

NIST Series Technical Note
NIST TN 2381

**An Instrumented Drop Tower for Impact
and Stab Testing**

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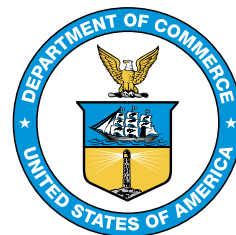
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Abstract

This report describes the design, capabilities, and applications of a 4 m instrumented drop tower (IDT) system at the National Institute of Standards and Technology (NIST). Drop tower systems are a class of test instruments for measuring material and system-level response to controlled impact conditions. Drop tower systems may allow control of impact energy, velocity, angle, temperature, and impactor shape. They are widely used to evaluate armor, protective equipment, packaging, and impact-mitigating materials at rates between servohydraulic instruments and below ballistic testing. The NIST IDT is based on the National Institute of Justice Stab Resistant Body Armor Standard - 0115.00 [1] with capabilities substantially expanded into a modular, highly instrumented platform for a broad range of impact and material-characterization studies.

The current system can measure acceleration, contact force, transmitted force and force distribution, impact velocity, and test-piece deformation. The modular design enables configurable impactor mass, impactor geometry, drop height, specimen or test-artifact type, and fixturing. These capabilities allow testing across diverse applications and test types, from stab of commercial armor systems with simulated improvised threats to high-rate uniaxial testing of impact-mitigating foam. This report describes sensor packages and resulting datasets. Illustrative examples are used to demonstrate the ability of the IDT to measure forces on the impactor, pressures transmitted through the material, and strains in complex, heterogeneous packages. The NIST IDT platform delivers a rich experimental dataset that supports complex dynamic material models for next-generation impact mitigating systems.

Keywords

Armor; Foam; Helmets; Impact; Material testing; Protective equipment; Stab; Impact mitigating materials.

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Author Contributions

Alexander K Landauer: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Project administration, Data curation, Visualization, Software. **Ran Tao:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Project administration. **Amanda L Forster:** Investigation, Resources, Supervision, Project administration, Writing - review & editing. **Aaron M Forster:** Conceptualization, Investigation, Resources, Methodology, Project administration, Writing - original draft, Writing - review & editing, Supervision. **Michael A Riley:** Conceptualization, Investigation, Resources, Methodology, Project administration, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Software.

1. Overview

Drop towers¹ are an important class of mechanical testing systems for realizing impact-like conditions in a controlled experimental environment. Drop testing probes the intermediate strain rate regime, usually 10^1 s^{-1} to 10^3 s^{-1} , where inertial and viscous effects are significant for most materials, but do not dominate, and shock effects (i.e., dynamics due to the strain wave propagation transients in the material) remain small. This is a challenging regime to study since it is faster than controlled actuator systems, such as hydraulic universal testing machines or rheometers, and slower than systems that leverage strain wave propagation effects, such as the Kolsky Bar or Taylor Impact [3–6]. Figure 1 illustrates the strain rate ranges of these techniques in an Ashby-style diagram.

Given the relatively uniqueness and simplicity of drop towers for accessing the intermediate rate regime they are broadly used for testing in this range, including the validation of protective equipment (e.g., ASTM F1446 [7]), performance assessments of packages (e.g., ASTM D3332 [8] or D5276 [9]), and testing electronic devices (e.g., JESD22-B111A [10]). A subclass of drop testing is the instrumented drop tower (IDT) test, which involves a linear drop of a specific mass from a known height in a controlled fashion onto a fixed table, which is outfitted with instrumentation to record drop characteristics such as accelerations and/or forces. The test artifact is either fixed to the drop mass, in which case the table is often called an anvil, or is installed on a fixed table. In addition to validation and performance assessment, this type of testing can be used for material characterization of protective and impact mitigating materials as in, e.g., ASTM standards D5628 [11] and D7136 [12], and described in the academic literature [13–15].

The National Institute of Standards and Technology (NIST) drop tower system was originally constructed in the 1990s as one of several identical systems fabricated by a United Kingdom-based company to provide a basis for standardized testing of stab resistant armor. The original system was lightly instrumented, and purpose-specific for the requirements of the National Institute of Justice (NIJ) [1] and UK Home Office Police Scientific Development Branch [16] stab resistant armor test standards. Since this system was installed, it has been used for a wide variety of projects beyond the intended test methods, and extensively upgraded with new instrumentation and testing capabilities, many of which were developed and deployed specifically for these projects. For example, during the Head Health Challenge III [17] it was employed to evaluate novel impact-absorbing materials designed for helmets, where a custom instrumented drop mass was used to provide extensive response data to the challenge participants. It has also been used for wide-ranging applications for evaluating protective equipment for military, police, and sports, such as military footwear, riot helmets, and stab resistant materials. This Technical Note

¹This type of system, with small variations but similar operating principals and physics is also called drop mass, drop weight, or linear drop, and refers to a systems using a vertical drop mechanism. Pendulum drop, or swinging mass, impact tests such as Charpy and Izod have many similarities but are distinct techniques. In this Technical Note we focus on the vertical drop systems.

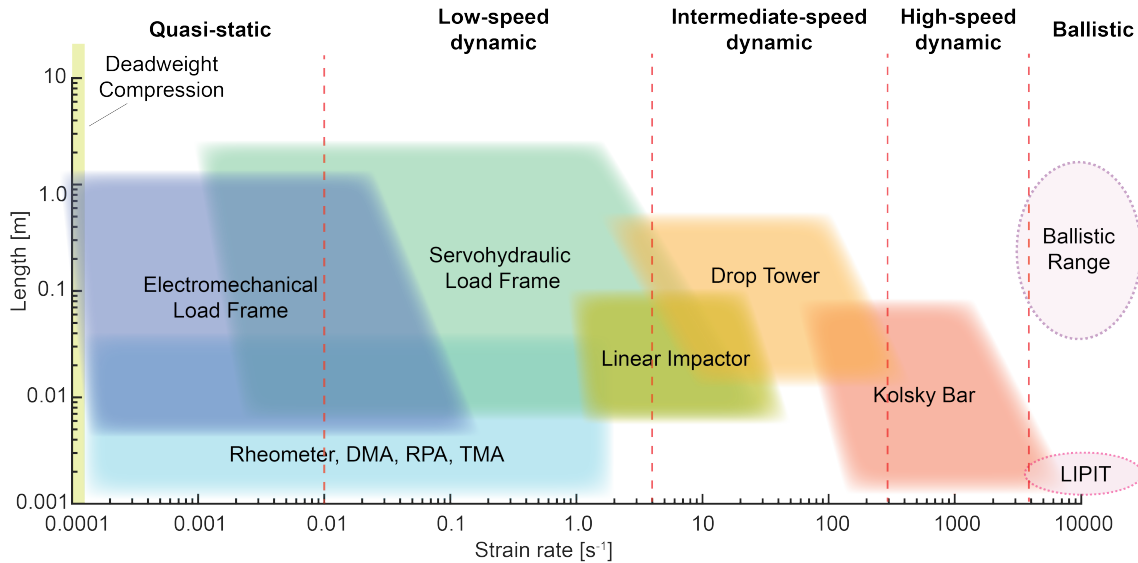


Fig. 1. Ashby-style diagram showing the length scale vs. strain rate space of several mechanical testing techniques available at NIST. The drop tower instrument described in this Technical Note provides testing capacities that bridge between universal testing machines (load frames) and servo-controlled linear impactors in the sub- 10 s^{-1} regime and Kolsky Bars, Laser Induced Particle Impact Testing (LIPIT) instruments and ballistic techniques in the 200 s^{-1} and higher regimes.

focuses on the current design and implementation of the NIST instrumented drop tower, including detailing the specifications and instrumentation, modularity and adaptability, and providing use-case examples for material characterization and stab testing.

2. Drop tower design and construction

The drop tower impact testing system, shown in [Figure 2](#), consists of a 4 m vertical drop tower, an instrumented impactor with on-board force and acceleration sensors, a laser break-beam system for inbound velocity measurement, a force table for transmitted force measurement, and a high-speed video system for impact monitoring.

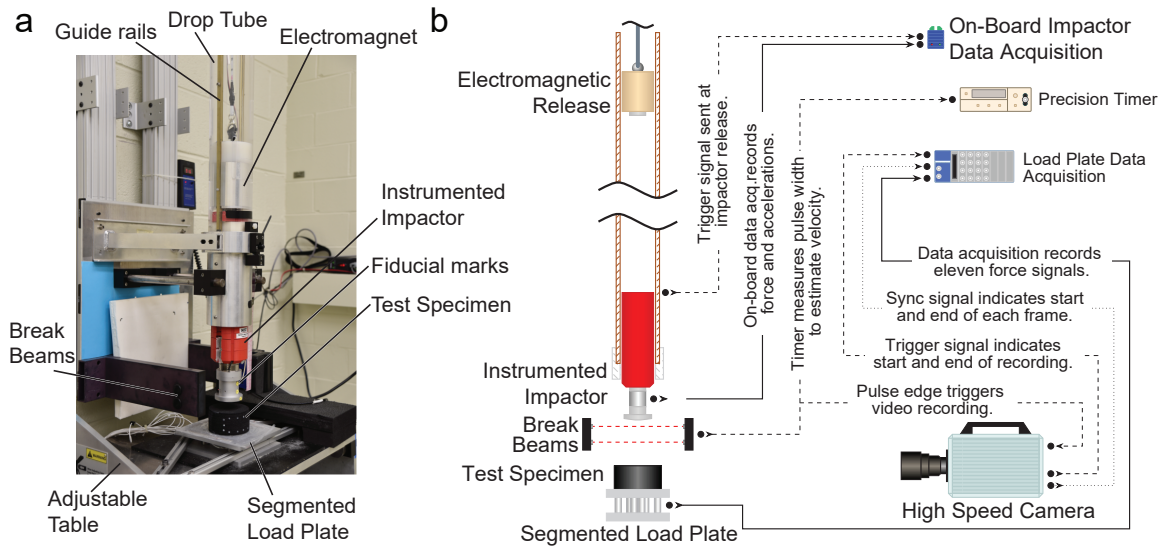


Fig. 2. Overview of the drop tower system. (a) Photograph of the bottom of the tower showing the instrumented impactors and related subsystems. (b) Schematic showing the components of the drop tower system and how the signaling and data flows are interconnected.

The 4 m drop tower employs a permanent electro-holding magnet to attach and release the drop mass, or impactor. After being raised to a desired height, the power is applied to the coil of the magnet, which nullifies the permanent magnetic field and releases the impactor, allowing it to fall freely within the drop tube. Two vertical rails along the inside surface of the tube prevent the impactor from pitch and yaw movement such that the attitude of the impactor is perpendicular to a planer sample at contact. Comparison between idealized free-fall impact velocity and measured impact velocity indicate minimal ($< 5\%$) reduction in impact velocity due to confinement effects such as rail friction and aerodynamic drag or cushioning. The initial drop height is measured to within 1.0 mm by a graduated tape directly attached to the locking carrier of the impactor.

2.1. Instrumented drop mass

Figure 3 shows an image of the instrumented drop mass with on-board sensors and data acquisition (DAQ), drop weights, and a hemispherical impact tip. The dimension of the carrier is 92 mm in diameter, with a variable length (roughly 470 mm in the configuration shown in Figure 3), which is designed to allow the use of multiple sensors and impact tips of different shapes and sizes. The total mass of the impactor can be adjusted between approximately 2 kg and 15 kg by adding or removing steel disks. The impactor is equipped with two triaxial accelerometers (Endevco 7268C) with a 2000 g range ($1.0\text{ g} \approx 9.807\text{ m/s}^2$; 1 % full scale range non-linearity and hysteresis) on all three axes with the

first one mounted above the impact tip and the second one mounted alongside the DAQ system. The first accelerometer is used to measure the acceleration of the impactor; the second accelerometer is used to monitor the acceleration being imparted on the DAQ system. To measure the total impact force as a function of time a dynamic force transducer (either HBM U9C or U93 depending on the impactor tip and force range) installed in line with the vertical axis of the first accelerometer, between the steel weights and the impact tip, and typically records synchronously with the accelerometers at 20 kHz.

Various impactor tips are available and custom tips are easily machined. The common tips include the blunt hemispherical option shown in [Figure 3](#), flat faced compression-platen like or punch-like options in a variety of diameters, a drill chuck that can hold a variety of improvised threats, and fixtures for standardized blade or spike threats. Given these options and the ease of switching tips, designing and installing custom geometries or styles of tips is straightforward. However, it is important to keep in mind that tip mass corrections may be needed to correct for force discrepancies for more massive tip, because the force sensor is above the tip and thus the inertia of the tip is not inherently included in transducer readout. For example, a standard blunt impact hemispherical impactor tip has a mass of $0.140 \text{ kg} \pm 0.002 \text{ kg}$ and one configuration of the drop mass without the tip is $2.906 \text{ kg} \pm 0.002 \text{ kg}$. The drop weight-to-tip mass ratio in this case is approximately 20.76, defined as the ratio of the mass of weight above the load cell to the mass of the head. Thus the contact force (F_c) is higher than the measured impact force (F_{lc}) by about 4.8 %. Since the mass of the tip and fixtures below the force sensor is known, and the lower accelerometer is located adjacent to the force sensor, the total constant force can be estimated by adding the inertial force to the measured force.

2.2. Force table

A segmented force table is designed to measure the forces transmitted through the specimens and the distribution of those forces. The force table system consists of eleven 22.2 kN piezoelectric force sensors (Kistler Type 9712B5000). The sensors are segregated to provide force distribution at three locations: center (C), ring (R), and outer (O), as shown in [Figure 3b](#). The center location is a single force sensor with a sensing area of approximately 428 mm^2 . The ring location is composed of six load cells around the center, each with the same sensing area as the center sensor and with a combined sensing area of 2568 mm^2 . The outer location is composed of four load cells to measure the force distributed to the remainder of the plate. The load cells are connected to a DAQ system (National Instruments) that is triggered by either a minimum force level or by a trigger signal from the high speed camera. Data is recorded at a rate of 20 kHz to 50 kHz. The data is typically filtered using a 6 pole Butterworth filter with a 1650 Hz cutoff frequency.

The total transmitted force is reported as the sum of the forces on all sensors. The reported pressures on the center and ring pads are computed as the force measured by the relevant force sensor divided by the corresponding sensing area. The pressure on the outer plate is

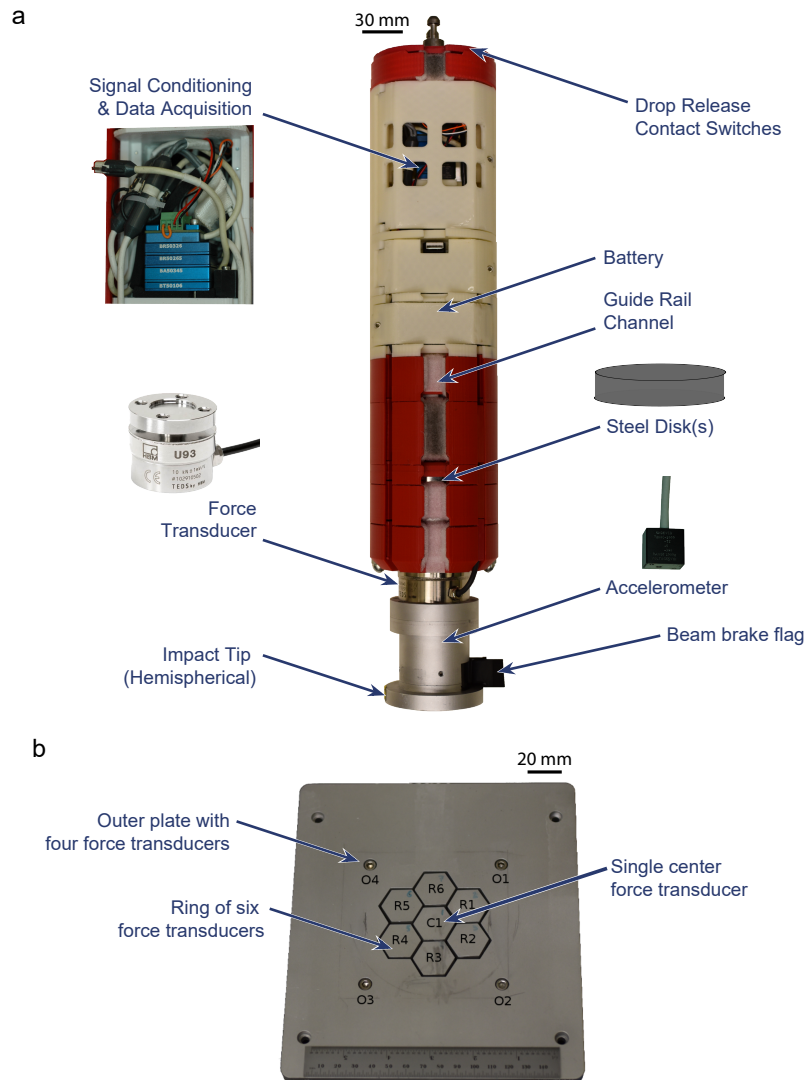


Fig. 3. Photograph of the drop mass (a) and force table (b) showing the instrumentation and structural components of the each. For the impactor this includes an on-board DAQ system, force and acceleration sensors, weights, and a hemispherical impact tip of 127 mm impact face radius and 70 mm diameter. Other impactor tips are readily interchangeable. For the force table this includes the plate and segmented areas with individual force transducers.

reported as the total force on the four outer sensors divided by the area of the specimen on the outer plate. However, the area of the plate that is loaded varies with the size of the test specimen. The dimension of the entire plate is 177.8 mm by 203.2 mm. For example, for specimens smaller than the entire plate (in most cases), the pressure exerted on the outer portion of the specimen is reported as the sum of the forces on the four outer transducers divided by the area of the specimen minus the area of the seven hexagons above the center and ring transducers.

2.3. Image acquisition system

A high-speed video camera (Photron SA-5) is used to record video of each impact. The camera is configured to collect images at an appropriate rate for the test, but typically at 10 kHz, and image analysis software can be used to measure the position and velocity of the impactor throughout the test. As in the first example use case below, this can be achieved with digital image correlation when full-field pixel-wise displacements, strains, or velocities are needed and the test artifact has been appropriately speckled. For less involved post-processing when pixel-wise quantities of interest are not needed, fiducial point tracking is used with a software package provided by the camera vendor. Fiducial marks are typically used on the impactor regardless of the specimen configuration to allow estimation of the position and velocity time histories of the impactor, including the incoming speed of the impactor (V_{in}) and the rebound speed (V_{out}).

2.4. System integration and data reporting and processing

Data recorded by the instrumentation on the drop mass is retrieved after each test using a wired USB connection and manufacturer supplied software. The software automatically saves all downloaded data in a proprietary format and allows selected data sets to be exported in a variety of standard formats, with the option to filter the data during the export process. Most commonly, data is filtered and exported to comma-separated variable (CSV) format files. Data recorded by the force table is automatically saved to the CSV format file by the data acquisition control software immediately after the acquisition of each test is completed. Videos recorded by the high-speed camera are downloaded after each test and saved as either .AVI format videos or a series of .TIFF images. These videos are then manually analyzed to estimate the motion of any fiducial marks or speckle patterns, and the resulting time series data is exported to a CSV format file as discussed above.

Once collected from the instruments and stored, the CSV files are typically analyzed with custom in-house scripts written in Python and R [18, 19]. For example analysis and visualizations see the section below. Many additional analyses are possible and have been conducted, but are outside the scope of this document to discuss in detail, see for example other published reports [17], data [20], and code [21].

3. Example use cases

3.1. Impact-rate characterization of monolithic foam

This example case examines the impact response of three different closed cell elastomeric impact protection foams. The sample set is composed of a neoprene/EPDM/SBR (poly-chloroprene/ethylene-propylene-diene-methylene/styrene-butadiene rubber) blend with a density of 192 kg/m^3 , denoted as N192, and a pair of vinyl-nitrile foams with a density of 104 kg/m^3 and 111 kg/m^3 , denoted as VN104 and VN111 respectively. N192 has is the stiffest foam with a nominal 25 % compression deflection of 137 kPa followed by VN104 (76 kPa), and VN111 (59 kPa). The linear viscoelastic dissipation ($\tan(\delta)$) is highest for VN111 followed by N192, and VN104 measured by dynamic mechanical thermal analysis over a frequency range of 10^{-1} Hz to 100 Hz. The cylindrical test specimen, approximately 100 mm diameter and 50 mm height, is composed of two layers of foam mounted onto the load plate with double sided tape as the adhesive. See [Figure 4a](#). Preliminary results show little difference between a single piece and layered foams in this configuration, and some materials are unavailable in thicknesses needed for these experiments.

The impact response of each foam is measured by dropping the instrumented impactor (mass = 3.3 kg) in a series of stepped heights. The impact energies range from 10 J to 75 J, with velocities of 2.5 m/s to 6.7 m/s, respectively. The foams are allowed to recover, $t \sim 60000t_{\text{impact}}$, after each impact. Preliminary work showed this to be sufficient time to obtain repeatable results for these foams. At least two samples and two repeat impacts are tested at each impact energy. The load plate captured synchronized force data at 50 kHz and the drop mass data was recorded at 20 kHz. [Figure 4](#) shows the peak deceleration ($g \text{ [m/s}^2\text{]})$ of the drop mass for all three foams. The response difference of each foam is clear as the impact energy increases above 50 J. VN111 and N192 exhibit the least change in deceleration across a 7x increase in impact energy demonstrating the combination of density, stiffness, and dissipation efficiently absorb the impact energy.

The segmented force table provides a rich data set to understand how force is transmitted or dissipated through the foam during the impact. The 45 J impact energy is a conjunction point where N192, VN111, and VN104 exhibit similar peak deceleration. [Figure 4b](#) shows heat maps of the distribution of pressure at the maximum force. In the heat map, the circle approximates the area covered by the foam sample and the hexagons represent individual force sensors in the center and ring areas. The heat map shows a clear difference in pressure distribution between the two samples. The maximum pressure for each area (in kPa) is noted on the figure. For N192, the pressure is highest at the center of impact with a relatively uniform 10 % decrease in pressure at the edge of the sample. For VN111, the impact pressure is approximately 25 % lower in the center than N192 and the pressures are more uniformly distributed to the sample edge.

For time analysis, the force table sensors are grouped into a center pressure (orange), ring pressure (green), and outer pressure (purple) ([Figure 4a](#)), which allows visualization of the

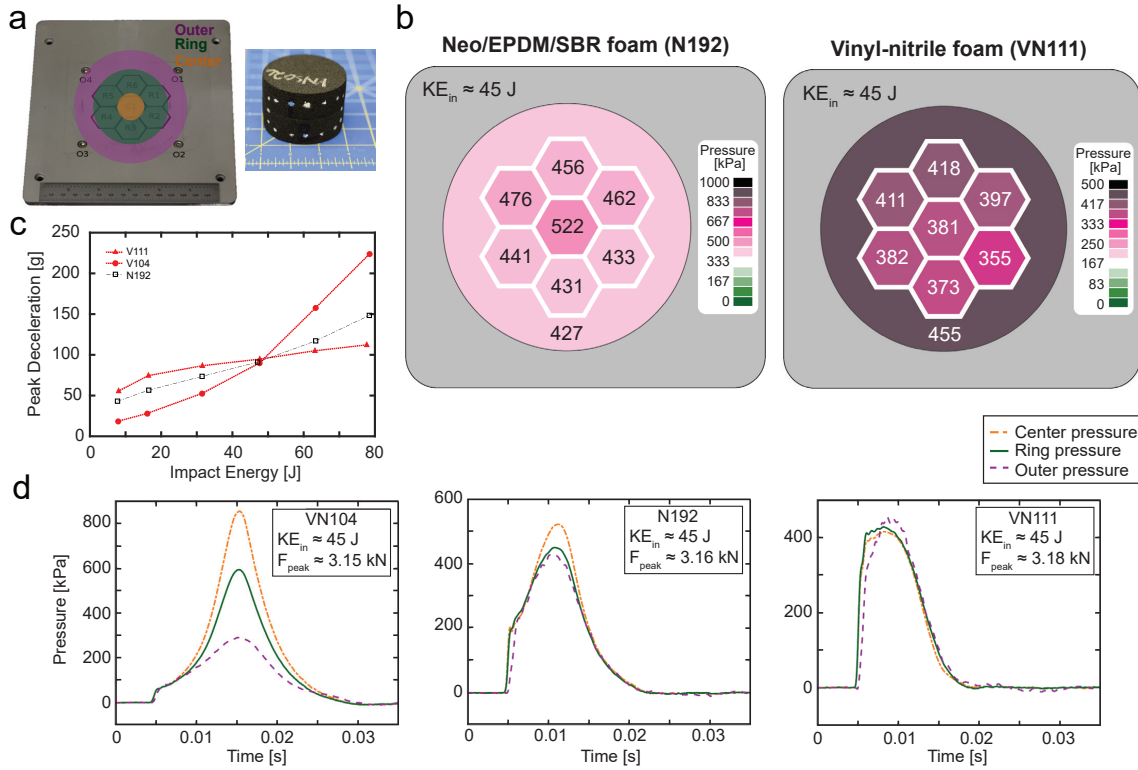


Fig. 4. Sample results from a monolithic foam test with the segmented load plate to assess pressure distribution under a hemispherical impactor. (a) Snapshot of an example foam stack (N192) and the center, ring, and outer sensor layout. (b) Visualization of the pressure distribution under a 45 J $\pm$ 0.08 J impact for two foams at peak force, demonstrating the difference in force redistribution between different materials. (c) Peak deceleration as a function of impact energy (uncertainty 1 % non-linearity and hysteresis). (d) Pressure as a function of time for the center, ring and outer sensor groups for the 45 J drop case. These show data from a single specimen of each foam. Typical uncertainty on pressure is ± 7 kPa. Typical percent variability between runs in peak acceleration is < 3 %, in peak transmitted force is < 3 %, and in pressure < 5 %).

transmitted force radially from the center of the impact as a function of time (Figure 4d). In this view, the impulse loading across the plate is relatively uniform across all sensors for N192 and VN111. VN111 shows a rapid loading to the maximum force that persists until the foam begins to unload (drop mass rebound phase, ca. 12 ms) which is closer to ideal foam energy absorption behavior than the continuous pressure peaks for VN104 and N192. N192 quickly and evenly loads to approximately 200 kPa and transitions to an, even continuous loading phase. The VN104 foam exhibits a poorly distributed backface pressure Figure 4d (left) concentrated on the center (with peak pressure > 800 kPa) and ring (approximately 600 kPa) areas. The segmented force table enables a view into the material response not possible when only measuring the impactor response or a single sensor reaction table. The ability to quantify force distribution during impact is critical. Modern and next-generation protective systems leverage advanced manufacturing, auxetic structures, elastic-snap transitions, and novel materials that are coupled with machine learning algorithms to optimize systems based on threat and risk profile, biology (e.g., gender, body shape), and injury type and tolerance. High fidelity data during dynamic impact is critical to an experimental-simulation feedback loop to achieve system designs that optimally reduce the risk of blunt trauma and acute injury.

3.2. Impact-rate characterization of helmet liner foam

For this example case, adapted from [2], we focus on a material system characterization experiment for impact mitigating materials (IMMs), specifically layered foams. The materials are designed to protect from impacts of $O(10\text{ J})$ and $O(10\text{ ms})$ with strain rates reaching 10^1 s^{-1} to 10^2 s^{-1} . In practice, the IMM package often includes a hard shell for penetration or fracture protection and one or more viscoelastic foam layers [22]. Foam-like viscoelastic materials are typically characterized by a large constant-stress plateau in the stress-strain response, allowing for substantial energy absorption at near-constant acceleration, which is important for efficient linear impact protection [23]. Foams in IMM packages are often layered or gradient stiffened to provide both protection and comfort, usually with hard distal and soft proximal layers, as sketched in Figure 5b. A combination of material properties and structure are sought that minimize injury risk either via top-down design, e.g. via models of discrete material layers that minimize stress wave propagation, e.g. [22, 23] or promote dissipative mechanisms, e.g. [24] or limit rotational (i.e., shear) loads, e.g. [25], or via computational topology optimization of lattice-like architected structures, e.g. [26, 27] which can then be fabricated through additive manufacturing techniques [28]. This section discusses the application of the instrumented drop tower to apply impact-like conditions to multi-layer foams using digital image correlation to quantify the deformation in each layer.

Foam specimens approximately $50\text{ mm} \times 50\text{ mm} \times 25\text{ mm}$ were excised from as-received sheets of a stiff vinyl-nitrile foam (VNW, density approximately 111 kg/m^3) and a less stiff vinyl-nitrile foam (VNB, density approximately 135 kg/m^3). Both are closed-cell viscoelastic

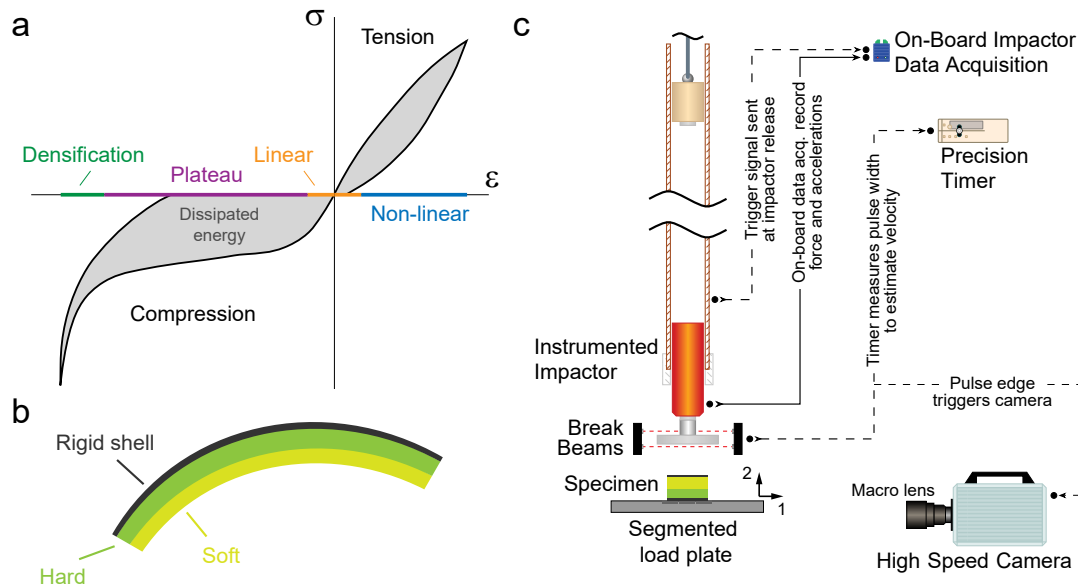


Fig. 5. Schematics for the foam test example case. (a) Sketch of the typical stress-strain response of a foam-like material at constant strain rate. (b) Simplified schematic of a bi-layer IMM, with hard and soft layers of foam and a rigid external shell. (c) Components (not to scale) of the drop-mass system, including synchronized single camera, load-plate, and instrumented adjustable-weight drop mass showing the specimen configuration and coordinate system. Adapted from [2].

foams. Specimens were either monolithic foam or layered in a VNB (bottom) + VNW (top) as in the schematic of [Figure 5c](#), or VNW (bottom) + VNB (top).

To measure the surface deformation and the strain distribution during impact, a digital image correlation (DIC) algorithm [29] designed for finite deformations was incorporated into the instrumented drop tower experiments using high-speed imaging (see [Figure 5](#)). Typical settings and calibrations for the DIC analysis are summarized in [Table 1](#). DIC was conducted following the practices outline in the the International Digital Image Correlation Society's Good Practices Guide, to the extent possible, for the setup [30]. Images were collected at nominally 10 kHz (exposure 1/20000 s, f/5.6) using a 1:2 macro lens (standoff distance approximately 0.5 m). The load plate captured synchronized force data at 50 kHz. The impactor was configured with a flat impactor of larger diameter than the hypotenuse of the foam. The drop mass recorded synchronized triaxial accelerations and axial load data from the onboard sensor package. The segmented load plate and camera data are synchronized to the break of the light beam above the sample. The data package from the drop mass, segmented load table, and camera are useful for comparison and manual synchronization of timing. Caution should be exercised with manual synchronization as the potential errors in timing mismatch are dependent on data collection rate and impact velocity. The displacement field data is used to compute the surface strain via an optimal-tap spatial differentiation filter and strain rate history via temporal central differencing. The drop details and key performance metrics are summarized in [Table 2](#). Monolithic materials were subjected to a 0.4 m drop of approximately 12 J of energy. Layered foams were approximately twice the height of the monolithic foams, therefore the layered foams were subjected to a $3\times$ increase in energy, approximately 36 J, to achieve a similar degree of maximum compressive strain in the stiff layer (VNW) as the monolithic cases.

The scalar metrics of interest for impact protection selected from the drop mass experiment include the peak acceleration of the drop mass, the peak force applied to the top of the specimen, and peak force transmitted through the specimen. These results are given for the monolithic foams and both stack configurations in [Table 2](#). An example of stress and strain rate as a function of compressive axial engineering strain for the monolithic foam samples is shown in [Figure 6](#). In this case, the 12 J impact leads to approximately 50 % mean axial engineering strain, which is at the upper end of the plateau regime of the foam. The sample rapidly loads at impact, reaching a maximum strain rate of $\dot{\epsilon} \approx 90$ 1/s within a mean axial engineering strain of $\epsilon \approx 0.5$ and a maximum engineering stress above 800 kPa. This is followed by a period of constant strain rate (approximately $0.05 < \dot{\epsilon} < 0.2$) as the engineering stress begins to plateau around 800 kPa. As the impact continues, at about 18 % strain to 20 % strain, strain rate reduces to less than 20 1/s and becomes noisy, likely due to challenges with speckle distortion and DIC decorrelation under large strain.

The multilayer foam stacks present additional challenges to analyze. To illustrate the deformation inhomogeneity, undeformed and deformed images of the specimen are given in [7a](#). To quantify inhomogeneous deformation habits, a normalized representation of the

Table 1. Image and process parameters for digital image correlation of a typical monolithic specimen.

Parameter	Value
Frame rate	10 kHz
Camera Noise	0.026 %
Prefilter	Gaussian, 3 px by 3 px, $\sigma = 0.5$
Run mode	FFT-based, Hybrid stepping
Image size	818 px by 765 px
Subset size (final)	16 px by 16 px
Step	8 px
Strain filter	Optimal-7 tap
Virtual strain gauge	58 px
Temporal (rate) filter	Central difference
Interpolation	Cubic spline
Measurement points	10185
Total images	235
Static displacement uncertainty	x : 0.020 px; y : 0.019 px
Static strain uncertainty	$\epsilon_{11} = 427 \mu\text{m/m}$ $\epsilon_{22} = 450 \mu\text{m/m}$ $\epsilon_{12} = 261 \mu\text{m/m}$

DIC data is helpful, as shown in 7 for an example 36.9 J impact. In this analysis, a map of axial strain as a function of height of the specimen and post-impact time is given, see 7b, where each time slice represents the mean axial engineering strain, $\bar{\epsilon}_{22}^1$, taken across the x_1 -direction. This representation reveals that in the initial approximately 2 ms of loading the top layer deforms relatively uniformly until densification at roughly 50 % strain. Although the strain appears to rapidly increase near the VNW/VNB interface this is likely an artifact of the experimental configuration, since initial conformal contact is not guaranteed. At approximately 4 ms the lower layer begins to rapidly deform until it densifies at about 5.5 ms.

This example highlights the complexity of the impact event compared to the well-controlled conditions of a conventional uniaxial compression test. The method to extract strain evolution information from multilayered foam system highlights the non-uniformity of these types of systems.

3.3. Stab testing a novel body armor prototype

In this example, a stab test of a novel bio-inspired composite armor prototype is described.

Personal armor systems must balance the critical requirement of providing intended protection with the need for the armor to be sufficiently flexible and lightweight for it to be

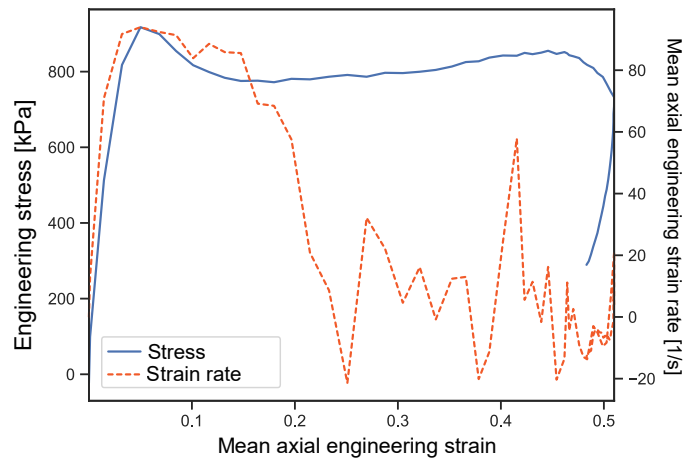


Fig. 6. An example stress and strain rate vs. strain result. This shows mean axial engineering surface strain rate, $\dot{\bar{\epsilon}}_{22}^1$, and engineering stress, σ_{22} , measured from the segmented the force plate and plotted against the engineering strain, $\bar{\epsilon}_{22}$, from a 0.4 m impact on VNW. Typical stress uncertainty is ± 7 kPa. Adapted from [2].

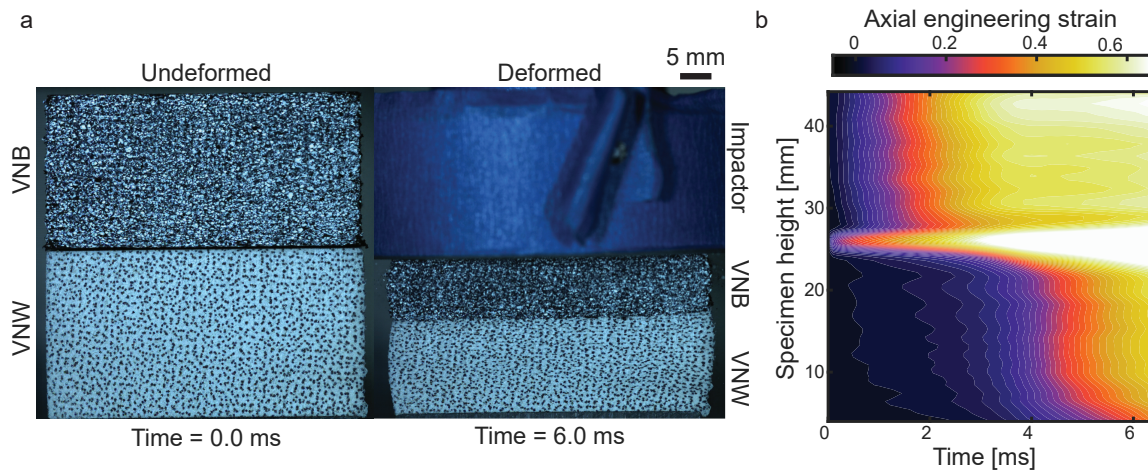


Fig. 7. An example visualization of the deformation process for a multilayer stack. (a) Snapshots of the multilayer VNB + VNW foam in the undeformed and deformed configurations. (b) The evolution of mean (x_1 -direction) axial engineering strain $\bar{\epsilon}_{22}^1$ during the first ca. 6 ms of a 36.9 J impact shown as a contour map. Adapted from [2].

Table 2. Drop mass impact data for impacts on monolithic and layered foams. Data are listed as mean $\pm$ one standard deviation for two repeats on two specimens ($n = 4$) for monolithic foam and two repeats per stack type for layered foam ($n = 2$).

Specimen	Drop height (m)	Energy (J)	Peak impactor acceleration (g)	Peak applied force (kN)	Peak transmitted force (kN)
VNW	0.4	12.3	45.4 ± 3.5	1.09 ± 0.11	1.00 ± 0.07
VNB	0.4	12.3	63.0 ± 2.6	2.03 ± 0.07	1.96 ± 0.06
VNB + VNW	1.2	36.9	81.3 ± 0.3	2.73 ± 0.3	2.68 ± 0.12
VNW + VNB	1.2	36.9	71.2 ± 1.9	2.43 ± 0.06	2.31 ± 0.06

wearable and reasonably comfortable. Ballistic armor systems face these fundamental trade-offs – thick metal plates, such as steel or titanium can provide sufficient protection, but are heavy. Ceramic plates improve upon this, but remain cumbersome [31]. High-strength fiber-based armor improves weight and comfort, but typically cannot be rated to withstand the most severe threats [32–35].

Academic collaborators at the University of California - Berkeley have taken inspiration from the structure of fish scales, a historically important class of armors that has received increasing interest in recent years [36–38], to achieve both rigidity and flexibility through overlapping stiff elements embedded in a soft substrate [39]. This design prototype features hard circular scales that mechanically interlock with a soft substrate using a dovetail-type interlocking geometry to retain scales during the impact. The first prototypes of this design have been considered for stab resistance, with the research focused on developing accurate models of the system response.

To fabricate the test specimens, the compliant substrate is additively manufactured using fused deposition modeling with thermoplastic polyurethane, the ceramic scales are slip-cast with alumina, and the scales are then manually inserted into the dovetail negative feature, see the geometry in [Figure 8a](#). The prototype is mounted below the drop tower and impacted with a 17 J drop using a standardized knife-like threat as illustrated in the diagram in [Figure 8b](#). Fiducial marks are placed on the specimens and drop tower components to track relative motion and velocity using single-point tracking from the high speed videography (see the snapshot in [Figure 9a](#)). Before and after images of the prototype are shown in [Figure 9](#).

To configure the drop tower for this test three specific changes are required, each of which is relatively straightforward due to the modular design of the system. First, the instrumented impactor is outfitted with the standard “S1” knife blade that is specified in the NIJ stab resistant armor standard, NIJ–0115.00 [1]. To achieve this, the interchangeable nose-piece is switched for a mount that rigidly holds a replaceable blade parallel to the direction of travel. The mass of each component and the final assembly is recorded for later analyses. Second, the base stage beneath the drop tower is changed to a stab-test specific, rigid

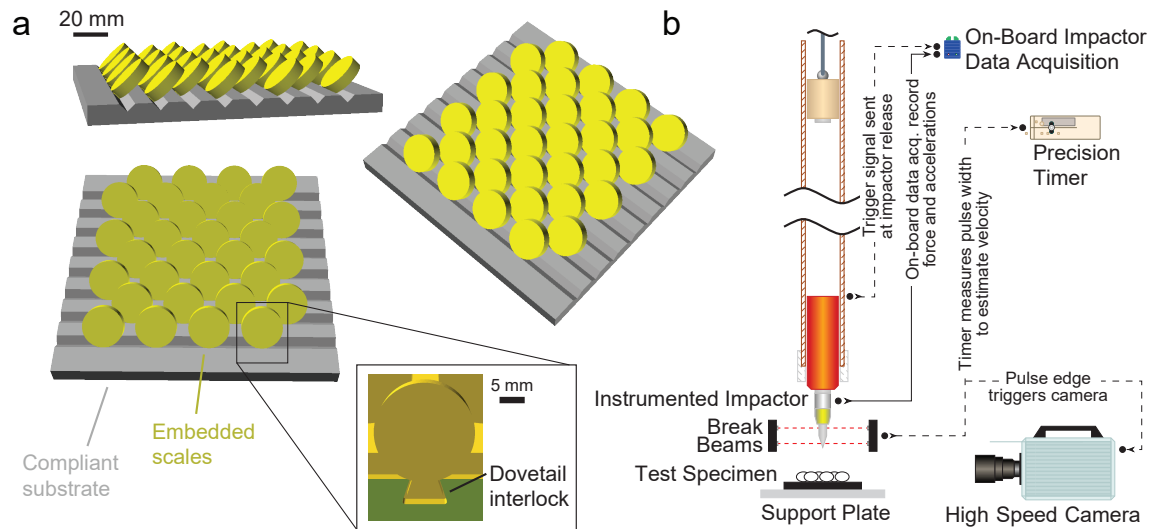


Fig. 8. Sketches of the specimen configuration and drop tower system. (a) Rendered views of the prototype system. *Inset* showing the embedded dovetail interlocking feature. (b) Components (not to scale) of the system, including synchronized camera, load-plate, and instrumented adjustable-weight drop mass and fixtured specimen.

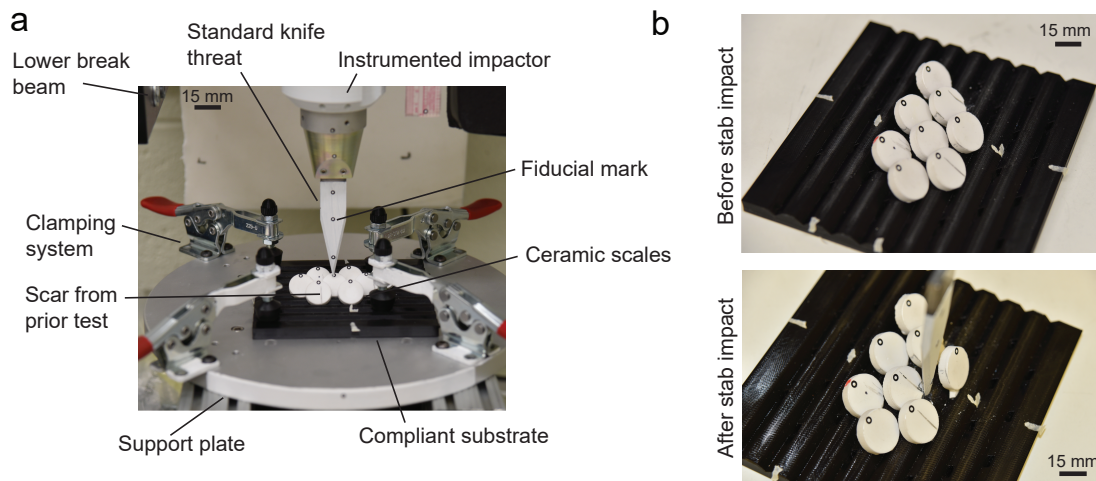


Fig. 9. Snapshots of the prototype. (a) Labeled photograph of the fixtured specimen and incoming drop-mass mounted threat. (b) Before and after snapshots of the prototype showing the blade embedded in the compliant backer after impacting a scale and sliding down its face. Note scars (wear marks) on other scales from previous tests.

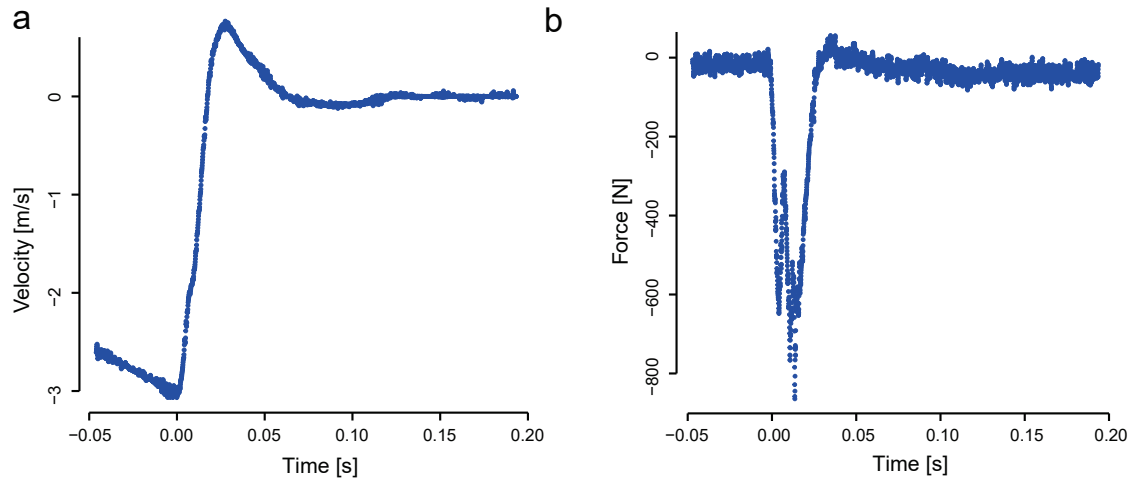


Fig. 10. Velocity and force for an example stab test on the armor prototype. (a) Velocity time history for an example stab test, show the initial free-fall at negative times, and the impact and rebound out to about 200 ms. (b) Force time history recorded by the impactor showing the rapid rise in force during impact, a small reversal during rebound, followed by a smaller static force as the impactor comes to rest on the substrate.

support plate with clamps designed to hold the specimens. These tests used a support plate with a 75 mm diameter hole, centered under the impact location. Third, the high-speed camera lens and physical position is adjusted to capture the necessary field of view for the test. The drop tower system is operated as described above with the camera positioned 2.15 m from drop tower and configured with an [80-200] mm zoom lens adjusted to approximately a 135 mm focal length and the aperture of f/2.8. Video is recorded at 10 kHz with an exposure of 1/20,000 s and a resolution of 448 px $\times$ 1024 px, which results in a field of view of about 125 mm by 287 mm. Sensors on the instrumented impactor are sampled at 20 kHz.

For the experiments on this prototype, the force and velocity history from the instrumented impactor is shown in [Figure 10](#). The velocity trace indicates the impactor has a relatively smooth rebound during the transition from negative (i.e., downward) velocity to positive velocity, before coming to rest. The small deviation at about 20 ms might be attributable to the blade tip sliding off of the scale and impacting the TPU substrate. This is corroborated with a force trace, which also shows a spike at about 20 ms that could indicate the knife point transitioning from sliding to embedding in the substrate, where it was located at the end of the test as shown in [Figure 9b](#). Quantitative evaluation of stab-like impacts in this way provide important insight and design targets for prototyping armor system.

This example of stab testing of a prototype armor system highlights the flexibility testing various types of test artifacts. The qualitative and quantitative measurements from the instrumented drop tower can be used to better understand the time history of the response of the armor to a given threat under stab-test conditions. These include a challenging mix of physics including rate sensitivity, dynamic cutting, fracture, friction, and high-rate wear among others. This can help refine concepts and improve designs, and rapidly iterate on prototypes due to the streamlined and modular experimental platform.

4. Summary

This Technical Note has described the background, history, and current testing capabilities of the NIST Instrumented Drop Tower system in the Security Technologies Group in the Material Measurement Lab at NIST and provides descriptions of example applications. The system dates back to the 1990s as a system for stab testing armor, and in its current form provides a flexible test platform for stab testing, material characterization, protective equipment and sub-component evaluation, allowing continued test flexibility into the future. As such, it provides access to a unique testing rate range in the impact-like regime, which bridges between our servohydraulic load frame and ballistic and Kolsky bar capabilities. With extensive instrumentation for forces, acceleration, imaging, on both side of the specimen we obtained rich data on the test artifact. Two example applications were discussed, which highlight typical testing modalities used in the Drop Tower at NIST over the past several years. It is a valuable asset for evaluating protective systems, guiding prototype development, and supporting future advances in impact and protection technologies, and we welcome collaborations.

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