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Servohydraulic Methods For Mechanical Testing in the Sub-Hopkinson Rate Regime up to Strain Rates of 500 1/s

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Abstract

Tensile and compressive stress-strain experiments on metals at strain rates in the range of 1-1000 1/s are relevant to many applications such as gravity-dropped munitions and airplane accidents. While conventional test methods cover strain rates up to ~10 s^{-1} and split-Hopkinson and other techniques cover strain rates in excess of ~1000 s^{-1}, there are no well defined techniques for the intermediate or "Sub-Hopkinson" strain-rate regime. The current work outlines many of the challenges in testing in the Sub-Hopkinson regime, and establishes methods for addressing these challenges. The resulting technique for obtaining intermediate rate stress-strain data is demonstrated in tension on a high-strength, high-toughness steel alloy (Hytuf) that could be a candidate alloy for earth penetrating munitions and in compression on a Au-Cu braze alloy.

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Introduction

Conventional mechanical test methods (e.g. tensile, compression, bend, fracture, etc.) performed with screw-driven or servohydraulic load-frames have been at the core of materials property evalution for over a century. These techniques have long permitted the evaluation of deformation and failure over test durations ranging from years to seconds. Much more recently, the development of elastic wave techniques such as the split-hopkinson bar technique have permitted the evaluation of mechanical properties over durations shorter than a millisecond. In conventional testing, the quasi-static strain-rates permit the entire load train to be in dynamic force equilibrium at all times, where as in the hopkinson techniques, a single elastic wave pulse is propagated through the sample. However, testing at intermediate rates between these two regimes is inherently challenging due to the possibility of elastic wave reflections and difficulty in establishing dynamic equilibrium in the sample and the load sensors. For example, an elastic wave pulsed through a 2” long steel bar would bounce back-and-forth along the length of the bar approximately 30 times over 0.4 ms, the duration of a test in tis intermediate test regime. For these and other reasons, the amount of testing in the sub-Hopkinson rate regime has been limited and the methodology is far from well-established. As shown in Fig. 1, this essentially inaccessible intermediate or “sub-Hopkinson” regime is quite relevant for many important material failure scenarios such as plane crashes and gravity dropped munitions [1].

There have been early developments of at least three different methods for this “inaccessible” rate regime: gravity-drop experiments [2], electromagnetically-actuated experiments, or high-rate servohydraulics. The first of these three is sometimes preferred for its simpler test setup while the latter two benefit from improved control over test parameters such as loading rate. In each of these three methods, unique complications make the test method and data analysis non-trivial. Specifically, because of the inherent time constant of these tests, the entire load frame may not be in dynamic equilibrium leading the elastic wave propagation through the frame to impart fluctuations in the load cell readout. Also, there are very few methods available for dynamic strain-sensing in these techniques. These challenges have been

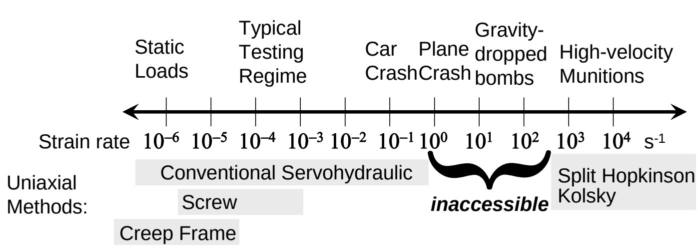
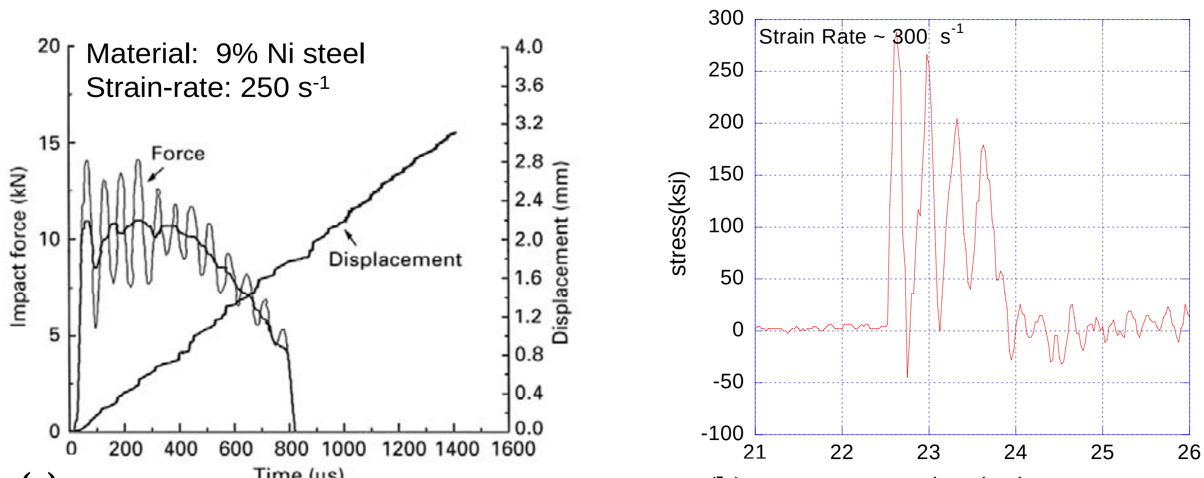


Figure 1. *The strain-rate scale showing some common test instruments and types of failure events.*

an impediment to quality research in this sub-Hopkinson rate regime, and have led to sparse and often unsatisfactory publications on the topic. This problem is highlighted by the absence of any direct comparison of data obtained with the split-Hopkinson bar method to data obtained by a more conventional method. The current document describes a recently developed servohydraulic method that attempts to overcome many of the challenges in materials testing in this rate regime.

Methods To Mitigate Force Oscillations

Essentially all of the existing literature on mechanical testing in the sub-Hopkinson regime is plagued by the elastic wave propagation that lead to oscillations in the force signal. Many researchers choose to simply average-out the oscillations by a mathematical method, assuming that the oscillations are essentially "noise" that has no mechanical relevance. For example: *"At high strain rates the force signal was superimposed by oscillations caused by the inertia of the test equipment making the direct determination of characteristic values impossible. Therefore a cubic spline was utilized to approximate the unfiltered stress-strain signal..."* [3]. In some cases, the researchers include the raw data in the publication, although in many cases the raw data is omitted. An example from the recent literature is shown in Fig. 2a, from an experiment on a 9%Ni steel where the initial oscillation amplitude is ~50% of the average signal [4]. A second example, Fig. 2b, is taken from our own initial efforts on a 304 stainless steel alloy with a servohydraulic frame configured for high-rate testing directly from the manufacturer using a quartz load cell. In the latter example the oscillations are so overpowering that even an average line would be difficult to assess. Moreover, most or all earlier works have failed to



(a) **(b)**

Figure 2. *(a) Force oscillations and averaged force signal for 9%Ni steel tested at a strain rate of 250 s^{-1} [4], (b) force oscillations on 304 stainless steel at 300 s^{-1} with an "off-the-shelf" high-rate test frame.*

examine the possibility that the force oscillations are a direct result of the test sample and load cell not being in dynamic equilibrium.

To mitigate these force oscillations we have identified two tools that will be described in more detail: passive damping material and a custom-designed load cell.

1. Passive damping material. Pulse-shaping materials are used in split-Hopkinson bar testing to essentially smooth or dampen the elastic wave imparted on the striker bar. For a simple cylinder as used in split-Hopkinson testing, the requisite dimensions and material required for pulse-shaping can be derived from elastic wave theory [5]. In the servohydraulic application, a similar damping material can be used to reduce the elastic oscillations, although the material must be determined empirically. Through a series of experiments, we have found that 0.25"-thick felt or rubber materials incorporated in the slack adapter (discussed in the following section) reduce the inertial oscillations by more than 50%. The only challenge in the use of damping materials is that the elastic compression of the damping material occurs simultaneously with the deformation of the test coupon. This results in the actual strain rates at the test coupon being considerably slower, especially at low loads, until the test coupon begins to plastically deform.

2. Custom-designed load cell. The high-rate load frames are typically coupled with quartz load cells that are utilized for their very fast response time. However, these load cells may themselves be more susceptible to elastic waves with wavelengths in the 10-1000 μs range than other designs (i.e. as would be caused by the excitation of a resonant frequency). A custom load cell was designed and built that consisted simply of a short, stout load-link with two diametrically opposed biaxial strain gages. The load cell, designed for loads up to ~10,000 lbs, can be empirically calibrated quasi-statically against a standard load cell. This load cell shows a significant ~50% reduction in the amplitude of the oscillations compared to rubber-dampened system with a quartz load cell. The response time of these custom load cells is limited by the response frequency of the strain-gage amplifier which is specified as 125 kHz, or a rise time of 8 μs.

A Method for High-rate Tensile Testing

Tensile testing has been performed on high-strength steel alloys using an MTS servohydraulic load frame capable of an actuator displacement rate of 300 in/sec. Force sensing is accomplished with a quartz load cell and/or custom load cells described in the previous section. Actuator displacements are sensed with and LVDT. Strains in the gage section of the tensile bar are monitored with a high-elongation strain gage attached to the gage section. This gage permits strain measurement up to strains ~15%. A typical configuration with the quartz load cell and two custom load cells immediately above and below the tensile dogbone sample is shown in Fig. 3. The duplicate load cells provide a means to evaluate the degree of stress equilibrium.

A slotted slack adapter is used to permit the actuator to accelerate to the desired displacement rate prior to the application of force on the test coupon. The slack adapter consists of a cylindrical ram (1.3"dia x 4"long) with a 3" slotted hole. The ram rides in a sleeve connected to the actuator and a hardened steel pin is used to engage the ram with the sleeve. As described previously, a rubber pad in the slot of the slack adapter has been utilized to reduce the inertial oscillations in the load signal.

The specimen geometry is a cylindrical dogbone tensile geometry with treaded grip ends, similar to the industry standard round tensile geometry of ASTM E8 [6]. The specimen gage length is 1" or less so that the 300 in/sec maximum displacement rate corresponds to a strain rate of 300 s^{-1} or better. Gage diameter is chosen such that the maximum forces are in the range of 5,000 – 15,000 lbs. In the example shown in the following section, the gage diameter of a Hy-Tuf alloy (yield strength ~200 ksi) was 0.2" and the gage length was 0.5". The short gage length enables the highest strain rates, but the length-to-diameter ratio is 2.5:1, smaller than the recommended value of 4:1 in ASTM E8; the small aspect ratio will likely lead to percent elongation values that are somewhat larger than obtained with conventional geometries. Nevetheless, this geometry used for high-rate testing can be used for quasi-static tests and moderate dynamic tests as well, enabling direct, unambiguous comparison of rate-induced changes in all tensile properties.

The length of the load train is kept to a minimum to keep the load frame as stiff as possible. Threaded grips are used to interface the load cell and actuator with the tensile specimen. The MTS 458 analog controller is programmed to ramp the actuator for a total travel of 3". The first 2" of the travel are within the slack of the slack adapter so that the actuator can attain the desired constant displacement rate. After the actuator has traveled 2", the sleeve pin engages the rubber pad in the slack adapter and the load train is loaded. As the displacement ramps linearly, the increasing force causes elastic and plastic deformation of the test specimen as well as non-linear elastic deformation of the rubber pad. The strain is measured locally at the specimen gage section to eliminate any contribution from the non-linear compliance of the pad.

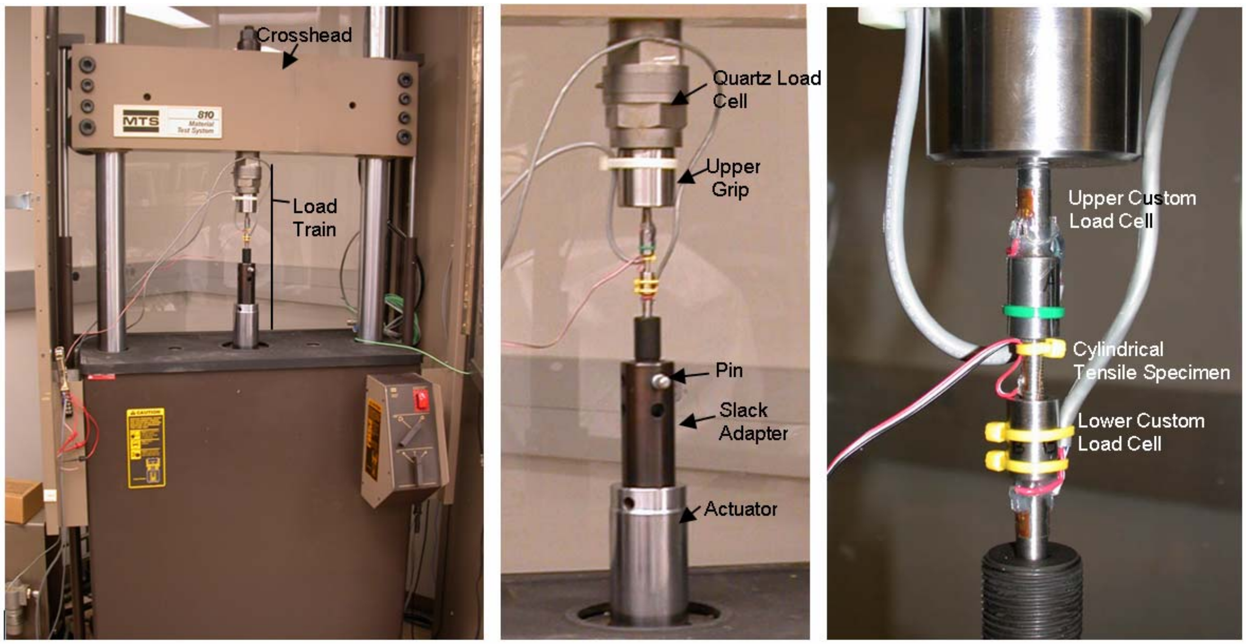


Figure 3. *Experimental configuration with two custom load cells and a standard quartz load cell.*

An Example of High-Rate Tensile Behavior in a Hy-Tuf Alloy

The newly developed high-rate testing method was applied to the characterization of a high-strength, high-toughness steel alloy, *Hytuf* (AMS6418, UNS K32550) that could be considered for large-scale earth penetrator applications [1]. Fig. 4 shows data obtained from two dynamic tensile tests performed at a nominal actuator displacement rate of 280"/sec. Two custom-built load cells are used in series immediately above and below the specimen. Fig 4a shows the force-time profile from both of these load cells, showing reasonably good agreement and minimal oscillations compared to the quartz cell that is sold for high-rate testing. The quartz cell shows a significant time lag and large oscillations before and after fracture. This plot also shows the linear displacement-time profile for the actuator travel. The entire duration of the test from elastic loading to fracture was less than 0.5 ms. In Figs. 4b-d, a second test is shown with data from a high-elongation strain gage attached to the gage-section of the test sample. In Fig. 4b, the strain signal is non-linear during initial load up, as the rubber pad is compressed. This ramp in strain-rate during elastic loading dampens inertial shock in the system. From this direct measure of strain, we can determine that the strain-rate at yield in the gage section was ~500 s^{-1}, which is consistent with the displacement rate of 280"/sec and the gage length of 0.5". Figs 4c and 4d show the stress-strain behavior and the extraction of the 0.2% offset yield strength, respectively.

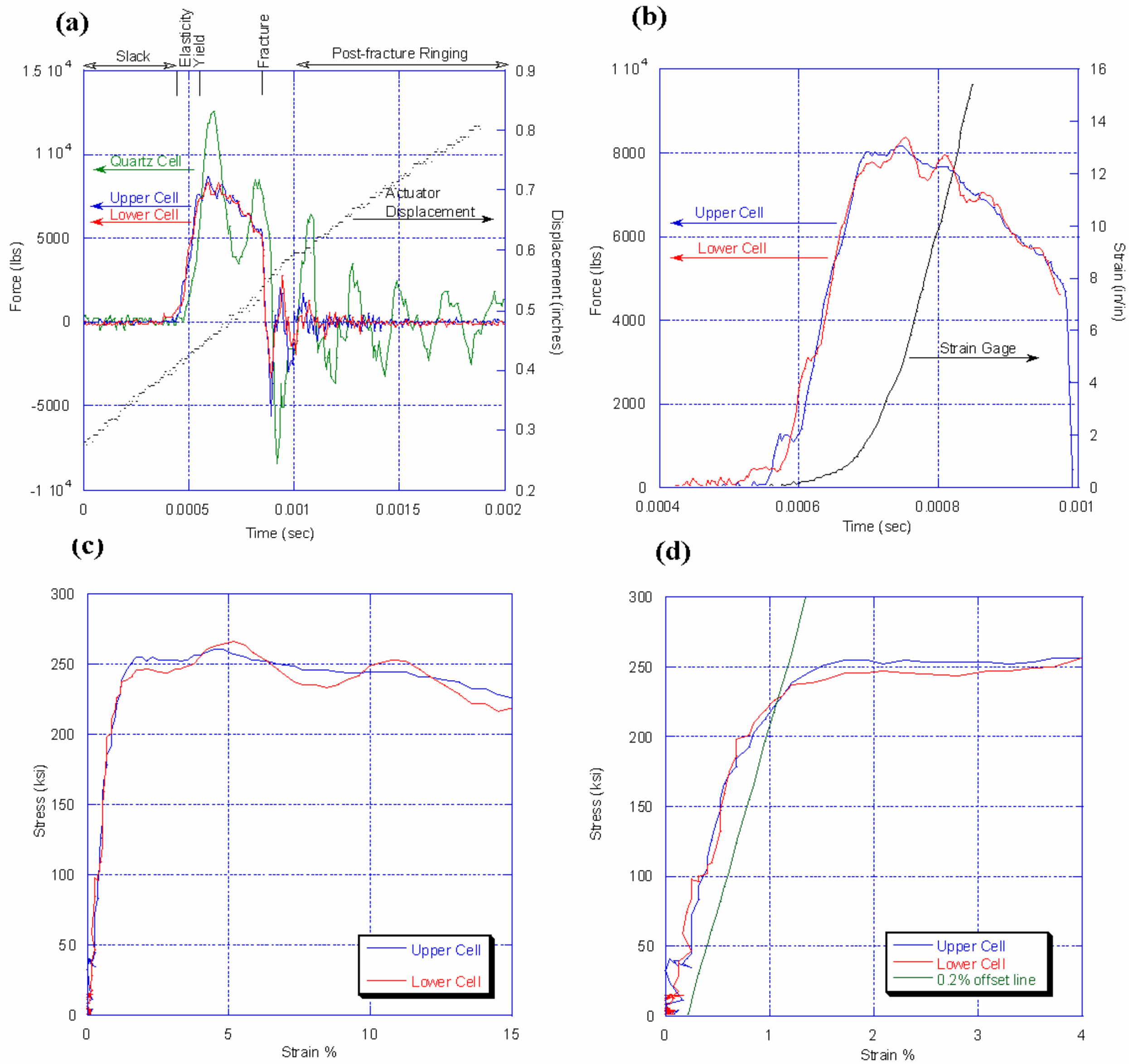


Figure 4. ***(a)*** *Force-time profile from a tensile test on a Hy-Tuf alloy at a displacement rate of ~280"/sec showing the improved quality of the custom load cells over the quartz load cells and showing the linearity of the displacement ramp over the test duration.* ***(b)*** *Force-time profile from a similar test at 280"/sec on Hytuf showing the strain signal from the gage section,* ***(c)*** *data from (b) plotted as stress-strain,* ***(d)*** *0.2% offset line used to determine yield stress.*

One of the significant features of this dynamic test method is that the same method can be used at all lower strain-rates, even quasi-static rates down to ~10^{-4} s^{-1}. This enables direct comparison of strain-rate effects without ambiguity arising from differences in the sample geometry or test method. In Figure 5, the high-rate behavior of Hytuf is compared at strain rates ranging over 4 orders of magnitude. The duration of the fastest test was ~1 ms and the duration of the slowest test was ~1 s. Tests at lower strain rates would have been possible but were expected to produce no changes and were omitted due to constraints on the number of available specimens. It is apparent that there is almost no strain-rate effect in this alloy until a strain-rate of 200 s^{-1}, at which point there is a ~7% increase in the yield and ultimate strengths. This is quite a low strain-rate sensitivity, and other alloys are expected to have as much as a 30-50% increase in yield strength at strain rates of 200 s^{-1} [3], although these published trends were established by smoothing highly oscillatory data.

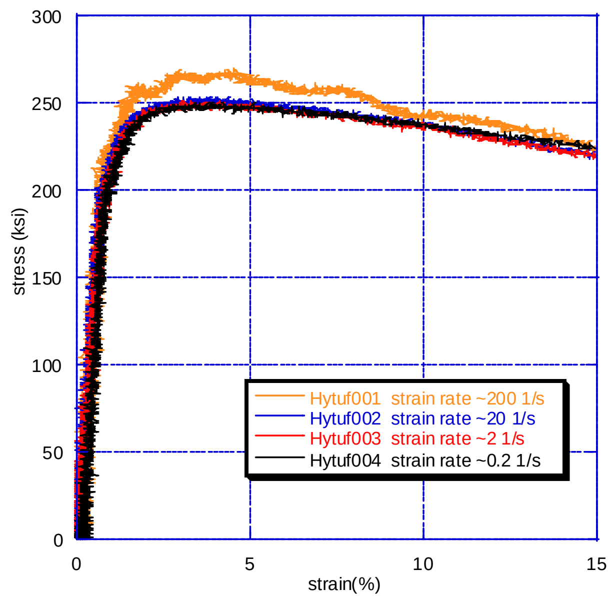


***Figure 5**. Stress-strain response of HyTuf at strain-rates from 0.2 s^{-1} to 200 s^{-1}.*

A Preliminary Attempt at High-rate Compression Tests

Compression or upsetting tests are sometimes preferred to tensile tests for the following reasons: (a) compression can replicate in-service loading conditions, (b) brittle materials have much higher strength in compression, (c) only small amounts of material are available, preventing the fabrication of tensile samples, (d) to compare to split-hopkinson bar results that are typically obtained in compression. The same MTS high-rate servohydraulic load frame described previously can also be coupled with appropriate fixturing to perform high-rate compression tests.

A schematic of a typical compression configuration is shown in Fig 6. The sample has a cylindrical or rectangular geometry with a cross-sectional area in the vicinity of 0.05 in^2 to 0.15

in^2 such that the desired deformation occurs within a load limit of ~15,000 lbs. The height-to-width aspect ratio is typically in the vicinity of 2:1 to balance two competing requirements: prevention of buckling and minimal frictional contribution. The specimen rests between two platens that are held in alignment with a reverse-cage compression rig. This reverse-cage serves two purposes (a) maintaining alignment and (b) converting the downward actuator motion into a compressive force on the test coupon. A slack adapter is used to allow the actuator to accelerate to the desired velocity before the test commences. A brass shear pin in the slack adapter is designed to fail at a specific force thereby breaking the load-train at the completion of the test to prevent machine damage. Force sensing can be accomplished by the OEM quartz load cell or with a custom-designed load cell. In the current arrangement, displacement is measured by the LVDT displacement. Small strain gages may enable direct measurement of strain in the low-strain regime. Alternatively, techniques such as laser Doppler extensometry could be employed in the future to measure strain directly throughout the experiment. Displacement-limiting stand-offs can be employed in the reverse-cage to restrict the amount of deformation that is imparted to the test coupon. Data acquisition is performed with a digital storage oscilloscope as used in high-rate tensile testing. At the machine's maximum displacement rate of 300 in/sec, a 0.5 in tall specimen would be tested at an engineering strain rate of ~600 1/s (ignoring compliance in the rest of the load train and the rubber damping pad).

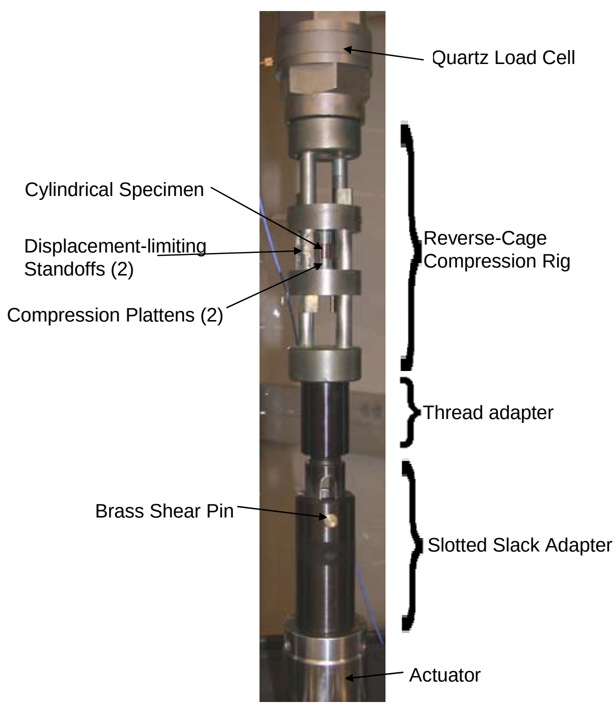


***Figure 6**. Load train configuration for high-rate compression.*

Such a compression configuration has been implemented in a preliminary assessment of the compressive mechanical response of Au-Cu alloys. Test specimens were machined into cylinders with a diameter of 0.21875" and a length of 0.4375". Compression tests were performed quasi-statically with a conventional test frame and at three dynamic displacement rates (1"/sec, 10"/sec and 100"/sec) with the high-rate load frame. These displacement rates correspond to nominal strain rates of 2.3 s^{-1}, 23 s^{-1}, and 230 s^{-1} (ignoring compliance in the rubber damping pad or load train). The results for the dynamic tests are shown in Fig. 7. The transition from elastic deformation to plastic deformation was not exceptionally clear for several reasons: (a) the alloy has a high work-hardening rate combined with a high geometric hardening associated with cylindrical compression, (b) the quartz load cell and oscilloscope configuration resulted in a large amount of scatter in the force signal, and (c) the rubber damping pad produces non-linear compliance that is superimposed on the test data. Nevertheless, an inflection appears in the 1"/sec data at a force value of ~750 lbs (engineering stress of ~5 ksi), consistent with the quasi-static yield strength. At the highest displacement rate, the quartz load cell shows a significant force oscillation in the vicinity of 800-1000 lbs. The ability to perform quantitative compression tests at strain rates in the sub-Hopkinson regime will require additional improvements: (a) higher resolution force sensing, (b) the replacement of the quartz load cell with a custom load cell that is less susceptible to inertial oscillations, and/or (c) a local measure of platen displacement or specimen strain that eliminates the contribution of the rubber damping pad. With all of these improvements, high-fidelity dynamic compression tests may become feasible.

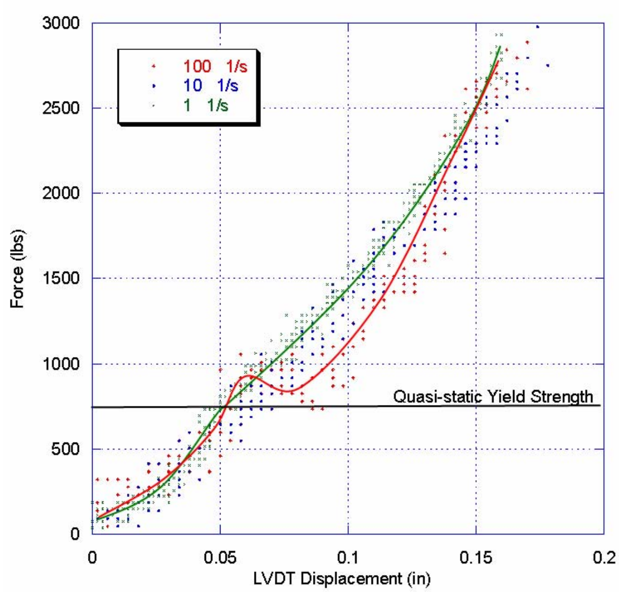


***Figure 7**. Compressive force-displacement profile for a 50Au-50Cu braze alloy at displacement rates from 1-100"/s.*

Summary

An understanding of the mechanical behavior of materials at strain rates in the range of 1-500 s^{-1} is important for many dynamic failure events yet the methodology needed to characterize material behavior is not well established. We have demonstrated a tensile technique that utilizes a high-rate load frame coupled with custom load cells and a shock-mitigating damper to obtain stress-strain data at strain rates up to ~500 s^{-1} with minimal force oscillations. This technique was used to show that the Hytuf alloy has a very low strain-rate sensitivity in this regime. A technique is also under development for the characterization of compressive stress-strain behavior. While initial results did not produce acceptable data quality, known improvements may lead to a reasonable method for dynamic compression tests.

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