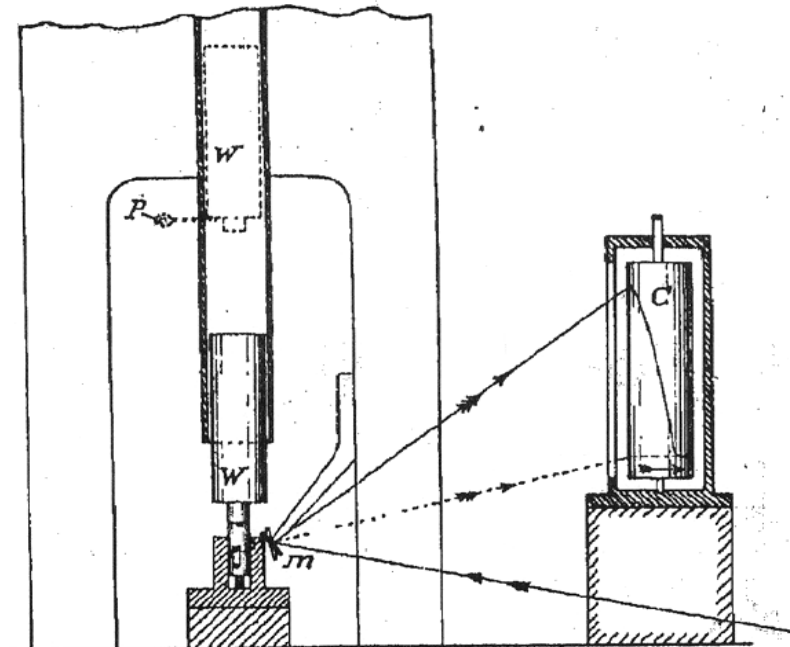


Figure 4 Schematic showing Dunn's method for measuring deflection data by projection of light onto a revolving photographic film⁶.

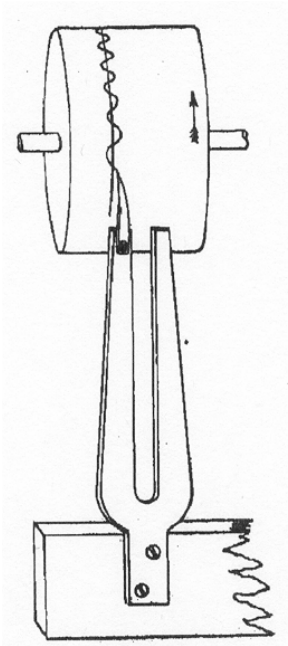


Figure 5 Dunn's original tuning fork arrangement for time measurement⁶.

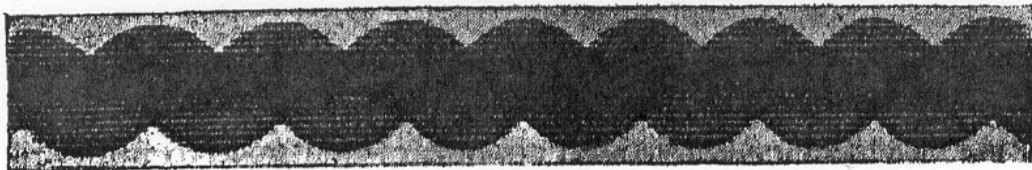


Figure 6 Data obtained by Dunn passing light through a small aperture on the tuning fork⁶.

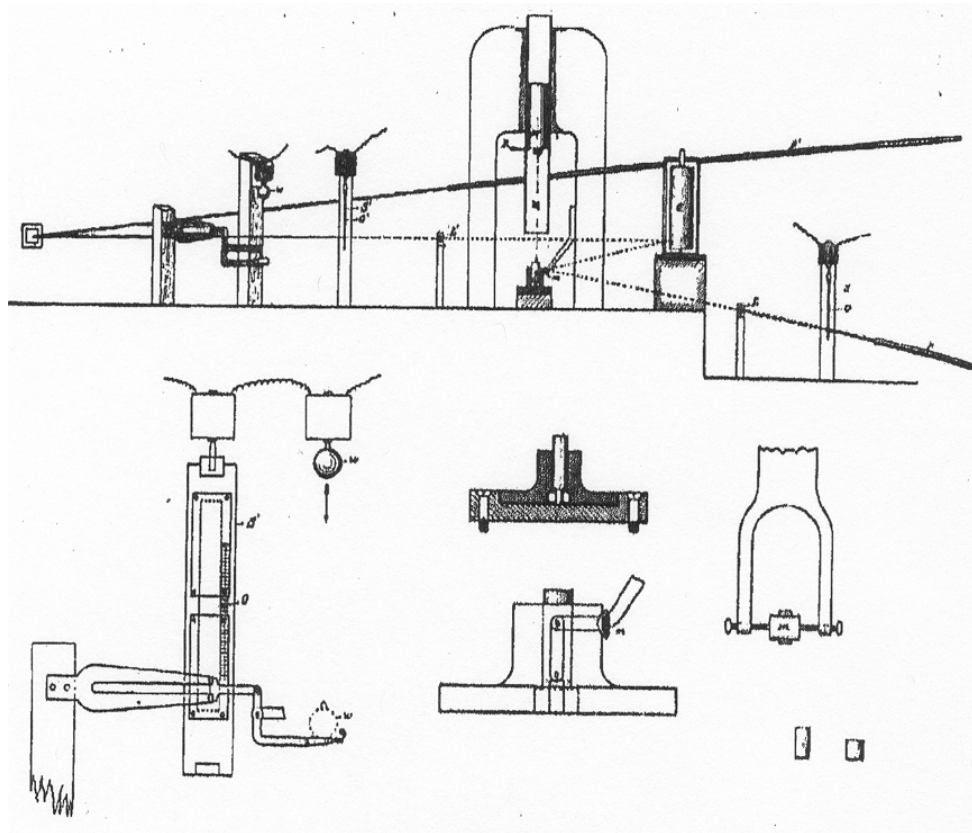


Figure 7 Schematic of Dunn's final experimental configuration⁶.

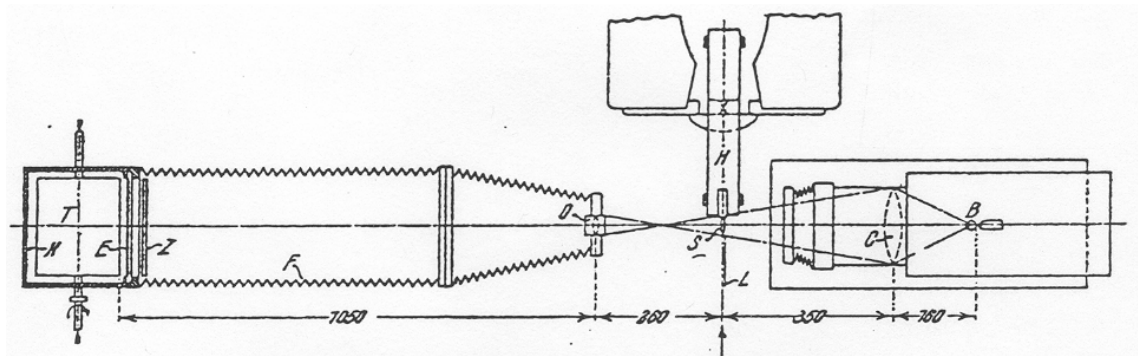


Figure 8 Schematic of experimental arrangement of Korber et. al. for measurement of hammer deflection at 4 x magnification⁷.

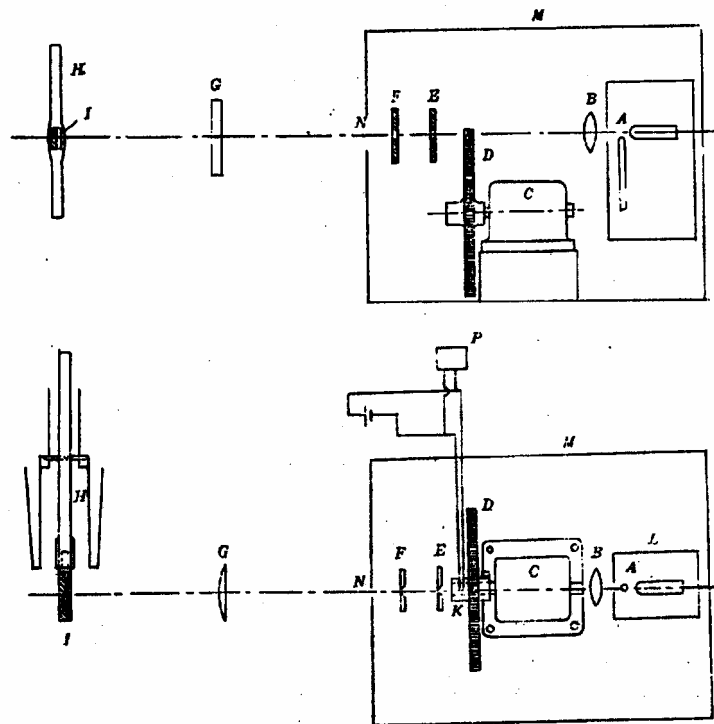


Figure 9 Schematic of experimental arrangement of Yamada for measurement of striker velocity¹².

Arrangement for measuring force

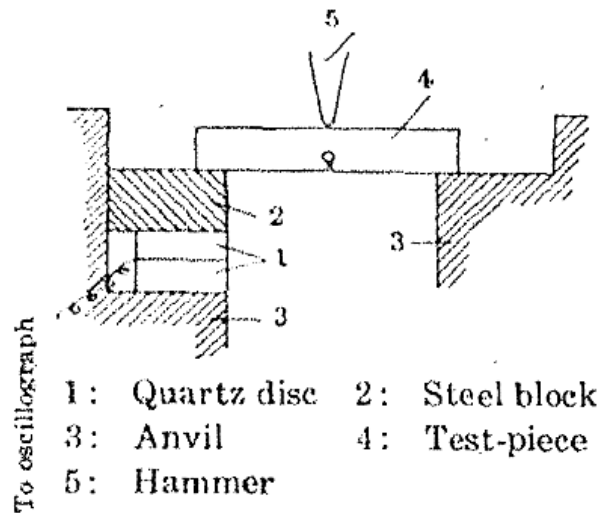


Figure 10 Schematic of Watanabe's piezoelectric load cell arrangement¹³.