

Drop Testing as a Surrogate to UNDEX: Investigating Damage to the Marine Mammal Melon from Impulsive Loading

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ABSTRACT

Given the importance of the marine mammal melon and surrounding structures in echolocation, melon damage (e.g., from nearby underwater explosions (UNDEX)) may compromise an animal's ability to navigate, communicate, hunt, and ultimately survive. For ethical and legal reasons, there is a dearth of UNDEX test data for marine mammals and an inability to gather such data in the future. As part of a basic research effort to investigate if there is the potential to damage the marine mammal melon via UNDEX, a series of drop-weight impact tests was performed on melon samples as a substitute shock-like event.

This test series captures data on the energy imparted to and deformation experienced by marine mammal melon samples during an impact event that imparts impulse levels similar to those from previous UNDEX tests on marine mammal cadavers where observed post-test melon damage (or lack thereof) was recorded (Ketten 2004; Rye 2019). The research described in this technical memo focuses on understanding the potential damage mechanisms for the marine mammal melon as relevant to impulsive UNDEX loading.

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LIST OF ABBREVIATIONS AND ACRONYMS

μm	Micrometer
2D	Two-dimensional
3D	Three-dimensional
A	Anterior
Adjust	Adjustment
ANT	Anterior
AP	Anterior-posterior
App	Appendix
ASA	Acoustical Society of America
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
AVG	Average
B	Branching
bTBI	Blast induced traumatic brain injury
C	Canopy
C	Core
C/M	Mixed, mostly core
cc	Cubic centimeter
cm	Centimeter
Cont'd	Continued
COVID-19	Corona virus disease-19
CT	Computerized tomography
CTI	Critical technical information
CUI	Controlled unclassified information
DAQ	Data acquisition
dB	Decibel
Ddel	<i>Delphinus delphis</i>
DIC	Digital image correlation
Displ	Displacement
DoD	Department of Defense

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

DOI	Digital object identifier
DPML	Dynamic Photomechanics Laboratory (at URI)
DTI	Deep tissue injury
DV	Dorsal-ventral
en	Endocranium
EOD	Explosive Ordnance Disposal
FE	Finite element
fps	Frames per second
FSI	Fluid-structure interaction
ft	Foot
g	Grams
GI	Gastro Intestinal
ID	Identification
iDICs	International Digital Image Correlation Society
IFAW	International Fund for Animal Welfare
ILIR	In-House Laboratory Independent Research
IMECE2017	International Mechanical Engineering Congress and Exposition
in.	Inches
in.-lbf	Inch-pounds of force
ISBN	International standard book number
kg	Kilogram
kg/m ³	Kilograms per cubic meter
kPa	Kilopascal
lb	Pound
lb/ft ³	Pounds per cubic foot
LR	Left-right
m	Meter
M	Mixed
m/s	Meters per second
Max	Maximum
me	Melon
mg	Milligram
MHz	Megahertz
MID	Middle
Min	Minimum
MIS	Minimally invasive surgery
MLDB	Monkey lips/dorsal bursae
mm	Millimeter
ms	Millisecond
MSB	Martius scarlet blue
Mt	Mount
N	Newton
N	None
n/a	Not applicable
N/T/B/C	None/Trunk/Branches/Canopy

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

NAVSEA	Naval Sea Systems Command
NPT	Newport
NRL	Naval Research Laboratory
NSMRL	Naval Submarine Medical Research Laboratory
NSWC-CD	Naval Surface Warfare Center, Carderock Division
NUWC	Naval Undersea Warfare Center
ONR	Office of Naval Research
OOP	Out-of-plane
Orig	Original
P	Posterior
PCB	PCB Piezotronics
POC	Point of contact
POST	Posterior
Pphoc	<i>Phocoena phocoena</i>
Press	Pressure
psi	Pounds per square inch
psi-ms	Impulse (pounds per square inch (psi)) time (milliseconds (ms))
PVC	Polyvinyl chloride
rnp	Right nasal passage
S	Shell
S/M	Mixed, mostly shell
SE	Standard error
sec	Second
Sec	Section
SINKEX	Sinking exercise
STDERR	Standard error
SWT	Service weapons tests
T	Trunk
th	Theca
TPC	Tympanoperiotic complex
U.S.C.	United States Code
UNDEX	Underwater explosion
URI	University of Rhode Island
URI DPML	University of Rhode Island Dynamic Photomechanics Laboratory
V	Ventral
V	Volt
VAS	Vibro-acoustic Simulator
Vasc	Vascularized
Y/N	Yes/no

LIST OF SYMBOLS

σ	Stress
E	Young's modulus
ε	Strain
ν	Poisson's ratio
σ_{ij}	Stress tensor
ε_{ij}	Strain tensor
δ_{ij}	Kronecker delta
λ	First Lamé parameter
μ	Second Lamé parameter (shear modulus)
$U(\varepsilon)$	Strain energy potential
N	Desired order of the model
μ_i, α_i, D_i	Temperature-dependent material constants
J	Total volume ratio
$\mathbf{B}$	Left Cauchy-Green tensor
$\bar{\mathbf{B}}$	Deviatoric stretch tensor
$\bar{\lambda}_i$	Principal stretches (associated with $\bar{\mathbf{B}}$)
λ	Principal stretches (associated with $\mathbf{B}$)
$\mathbf{F}$	Deformation gradient tensor
$\bar{\mathbf{F}}$	Distortion gradient tensor
K_0	Initial bulk modulus
μ_0	Initial shear modulus
$I(t)$	Impulse time history
Δ	Change
P_{cr}	Critical buckling load
E	Modulus of elasticity
J_a	Area moment of inertia
L	Sample height
F_{max}	Maximum impact force
A	Cross-sectional area
v_i	Impact velocity
g	Gravitational constant
h	Drop height
c_{axial}	Speed of the compression wave
W	Impactor weight
W_b	Sample weight
ρ	Mass density of the material
J_A	Impulse per area
$P(t)$	Cumulative integral of stress
ρ_{sample}	Density of the sample
$m_{sample, air}$	Sample mass in air
$m_{sample, submerged}$	Sample mass submerged
ρ_{water}	Density of the water
$F(t)$	Force
$m_{impactor}g$	Weight of the impactor
$m_{impactor}$	Mass of the impactor

LIST OF SYMBOLS (Cont'd)

$v(t)$	Velocity of the impactor
t	Time
E_{impactor}	Energy of the impactor
$\bar{x}$	Mean (average)
$\bar{c}_{orig}$	Original mean sound speed
$\bar{c}_{post}$	Post-test mean sound speed
Θ	Decay constant

EXECUTIVE SUMMARY

Given the importance of the marine mammal melon and surrounding structures in echolocation, melon damage (e.g., from nearby underwater explosions (UNDEX)) may compromise an animal's ability to navigate, communicate, hunt, and ultimately survive. For various ethical and legal reasons, there is a dearth of UNDEX test data for marine mammals and an inability to gather such data in the future, aside from opportunistic UNDEX. As part of a basic research effort to investigate if there is the potential to damage the marine mammal melon at UNDEX impulse/peak pressures equal to or below what would cause severe lung or GI-tract hemorrhage (U.S. Navy 2017), a series of drop-weight impact tests was performed on melon samples as a substitute shock-like event.

The intent of this test series was to capture data on the energy imparted to and deformation experienced by marine mammal melon samples during an impact event that imparts impulse levels similar to those from previous UNDEX tests on marine mammal cadavers where observed post-test melon damage (or lack thereof) was recorded (Ketten 2004; Rye 2019). In order to guide the drop height parameters for the test series, published data from mechanical testing of melon samples from a Cuvier's beaked whale (*Ziphius cavirostris*) was used (Soldevilla et al. 2004) to develop a model for the spatial variation of material parameters within the beaked whale melon (Soldevilla et al. 2004). By performing a statistical analysis of the Cuvier's beaked whale data (Soldevilla et al. 2004), it was possible to develop hyperelastic material models for the mechanical behavior of the soft core and stiff shell portions of the melon. These hyperelastic material models were then used in pre-test finite element (FE) simulations to estimate the structural response of melon samples (from other species) to drop weight impact loading.

These pre-test predictions guided the final selection of the drop test heights and weights for the target impulse levels. Due to the unpredictability associated with obtaining melon samples from freshly dead marine mammals through opportunistic means, testing logistics and data capture processes were developed using a representative melon analogue (artificial flesh material, Ecoflex 0030 (Smooth-On Inc., Macungie, PA)). Drop test experimentation was then performed with both the artificial flesh samples and several melon samples taken from a harbor porpoise (*Phocoena phocoena*) and a common dolphin (*Delphinus delphis*). The drop test sensor data was analyzed, focusing on derived quantities of impulse that were imparted to the specimen, and displacement, velocity, and energy of the impactor. A novel screening method was developed for identifying potential damage in the melon samples via mass density and compressive through-thickness sound speed measurements of the samples before and after impact testing. Next, a cutoff for sound speed reduction (assumed to result from reduction in stiffness due to impact-induced damage to the tissue) was applied to the sound speed data for the samples as an indicator of damage. Various measured quantities were cross-plotted against one another, with damage indicated for any samples meeting the sound speed reduction cutoff criteria, to identify trends in the data. Finally, preliminary digital image correlation (DIC) results were included for the drop-tested samples to be used as validation data in the future for FE models of marine mammal melons that are currently under development.

The authors plan to build on previous work by developing FE models of melons and melon-related structures. The developed FE models are intended for numerical simulations to predict whether there may be the potential to damage the melon at UNDEX impulse levels / peak pressures below what would cause severe lung hemorrhage (killing the animal outright). Given the importance of the melon in echolocation, melon damage may compromise an animal's ability to navigate, communicate, hunt, and ultimately survive. However, prior to the development of the FE models, it is of utmost importance to procure model validation data to give confidence in the predicted structural response of the FE models when subjected to simulated shock loading within a wetted environment.

The research described herein focuses on understanding the potential damage mechanisms for the marine mammal melon as relevant to impulsive UNDEX loading. To start, we researched the literature to understand and characterize a representative threat (relevant loading scenario) to target species of marine mammals from UNDEX threat. Given the lack of UNDEX test data for marine mammals and the inability to gather such data, we chose to perform drop testing as a substitute shock-like event. A properly designed drop test can provide validation data for the structural response of a marine mammal melon during an impact event while delivering impulse / pressure to the specimen that is equivalent to observed damage levels in UNDEX tests (Ketten 2004, Rye, 3 April 2019 and 13 September 2019).

1. INTRODUCTION

A subset of marine mammals (Odontoceti, or toothed whales) possess an ovoid melon located on (not within) their skull. The melon is involved in sound production and reception and is part of the echolocation system for these animals; the melon, skull and air sacs all play a role in forming the beam in which sounds are transmitted (Au 2009).

Marine mammals are potentially exposed to the effects of underwater explosions (UNDEX) in a variety of scenarios, including coastal construction activities, underwater demolition, mine neutralization, service weapons tests (SWTs), sinking exercises (SINKEX), weapons effect tests and ship shock trials. Limited UNDEX testing has been carried out in the past on marine mammal cadavers (Ketten 2004), where the testing was authorized through the required permitting process. Although the focus for these cadaver UNDEX testing efforts was primarily on damage related to the tympanoperiotic complex (TPC, the marine mammal ear), post-test hemorrhages were noted in the acoustic jaw fats and melons of the test subjects in some cases (Ketten 2004). In the very limited opportunistic examinations of odontocetes unintentionally exposed to UNDEX (e.g., Silver Strand), little has been reported other than the incidence of gross blast-related trauma that presumably led to mortality (Danil and St. Ledger 2011). Information from these opportunistic examinations is incomplete in that current necropsy protocols do not include melon inspection (Pugliares-Bonner 2007), nor are the results of the exam often made publicly available.

A main focus of marine mammal acoustic research, primarily funded by the U.S. Navy, has been on acoustic transmission and/or reception or the behavioral or anatomical effects of sonar. Echolocation click structure and beam patterns have been well-studied for many cetaceans; therefore, a full literature review of related tests will not be discussed here (see a sample list of references in Au 2009).

In a unique test series carried out at the Explosion Test Pond facility of the Naval Surface Warfare Center, Carderock Division (NSWC-CD), an instrumented dolphin cadaver was ensonified with external transducers at 5, 7, and 10 kHz. Pressure data were taken using embedded tourmaline pressure gages at multiple locations in the cadaver, including the melon and nares, in order to determine the influence of nearby sonar on the dolphin's body. A post-test necropsy showed no lesions attributable to acoustic transmissions in the animal (Foote et al. 2012). As part of the effort, the researchers attempted to develop an extensive finite element (FE) model of an entire beaked whale, with an intent to validate the model against the pressure data and then extend it to study the effects of a broader variety of sonar induced acoustic energy fields on the marine mammal model. However, this modeling effort was never finished as modeling 3D wave propagation throughout the entire animal was deemed too computationally complex at the time by the authors (Foote and Feijoo 2011; Foote et al. 2012).

Underwater sound can be broadly classified as either “impulsive noise — noise with high peak sound pressure, short duration, fast rise-time, and broad frequency content — or non-impulsive (i.e., steady-state) noise” (U.S. Navy 2017). Anything that produces sound underwater has the potential to impact marine mammals, whether that source is broadly classified as either impulsive (e.g. pile driving, seismic airgun, UNDEX) or non-impulsive (sonar, vessels, etc.). However, separating sound sources into mutually exclusive impulsive vs. non-impulsive bins is

an imperfect approach, with respect to potential marine mammal injury, for several reasons. Currently, there is active research on both (1) distinguishing between impulsive and non-impulsive sound sources through specific metrics (Martin et al., 2020) and (2) for understanding potential non-auditory injuries caused in marine mammals by cyclic/steady-state noise sources such as sonar (Fernandez et al. 2005, Ketten 2005).

Highly transient pressure waves, as are seen in UNDEX, represent the main applied loading studied in this work. UNDEX is well-known to cause both auditory and non-auditory injury in marine mammals (Ketten et al. 1993; Ketten 2004). Experimental findings on submerged terrestrial mammals and fish with swim bladders (Goertner 1978; Yelverton et al. 1973; Cudahy and Parvin 2001) historically have been assumed to apply to marine mammals (Yelverton et al. 1981; Goertner 1982) and thus have been incorporated into current U.S. Navy non-auditory injury and mortality criteria for marine mammals potentially exposed to UNDEX (U.S. Navy 2017). UNDEX effects on marine mammals depend on a variety of factors including animal size and depth; charge size and depth; depth of the water column; and distance between the animal and the charge (U.S. Navy 2017).

To date, no FE modeling of UNDEX effects on the marine mammal melon has been undertaken. FE modeling of the melon structure has been limited to vibro-acoustic analyses. Cranford, Krysl and Hildebrand (2008) constructed a 3D FE model of a Cuvier's beaked whale head from computerized tomography (CT) scans and simulated the sound propagation pathways into and out of the head from external and internal sources, respectively. Their simulations utilized an in-house Lagrangian FE software suite called the Vibro-acoustic Simulator (VAS), which leverages a voxel-based modeling scheme to handle the complex geometry. They used the VAS to simulate transient vibration and acoustic transmission in the time domain (Krysl, Cranford, and Hildebrand 2007). Their models leverage a substantial amount of lead-up research – e.g., an extensive database of material mechanical and acoustic properties (Soldevilla et al. 2004; Soldevilla et al. 2005) and code verification against benchmark test problems (Krysl, Cranford, and Hildebrand 2007) – to produce plausible results relevant to sound transmission and reception pathways for Cuvier's beaked whale.

As a follow-on, Cranford, Krysl, and Amundin (2010) exercised the VAS software to study the wetted modes and associated natural frequencies for a bottlenose dolphin in order to understand the vibratory function of the TPC and the middle ear. More recently, Wei et al. (2017) created a two-dimensional (2D) FE model of a sagittal slice of a harbor porpoise head from CT scan data, then performed acoustic simulations in the time domain (with the commercial software COMSOL). With this 2D model, their COMSOL simulations proceeded by solving the wave equation for an exponentially damped sinusoid monopole source at the location of the monkey lips/dorsal bursae (MLDB) complex of tissue constituents. Follow-on work involved the development of a similar 2D model for the Atlantic bottlenose dolphin (Wei et al. 2018), and an extension of both models to a slice in the coronal (horizontal) plane in addition to the sagittal (vertical) plane (Wei et al., 2020). With the advent of robust numerical FE modeling tools and high-resolution medical imaging, it is now possible to investigate possible impacts to the marine mammal melon from UNDEX, in addition to pure acoustic sources, using coupled fluid structure interaction (FSI) computational models.

The authors plan to build on previous work by developing FE models of melons and melon-related structures. The developed FE models are intended for numerical simulations to predict whether there may be the potential to damage the melon at UNDEX impulse levels / peak pressures below what would cause severe lung hemorrhage (killing the animal outright). Given the importance of the melon in echolocation, melon damage may compromise an animal's ability to navigate, communicate, hunt and ultimately survive. However, prior to the development of the FE models, it is of utmost importance to procure model validation data to be used to give confidence in the predicted structural response of the FE models when subjected to simulated shock loading within a wetted environment.

The research described herein focuses on understanding the potential damage mechanisms for the marine mammal melon as relevant to impulsive UNDEX loading. To start, we researched the literature to understand and characterize a representative threat (relevant loading scenario) to target species of marine mammals from UNDEX threat. Given the lack of UNDEX test data for marine mammals and the inability to gather such data, we chose to perform drop testing as a substitute shock-like event. A properly designed drop test can provide validation data for the structural response of a marine mammal melon during an impact event while delivering impulse / pressure to the specimen that is equivalent to observed damage levels in UNDEX tests (Ketten 2004, Rye, 3 April 2019 and 13 September 2019).

2. THE CHALLENGE

The research described herein, and that planned for the future, involves numerous challenges. Even within the laboratory setting, testing with soft, biological materials is quite difficult. Modeling the response of soft, biological materials to any sort of significant loading is also problematic, involving rate-dependence of material response as well as large deformations. In the subsequent sections, we discuss the challenges of producing accurate numerical predictions for the marine mammal melon response to UNDEX (future work) to give the current work context. We also explain several problems to be addressed as part of our drop test series.

2.1 UNDEX MODELING

Modeling UNDEX effects on submerged structures can be extremely challenging and computationally intensive, depending on the complexity of the scenario and object(s) and the desired level of accuracy. At its simplest, the pressure wave caused by an UNDEX can be described at a stationary free-field location via a time history that includes a decaying exponential (initial shock) followed by a repeating, decaying pulse (bubble pulse). Note that the bubble pulse corresponds to the oscillation of the bubble of gaseous byproducts of the explosion (Cole 1948). The well-known similitude equations can be used to estimate peak pressure, peak positive phase impulse, and decay constant of the initial shock, as well as period and maximum bubble radius for the subsequent bubble pulse. However, the similitude equations have a limited range of applicability: distances between 10 and 100 charge radii, and duration up to one decay constant in time (Cole 1948).

2.2 COUPLED MODELING OF SOFT STRUCTURES RESPONDING TO IMPULSIVE LOADING IN WETTED ENVIRONMENTS

The interaction between a fluid and a structure can be predicted with a variety of modeling approaches, from simple (but not as accurate) to extremely complicated (but very accurate). The expected level of accuracy increases with model fidelity, and depends on the modeling choices made about analysis coupling type, numerical techniques, types of elements, etc., all of which affect the amount and rate of information flow between the fluid and structure. At the low-resolution end, one-way coupling involves just calculating the UNDEX-induced pressure history at the structure location and then applying these loads to the structure in an uncoupled structure-only FE simulation. In a medium-resolution approach, the fluid can be explicitly modeled with acoustic elements that are tied to the structural elements at the fluid-structure interface; the acoustic elements only propagate pressure, but that pressure information is passed back-and-forth at the interface between the fluid and structure via two-way coupling. At the high-resolution end, the fluid is modeled with a mesh of Eulerian (stay-in-place) fluid cells through which the fluid material can flow and the structure is modeled with a mesh of Lagrangian (moving) elements. The location of the FSI interface is tracked throughout time as the structure (and interface) moves around in space and through the fluid. Here, the full spectrum of the current fluid state (pressure, velocity, etc.) near the interface and the stress state and deformation of the structure (stress, strain, displacements, velocity) near its wetted surface are passed back-and-forth between fluid and structure through the fluid-structure interface, for full two-way coupling.

Predicting the UNDEX response of a soft biological structure is especially challenging for several reasons:

1. The structure is soft enough that its mechanical response is strongly coupled to the surrounding fluid environment.
2. The structural material, and thus mechanical response, is rate-dependent and nonlinear.
3. Mechanical damage is hard to quantify given the complexity of injury processes in a living animal.

2.3 DEFINING INJURY OR DAMAGE TO THE MELON

UNDEX-induced damage mechanisms within the marine mammal head have been described previously (Ketten 2004). Although most of Ketten's work focused on the ear, the below excerpt from (Ketten 2004) is relevant to our study of UNDEX effects on the melon:

“Cetacean specific traumas were also found, most notably a distinctive ring hemorrhage found at the interface of the two blubber layers that may be diagnostic for the direction of the received blast wave, hemorrhages of the acoustic jaw fats, and melon hemorrhages. The ring hemorrhage phenomenon is particularly interesting since it demonstrates the importance of tissue density frontiers in determining the relationship of the pattern of hemorrhage with regard to the blast wave parameters. In this case the compressive wave

results in blood vessel hemorrhage and the rarefactive wave produces a migration of sero-sanguinous fluid outward up to the point that the hemorrhage front encounters the change in density between the two blubber layers. Consequently, a concentric “ring” develops concentrated at and demarcating the density interface.”

Tying numerical predictions within a FE model to observed injury levels can be extremely difficult. However, the typical approach has been to develop a FE model of an actual experimental test with an animal, validate the model to the test results at sensor locations, and then compare predicted results with published injury levels (observed in other experimental tests). As an example, researchers at the Naval Research Laboratory (NRL) developed a FE model of an entire pig, which they validated to air shock test data at a handful of instrumented sensor locations. Then, they compared the predicted simulated stress and strain fields in the brain to published mechanical injury thresholds in order to identify the brain areas most susceptible to blast induced traumatic brain injury (bTBI) (Tan et al. 2017). We intend to follow this general approach for our work.

2.4 PREVIOUS CADAVER TESTS

Publications on previous tests subjecting marine mammal cadavers to UNDEX loads discussed observed damage to the specimens as discovered post-mortem (Ketten 2004). However, there is insufficient detail on the UNDEX loading for these tests in (Ketten 2004) to draw any conclusions about damage imparted by known transient loads. We contacted Kent Rye at NSWC-CD to see if any further information might be found on the tests, specifically the charge weights and standoff distances for the various tested UNDEX cases. Through personal communications (Rye, 3 April 2019 and 13 September 2019), we were able to obtain crucial additional information and some limited data to supplement the published test report by the marine biologist D.R. Ketten (Ketten 2004). The supplemental data for marine mammals (cadavers) exposed to UNDEX (Rye, 3 April 2019 and 13 September 2019) exhibited a previously unpublished range-to-effect trend for documented UNDEX damage to the melon in the previously tested (1999-2003) cadavers.

Specifically, a subset of the cadaver tests exhibit a range-to-effect (in the melon) trend. This subset of tests includes three separate UNDEX tests with harbor porpoise cadavers where the only difference between the three loading scenarios is the standoff distance between the explosive charge and the specimen. All three tests employed a single cylindrical 1:1 charge of 0.25 lb (113.4 g) pentolite, at a depth of 6-ft (1.83 m) of the 25-ft (7.62 m) pond depth. For each test, the instrumented specimen is suspended within a submerged PVC frame at a water depth of 10-ft (3.05 m) below the surface. The pond has concrete sides and a concrete bottom (Rye, 3 April 2019 and 13 September 2019). Test details are listed in Table 1.

Table 1. Details of range-to-effect trend for melon damage observed in harbor porpoises subjected to UNDEX in the NSWC-CD test pond.

Observed Damage Level in Melon	Standoff, R (ft)	Specimen Weight (lb (kg))	Experimental Peak Pressure (psi)	Experimental Peak Positive Phase Impulse (psi-ms)
SEVERE	25	54.5 (24.7)	337	32.7
MODERATE	41.5	64.6 (29.3)	201	17.7
NONE	73	54.9 (24.9)	107	7.3

Additionally, Ketten’s cadaver test series involved three UNDEX shots at a nominal peak pressure of 300 psi; however, the actual measured peak pressure for these varied from 280-337 psi. The most severe test registered a peak pressure of 337 psi (harbor porpoise at a 25-ft standoff), with the intermediate test measuring a peak pressure of 305 psi (Atlantic white-sided dolphin (*Leucopleurus acutus*) at a 30-ft standoff), and the least severe test including a peak pressure of 280 psi (Atlantic white-sided dolphin at 31-ft standoff). In line with the range-to-effect subset of UNDEX tests described above, the charge depth, specimen depth, and charge weight/geometry also remained the same for these most severe shots (Rye, 3 April 2019 and 13 September 2019).

3. OBJECTIVES

This research had multiple objectives in mind while designing, executing, and analyzing our drop tests with melon specimens. These objectives included the following:

1. Identifying target impulse levels to those from previous UNDEX tests on marine mammal cadavers in which observed post-test melon damage (or lack thereof) was recorded (Ketten 2004, Rye 2019)
2. Developing a drop test series, as a surrogate to UNDEX, on marine mammal melon samples with target impulse levels in mind that range from no damage to severe damage, where data could be measured on the energy imparted to and deformation of melon samples during an impact event that imparts similar impulse levels to those identified above
3. Creating our own model for the spatial variation of material parameters within a melon, using published data from mechanical testing of melon samples from a Cuvier’s beaked whale (Soldevilla et al., 2004)
4. Developing hyperelastic material models for the soft core and stiff shell portions of a Cuvier’s beaked whale melon from published test data (Soldevilla et al., 2004)
5. Using our hyperelastic material models within pre-test FE simulations of melon samples (from other species) subjected to drop weight impact loading, to guide our final selection of drop test heights and weights for our target impulse levels
6. Developing a non-destructive screening method for potential damage in the melon samples through physical measurements of the samples before and after impact

testing, where any changes in measured data from testing could be cross-referenced against collected drop test data

7. Designing and piloting drop test logistics with a representative melon analogue (artificial flesh material, Ecoflex 0030)
8. Performing drop tests with several melon samples taken from target species: harbor porpoise (*Phocoena phocoena*) and common dolphin (*Delphinus delphis*)
9. Collecting digital image correlation (DIC) data via high-speed photography of a speckle pattern on the front face of the samples during testing, to be used as validation data in the future for FE models of marine mammal melons that are currently under development

4. THE MELON

4.1 FUNCTION

A subset of marine mammals (Odontoceti, or toothed whales) possess an ovoid melon located on their skull. The melon is involved in sound production and reception and is part of the echolocation system for these animals. The skull, air sacs, and melon (non-homogeneous) act together as a biological system that forms the beam in which sounds are transmitted (Au 2009). Sound vibrations propagate along multiple pathways through the melon and emerge into the environment (Aroyan et al. 1992; Cranford et al. 2008) as a click (Au 1993). The tissue properties of the melon are thought to focus sound energy generated in the MLDB complex and decrease acoustic attenuation at the tissue-water interface by impedance matching to seawater (Amundin and Andersen 1983; Au et al. 2006; Cranford et al. 2008; Norris and Harvey 1974)—this morphology provides an efficient means of transmitting sound across the tissue-water interface.

Melon morphology relates to acoustic function (e.g., the focusing of echolocation sounds and pathways for these sounds to travel in the forehead). Acoustic function has previously been investigated in some odontocete species (Au et al. 2010; Au et al. 2006; Au et al. 1999; Au et al. 1986; Carvan 1988; Evans 1973; Evans et al. 1964; McKenna et al. 2012; Møhl et al. 2000; Norris and Harvey 1974; Norris et al. 1961; Schevill and Watkins 1966). However, the most important functional characteristic is the speed of sound in biological tissue, which depends on the density and elasticity of the conducting and adjacent tissues (Duck 1990). Since sound bends or refracts towards lower density (e.g., lower sound speed) as it propagates (Blackstock 2000), the sagittal profiles of density changes in the melon provide useful information that bears on the sound refraction within the melon.

4.2 COMPOSITION

The melon itself is a large fatty body, resting on a concave pad of dense connective tissue on top of the bony rostrum of the skull (Figure 1) and anterior complex nasal passages with three pairs of air sacs (Figure 2). It contains a few muscle fibers and has a limited blood vascular

system (Harper et al. 2008). It is surrounded by musculature that extends asymmetrically, positioned into the muscle of the right nasal plug (slightly off to the right side). However, the size and firmness of the melon varies by species (Green et al. 1980; Norris 1975; Purves and Pilleri 1983).

The melon consists of a layered topology of lipids that are chemically distinct from blubber and other body fats. The melon and other key structures related to sound production and reception can be seen in Figure 3 for Cuvier's beaked whale (Cranford et al. 2008). Note the dorsal bursae, a pair of small elliptical fat bodies, located in the MLDB (Phonic lips in Figure 3) complex on each side of the head are the site of sound production (Au 2009; Cranford et al. 1996).

McKenna et al. (2012) examined the melon of nine odontocete species and provided a robust, quantitative and comparative framework, for evaluating tissue structures that form a key component of the echolocation apparatus. This was the first study to quantitatively define the melon's structure in a diverse array of species. However, previous work by several researchers (Harper et al. 2008; McKenna 2005; McKenna et al. 2007) noted diversity in morphological and functional differences across the Odontoceti. This is partially attributed to the melon's graded characteristics (Harper et al. 2008). Velocity measurements over the melon of a bottlenose dolphin by Norris and Harvey (1974) revealed a low velocity core surrounded by higher velocities that grade into the surrounding muscle and connective tissues (visible in Figure 4). This research was the first to suggest that the melon might focus and channel sound generated within the forehead tissues and acoustically couple it to seawater. Computer simulations of sound production within high-resolution FE models of various odontocete heads (Cranford et al. 2008a; Cranford et al. 2010) have verified that all of these acoustic behaviors do indeed occur in common dolphin tissue models based on melon velocity distributions measured by Norton and Harvey (1974).

At normal mammalian temperatures, the melon is a lipid and connective tissue structure, marked by changing density gradients, from a shell composed largely of collagen fiber mesh to a fluid-like core rich in specialized lipids. Defining the melon is complicated because it protrudes through a structure of similar density, the blubber, a lipid-infused blanket that covers much of the body and portions of the head. In the CT scans conducted by McKenna et al. (2012), the boundaries of the melon were represented by gradients in density, from a lower density core, composed largely of lipids, to higher density shell characterized by increasing proportions of connective tissue (Figure 4).

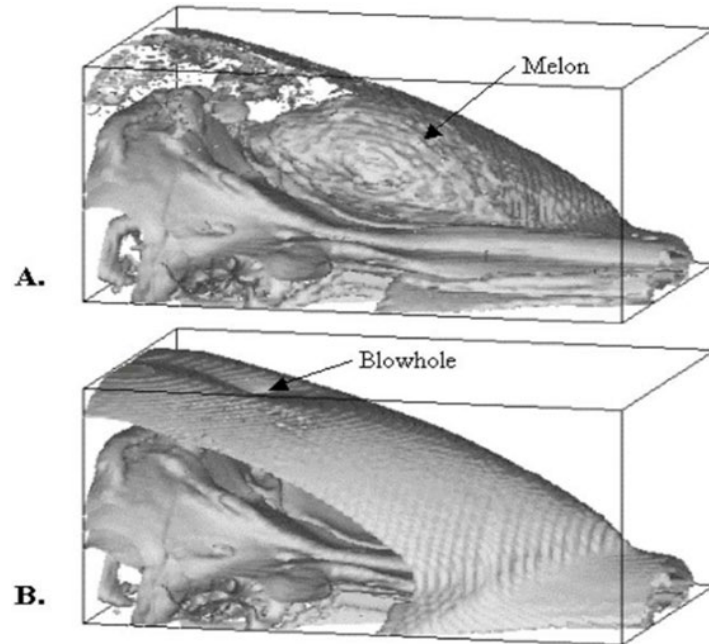


Figure 1. Two CT visualizations of the skull, melon, and skin isosurfaces. Adapted from Aroyan (1996).

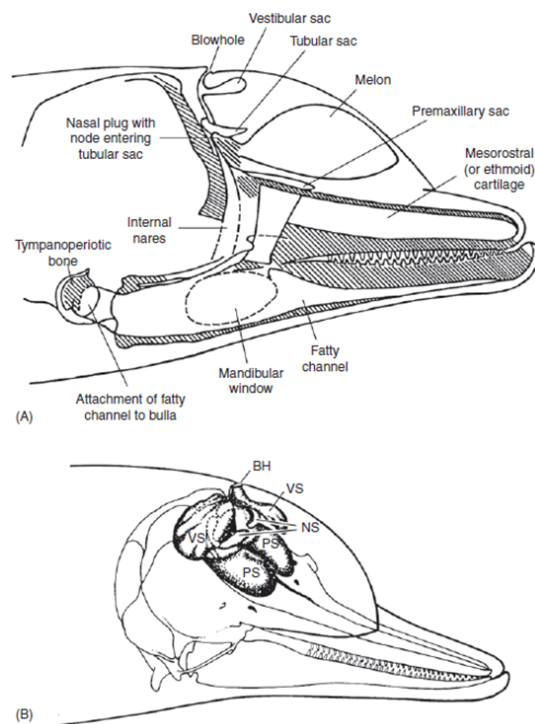


Figure 2. (A) Schematic of a dolphin's head from Norris (1968) and (B) 3D diagram of the air sacs (premaxillary, vestibular, nasofrontal, accessory) in a dolphin's head from Purves and Pilleri (1983). Entire figure from Au (2009).

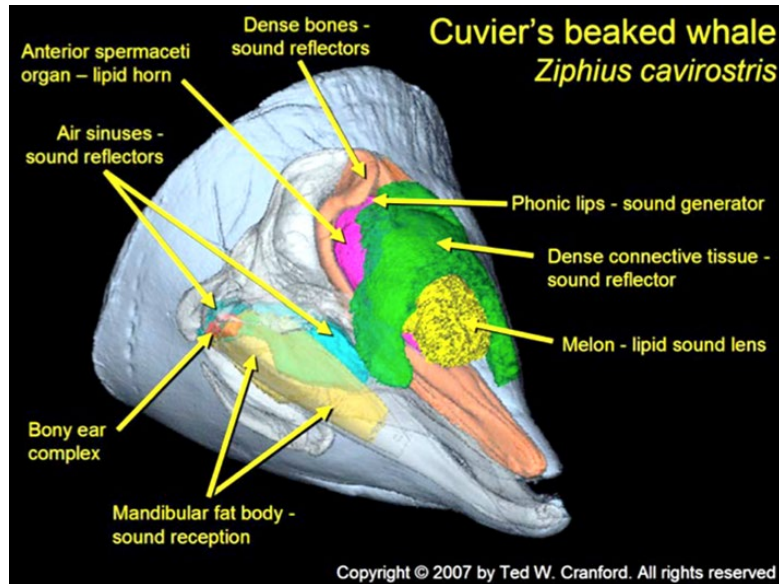


Figure 3. Schematic of Cuvier's beaked whale head and relevant acoustic structures. Adapted from Cranford et al. (2008).

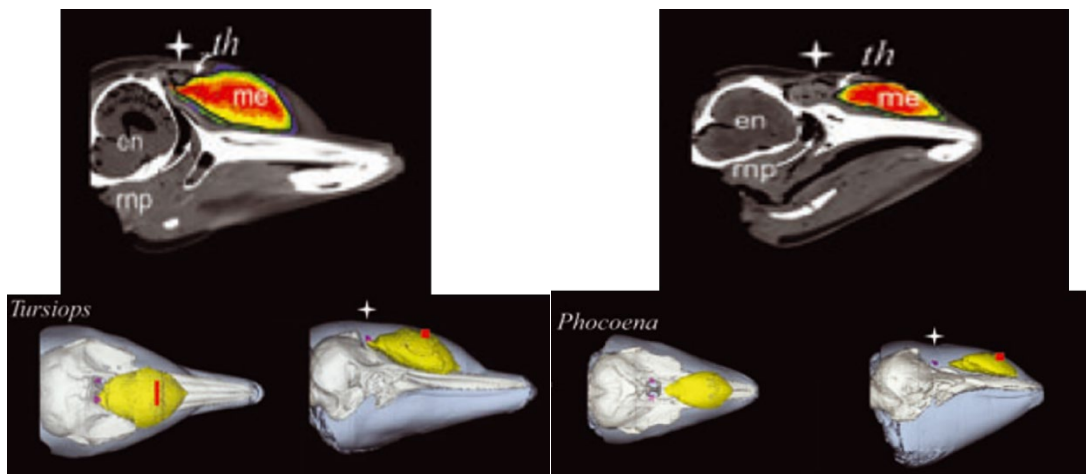


Figure 4. Top photos: 2D parasagittal views of CT scan section representing a bottlenose dolphin (*Tursiops truncatus*) and a harbor porpoise (*Phocoena phocoena*). Bottom photos: 3D reconstruction of melon morphology from a bottlenose dolphin and a harbor porpoise.

Note: In Figure 4, the color in the images represents the density of internal melon anatomy: white (bone), gray (soft tissue), blue (dense connective tissue) high density, green, yellow and orange the melon, and red (melon core) low density. The boundaries of the melon are outlined in black. Abbreviations: en = endocranium, me = melon, rnp = right nasal passage, th = theca indicated by white arrow. Adapted from McKenna et al. (2012).

4.3 MELON SPECIMENS

Due to the potential interspecies differences in melon composition, the team sent requests to Mystic Aquarium and the International Fund for Animal Welfare (IFAW) to obtain melon samples from stranded cetacean species.

4.3.1 *Common Dolphin*

In November 2018, we obtained a melon sample from a stranded (fresh), young, common dolphin (*Delphinus delphis*, Figure 5). M. DeAngelis and T. Fetherston extracted the melon from the carcass and froze the entire melon until it was sampled.

Based on the composition of the melon, we determined that preserving any melon sample by freezing would not alter the composition (Mckenna et al. 2007). Upon examination, the distinct density gradients described were visible and intact from the melon sample from the young common dolphin collected in 2018. For practical purposes and the ability to use in a variety of environments, we created a mold of a sampled melon using a commercially available silicone rubber material. This mold will be used for geometric scanning purposes rather than scanning the actual tissue. An additional request was made to Mystic Aquarium and IFAW to obtain at least one other common dolphin a (dependent on stranding event). This request was approved in March 2019. We then received a partial melon sample of a common dolphin that stranded in January 2020 (see Figure 6 for dimensions).



Figure 5. Photo of the young common dolphin before the melon sample was extracted. Dolphin carcass courtesy of the IFAW.

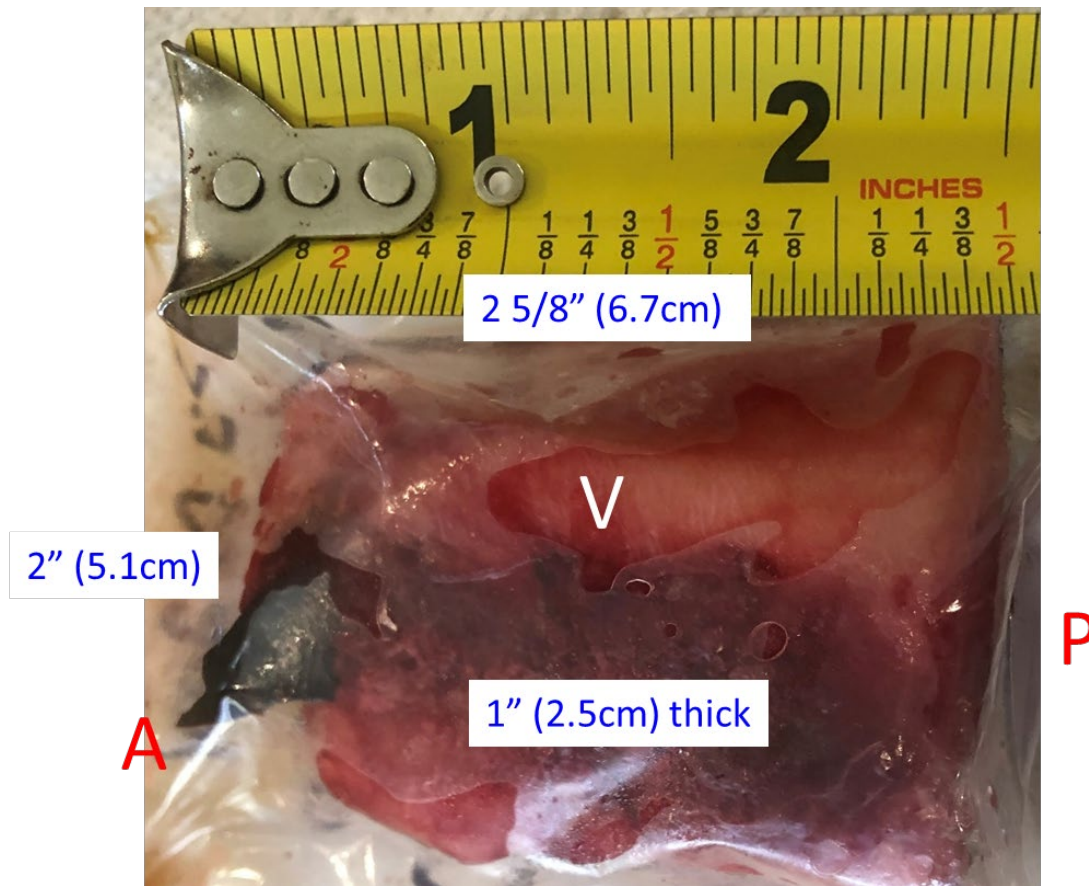


Figure 6. Partial sample from a common dolphin after the melon sample was extracted. Anterior (A), ventral (V), posterior (P). Dolphin sample courtesy of Mystic Aquarium.

4.3.2 Harbor Porpoise

On March 20, 2019, a harbor porpoise stranded in Wellfleet, Massachusetts and the entire carcass was frozen and stored at IFAW. The animal was necropsied on 14 August 2019 at the IFAW facility and M. DeAngelis took possession of the entire head of the animal that same day. On 15 August 2019, M. DeAngelis extracted the entire melon and froze it until samples were needed for drop testing (see Section 7.4) were needed. In addition, the skull was buried that same day and exhumed about a year later. It was thoroughly cleaned and dried and prepared so that the skull could be laser scanned.

4.3.3 Surrogate Artificial Flesh Material: Ecoflex 0030

Given the difficulty of obtaining suitable melon samples, we chose to develop and refine experimental procedures using samples manufactured from a readily available and easily replenishable artificial flesh material. Ecoflex 0030 (Smooth-On Inc., Macungie, PA) is a silicone rubber that was originally developed and marketed to the entertainment industry for manufacturing human-like props. We selected the Ecoflex 0030 material for our artificial flesh prototype samples for these reasons:

1. Low-cost (\$16.1/lb or \$35.5/kg for a material density of 66.8 lb/ft³ or 1.07 g/cm³)
2. Ease of manufacture via mixing, pouring into molds, and curing over short times (pot life is around 45 min)
3. Isotropic and homogenous material properties
4. Very low risk of spoilage in typical laboratory conditions
5. Its established use in medical research as an artificial tissue surrogate

To expand on the last bullet above, silicone polymers, including the Ecoflex series (Smooth-On Inc., Macungie, PA, USA), have increasingly been used in medical research for the construction of phantoms, or mechanical simulants. These phantoms can be used for medical training purposes, surgery simulation, or surrogate testing, e.g. for initial development and testing of novel imaging techniques. The following published phantoms utilize Ecoflex material: self-oscillating human vocal folds (Drechsel et al, 2008; Murray et al. 2012), life-size human thorax with bony structures, lungs (and lung tumors), and surrounding soft tissues (Hazelaar et al. 2017), and a human kidney, complete with internal collecting system morphology and attached tubing (Adams et al. 2017).

We recognize that using an artificial flesh material for a subset of our experiments will produce data without any biologically-based injury mechanisms for those samples. However, bridging the gap between mechanical behavior of artificial simulants and the intended injury behavior in real tissue is an active area of research. For example, Sparks et al. (2015) developed a prototype patient simulant with artificial materials and investigated its mechanical ability to mimic deep tissue injury (DTI).

5. MATERIAL MODELING

Material models typically define the mathematical relationship between applied stress and the resulting deformation (or strain) within a given material. The simplest material model is the linear elastic model, whereas biological tissue often follows a hyperelastic (or even viscoelastic) model.

5.1 LINEAR ELASTICITY

A linear elastic material definition is the most simple and common method for defining the behavior of a material. A pure linear elastic material model is insufficient to model melon or artificial flesh. However, concepts of linear elasticity are included to show relationships between various elastic constants that are assumed and incorporated within the used hyperelastic material models that best describe the mechanical behavior of melon and artificial flesh materials.

A linear elastic model be used in conjunction with a wide variety of materials and loading cases and, in the case of an isotropic material, only requires two material constants for a complete definition (values for the other four elastic constants can be derived from any two). An

anisotropic material, however, is direction-dependent and can require between three and twenty-one material constants depending on the level of anisotropy (Bower 2009).

There are several characteristics that can be used to classify a material as having linear elastic behavior. First, the specimen will deform reversibly when subjected to a small stress in uniaxial tension. This means that the specimen will return to its original shape when the load is removed. In addition, the strain in the material only depends on the applied stress and is not affected by the rate of loading or the loading history. Finally, for most materials, the stress will be a linear function of the strain (Bower 2009).

The stress-strain model that described here assumes infinitesimal deformations and in its simplest form, for uniaxial load cases, can be expressed as:

$$\sigma = E\varepsilon . \quad (1)$$

This is known as Hooke's Law, where σ is stress, E is Young's modulus (a mechanical property that defines the stiffness of a material), and ε is strain. Expanding Hooke's Law for an isotropic material into its directional components gives the following:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix} , \quad (2)$$

where E is Young's modulus, and ν is Poisson's ratio (the ratio of lateral strain to longitudinal strain). The subscripts for σ and ε denote the direction of normal or shear stresses and strains, respectively. This full version of Hooke's Law can be written concisely using indicial notation ($i=1,2,3$):

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \lambda\delta_{ij}\varepsilon_{kk} \quad (3)$$

where σ_{ij} is the stress tensor, ε_{ij} is the strain tensor, δ_{ij} is the Kronecker delta, λ is the first Lamé parameter, and μ is the second Lamé parameter, also known as the shear modulus and sometimes denoted by G instead of μ . The first Lamé parameter is related to Young's modulus and Poisson's ratio per the following equation:

$$\lambda = \frac{Ev}{(1+\nu)(1-2\nu)} . \quad (4)$$

The bulk modulus is another property of a material, and is related to Young's modulus and Poisson's ratio per the below:

$$K = \frac{E}{3(1 - 2\nu)} . \quad (5)$$

The first Lamé parameter can alternatively be calculated using the bulk modulus and the shear modulus, μ , per

$$\lambda = \frac{9K\mu}{3K + \mu} . \quad (6)$$

Young's modulus can be calculated in terms of Poisson's ratio, ν , and the shear modulus, μ , per

$$E = 2\mu(1 + \nu) . \quad (7)$$

As previously stated, homogeneous isotropic linear elastic materials have their elastic properties uniquely determined by any two moduli among the full set of elastic constants: $E, \nu, \lambda, \mu, K, M$. Equations (4), (5), (6), and (7) represent just a few of the relationships between these constants. Data to define appropriate parameter values in a given material for any of the elastic constants appearing above are typically obtained from mechanical testing, e.g. uniaxial compressive or tensile testing to obtain E or confined and unconfined creep testing to define K and ν (Bower 2009).

5.2 HYPERELASTICITY

The theory of elasticity typically only holds true for small deformations, so when a material undergoes larger deformations, it is necessary to further define the material model for large strain situations. We investigated several hyperelastic material models for potential use in describing the material behavior of the melon and artificial flesh materials. Ultimately, we chose the Ogden hyperelastic model due to its common implementation in several computational FE codes and its robustness for the large strain conditions that are typically produced by UNDEX loading. The Ogden model describes the nonlinear stress-strain behavior of a material through the use of the strain energy density, or strain energy potential, function, $U(\epsilon)$. This function describes the potential energy stored in the material on a volumetric basis, with the reference volume being defined in terms of the initial geometric configuration. This type of representation allows for the stress-strain relationship to be described in terms of the principal stretches, λ_i , and material constants. For isothermal deformations, the form of the Ogden strain energy potential model that is implemented within the widely-used FE software Abaqus is defined per the below:

$$U(\bar{\lambda}_1, \bar{\lambda}_2, \bar{\lambda}_3) = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} (\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3) + \sum_{i=1}^N \frac{1}{D_i} (J - 1)^{2i} . \quad (8)$$

Here, J is the total volume ratio, N is the desired order of the model ($N=1,2,3$, etc) , and μ_i, α_i, D_i represent temperature-dependent material constants. The total volume ratio is equal to the determinant of the deformation gradient, $\mathbf{F}$. The deformation gradient is a tensor that relates the deformation at a point to both its current (deformed) position and its original (undeformed) reference position. The left Cauchy-Green strain tensor, $\mathbf{B}$, is defined in terms of the deformation

gradient as $\mathbf{B} \stackrel{\text{def}}{=} \mathbf{F} \cdot \mathbf{F}^T$. According to the mathematical definition of a determinant, J then equals the product of the three principal stretch ratios in the reference configuration, or $J \stackrel{\text{def}}{=} \det(\mathbf{F}) = \lambda_1 \lambda_2 \lambda_3$. In Eq (9), $\bar{\lambda}_i$ are the principal stretches associated with the deviatoric stretch tensor $\bar{\mathbf{B}}$. These are related to the usual principal stretches according to $\bar{\lambda}_i = J^{-1/3} \lambda_i$. The full relationship between $\mathbf{F}$, J , and $\bar{\mathbf{B}}$ is $\bar{\mathbf{B}} \stackrel{\text{def}}{=} \bar{\mathbf{F}} \cdot \bar{\mathbf{F}}^T = J^{-2/3} \mathbf{F} \cdot \mathbf{F}^T$. Here, $\bar{\mathbf{F}}$ is the isochoric portion of $\mathbf{F}$ and is referred to the distortion gradient (Dassault Systèmes 2012).

A typical hyperelastic material stress-strain curve can be seen in Figure 7.

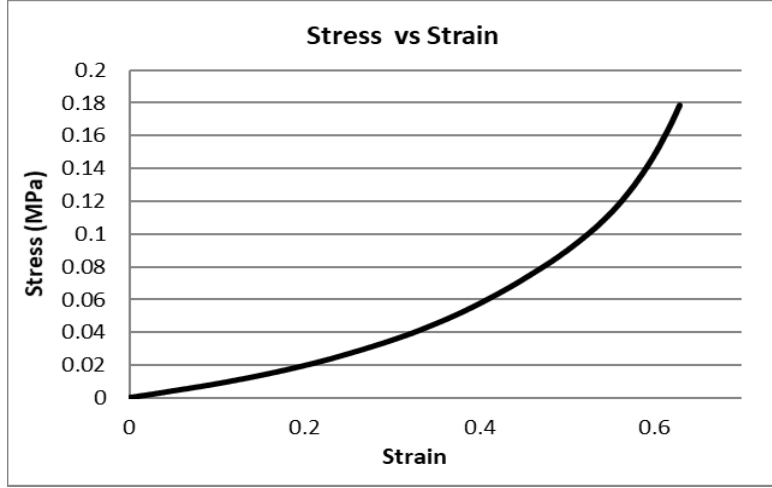


Figure 7. Typical hyperelastic stress-strain curve, obtained from uniaxial compression testing of Ecoflex 0030. Data courtesy of NSMRL, taken by URI DPML.

Material compressibility is generally expressed via Poisson's ratio, ν , with incompressible materials having a Poisson's ratio approaching 0.5. For hyperelastic materials, Poisson's ratio is defined in terms of initial bulk modulus, K_o and initial shear modulus, μ_o (Dassault Systèmes 2012).

$$\nu = \frac{3 K_o / \mu_o - 2}{6 K_o / \mu_o + 2} \quad (10)$$

For the widely-used Ogden hyperelastic material model, the initial shear modulus is the sum of the shear moduli, per the below equation (note that the number of shear moduli, N , depends on the order of the Ogden model) (Dassault Systèmes 2012).

$$\mu_o = \sum_{i=1}^n \mu_i \quad (11)$$

For the Ogden material model, the initial bulk modulus is calculated from the parameter D_1 per the below equation (Dassault Systèmes 2012).

$$K_0 = \frac{2}{D_1} \quad (12)$$

The above equations for Poisson's ratio and initial bulk modulus can be rearranged in order to calculate the parameter D_1 in terms of the desired/specified Poisson's ratio, for an Ogden material (Dassault Systèmes 2012).

$$D_1 = \frac{6}{\mu_o} \cdot \frac{2\nu - 1}{-2(1 + \nu)} \quad (13)$$

5.3 STATISTICAL ANALYSIS OF PUBLISHED UNIAXIAL COMPRESSIVE TEST DATA FOR CUVIER'S BEAKED WHALE

Published work by Soldevilla et al. (2004, 2005) studied the physical, acoustic, and mechanical properties of the soft tissues within the head of a neonate Cuvier's beaked whale. We used this dataset to reverse engineer our own model of an idealized melon. The intent was two-fold:

1. Develop a FE model of an idealized (smoothed) melon with spatially varying density, sound speed, and elastic modulus.
2. Determine appropriate material model fits (hyperelastic model choice and associated parameter values) to represent idealized melon core and shell regions.

5.3.1 *Spatial Interpolation of Published Data*

For the subset of tested samples that included melon tissue (Soldevilla et al. 2004), we imported the published test data (geometric location, and measured mass density, sound speed and attenuation, and elastic modulus as a function of stress) into the MATLAB software. We spatially interpolated the data for each slice of the Cuvier's beaked whale head into a 3D volume, and visualized the subset of results containing melon tissue. Our interpolation of the published material properties matches known melon morphology: a low density core, surrounded by a higher density shell, with a low density acoustic pathway located at the melon terminus. Sample figures of the spatial interpolation, with annotations, are shown in Figure 8.

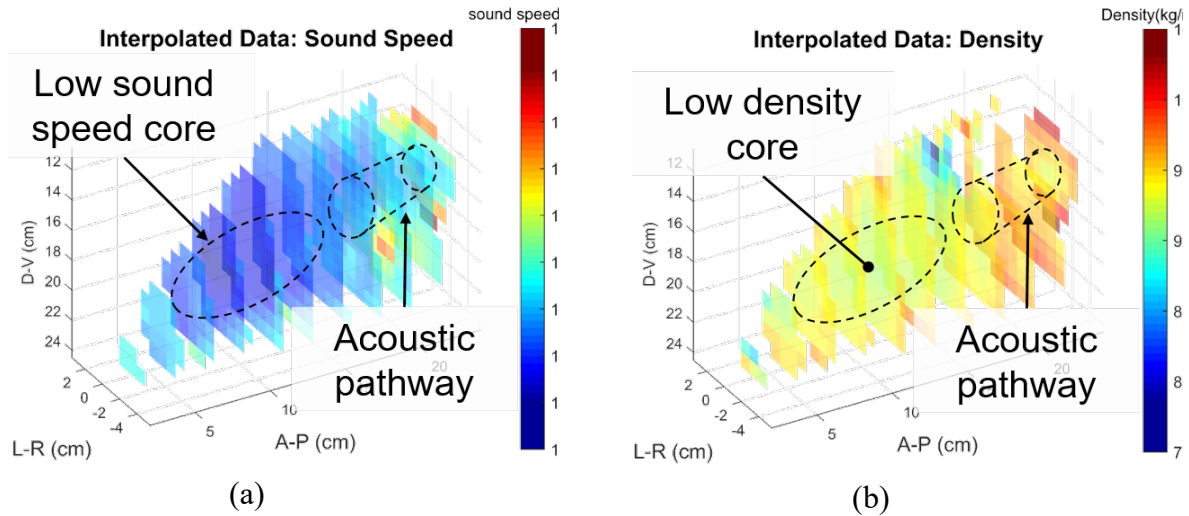


Figure 8. Spatially interpolated results for (a) sound speed, and (b) density, within the melon from a Cuvier's beaked whale neonate. Original data from (Soldevilla et al., 2004).

Figure 9 is included to provide context for the location of the melon core within the shell for the Cuvier's beaked whale melon investigated by Soldevilla et al. (2004), and used for our spatial interpolation of material properties. The inset in Figure 9 depicts a preliminary version of a FE model of a Cuvier's beaked whale melon developed for this research program.

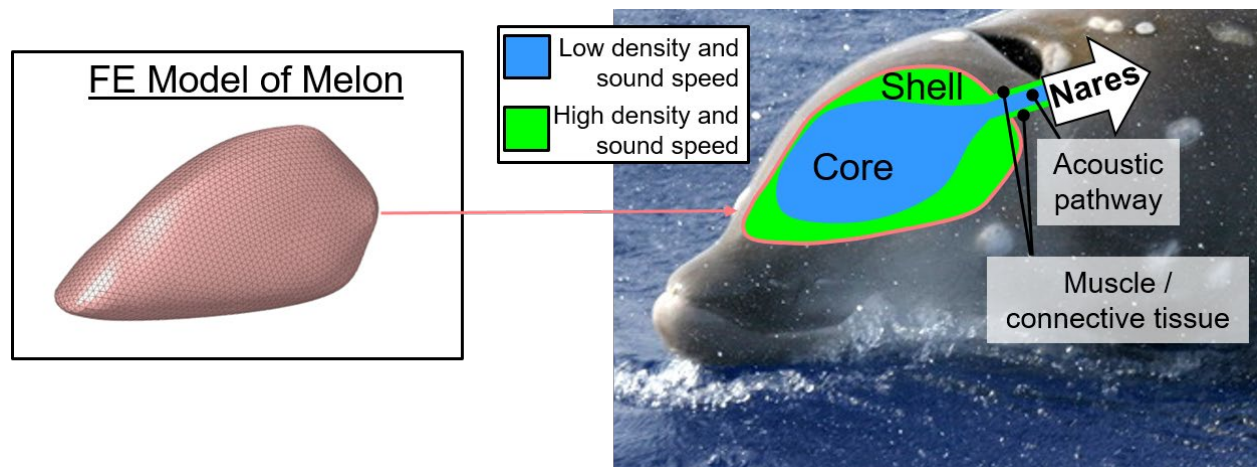


Figure 9. Schematic of spatial location of melon core and shell, with inset of meshed FE model of a Cuvier's beaked whale melon.

The uniaxial compressive melon data in Soldevilla et al. (2004) are listed as pairs of stress and elastic modulus, where the modulus is the tangent to the stress-strain curve at that particular stress. The discrete levels of stress where the tangent modulus is measured include the following: 5, 10, 20, 30, 40, or 50 kPa. Figure 10 is taken from Soldevilla et al. (2004), and depicts the stress-strain curve for a sample of *Ziphius cavirostris* forehead blubber. On Figure 10,

the annotations E_i depict the tangent modulus to the stress-strain curve at stress level i , where $i \in \{5, 10, 20, 30, 40, 50\} \text{ kPa}$.

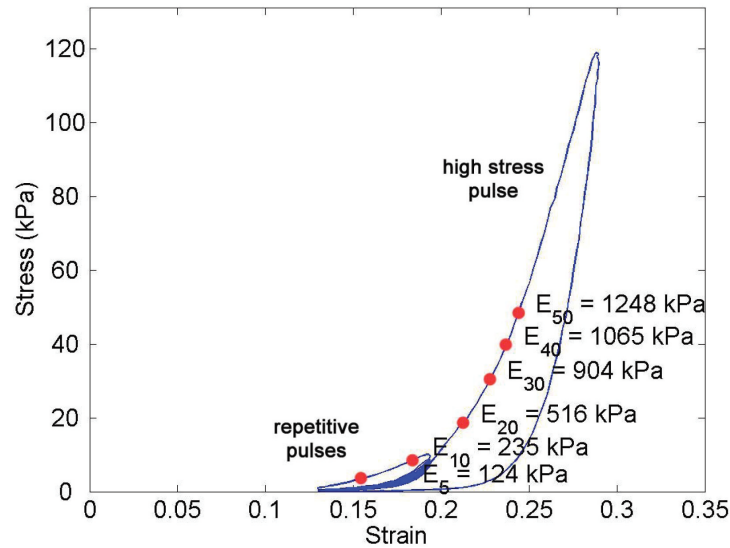


Figure 10. Stress-strain curve example for a sample of *Ziphius cavirostris* forehead blubber. Adapted from Soldevilla et. al. (2004).

The majority of samples investigated by Soldevilla et al. (2004) were tested over small, repetitive stress cycles, with only a few further subjected to higher stress levels. For the case where both low and high stress levels were tested, the hardware (Mini Bionix 858, MTS Corp) ran 10 low-stress cycles at 2 Hz with 0.08 mm displacement followed by one high-stress cycle at 0.5 Hz with a 2 mm displacement. The samples are tissue roughly 2 cm in edge length, and so this applied loading scheme corresponded to a strain rate of 0.016-0.1/sec. Each sample was tested in the three anatomic directions: anterior-posterior (AP), dorsal-ventral (DV), and left-right (LR) (Soldevilla et al. 2004). We averaged the data in the three directions and then spatially interpolated the values between the slices, as before. The below figures depict the spatial interpolation results at all stress levels. Note the increasing sparsity of data with increasing stress level.

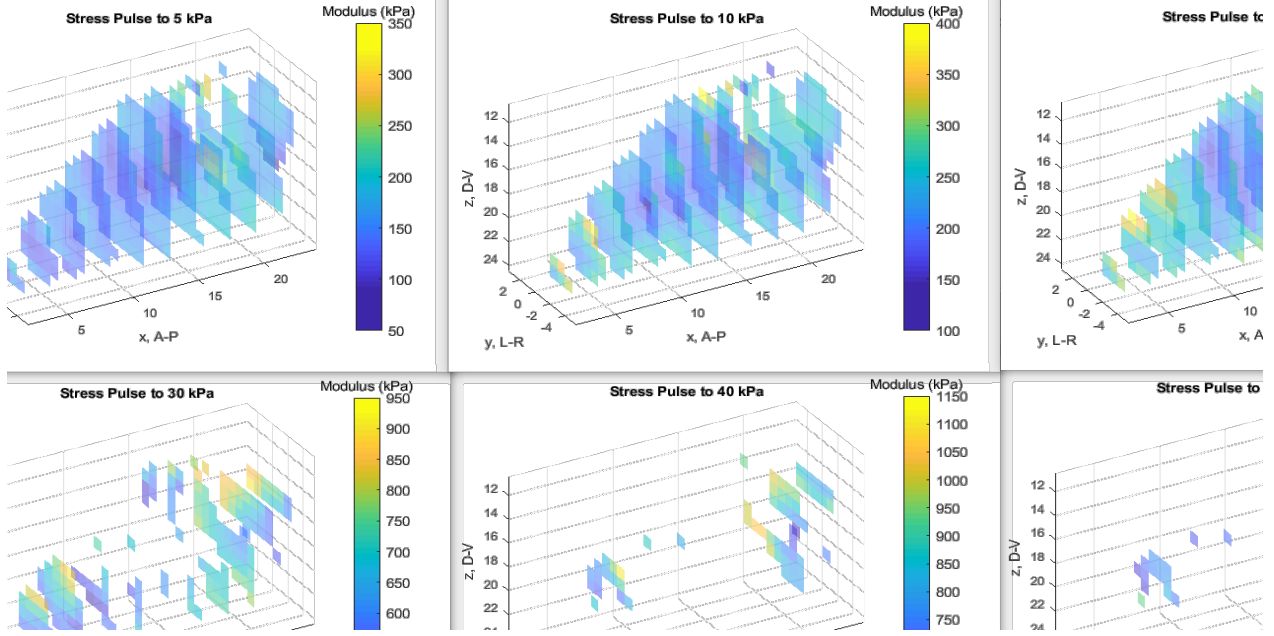


Figure 11. Spatial interpolation of published data on elastic modulus as a function of stress for stresses of {5, 10, 20, 30, 40, and 50} kPa.

5.3.2 Obtaining Idealized Material Properties for Soft/Stiff Cuvier's Beaked Whale Melon

We investigated the stress vs. modulus data from Soldevilla et al. (2004) in order to simplify the observed complex material behavior into a general model whose high-level features might be applicable across different species. Specifically, we chose to approximate the marine mammal melon using the mechanical analogue of an egg white encasing an embedded yolk, i.e. we assumed that the melon could be modeled with just two components: a soft core and a stiffer shell. The morphology of the soft core surrounded by a stiffer shell has been observed across multiple families of Odontoceti, as detailed in McKenna et al. (2012).

To obtain idealized material properties for our soft/stiff melon model, we first needed to calculate the median of the stress vs. modulus data from Soldevilla et al. (2004). Then the median could be used as a boundary to separate the dataset to soft (below median) and stiff (above median) subsets. As a first step of the statistical analysis, we made the following assumptions:

1. Spatially-varying material properties (discrete, assigned to blocks roughly corresponding to the 2 cm cube samples of Soldevilla et al. (2004)).
2. Spatially uniform material properties per cube, obtained by averaging directional test data across the three anatomical directions.
3. A linear relationship exists between the modulus and the stress levels.

We performed a linear regression of the averaged (across the three tested anatomical directions) data for each sample in order to determine the slope of the modulus vs. stress

comparison. The median value of all of these fitted slopes represents the boundary separating the soft and stiff material regimes: the data subsets with fitted moduli above this value are binned into the stiff group and the other data into the soft group. Then, we analyzed the soft and stiff subgroups separately to determine the slope and intercept values for each group for the assumed linear relationship between modulus and stress. Figure 12 depicts a schematic of the entire process to extract and isolate uniaxial compressive material response of the soft and stiff Cuvier's beaked whale melon.

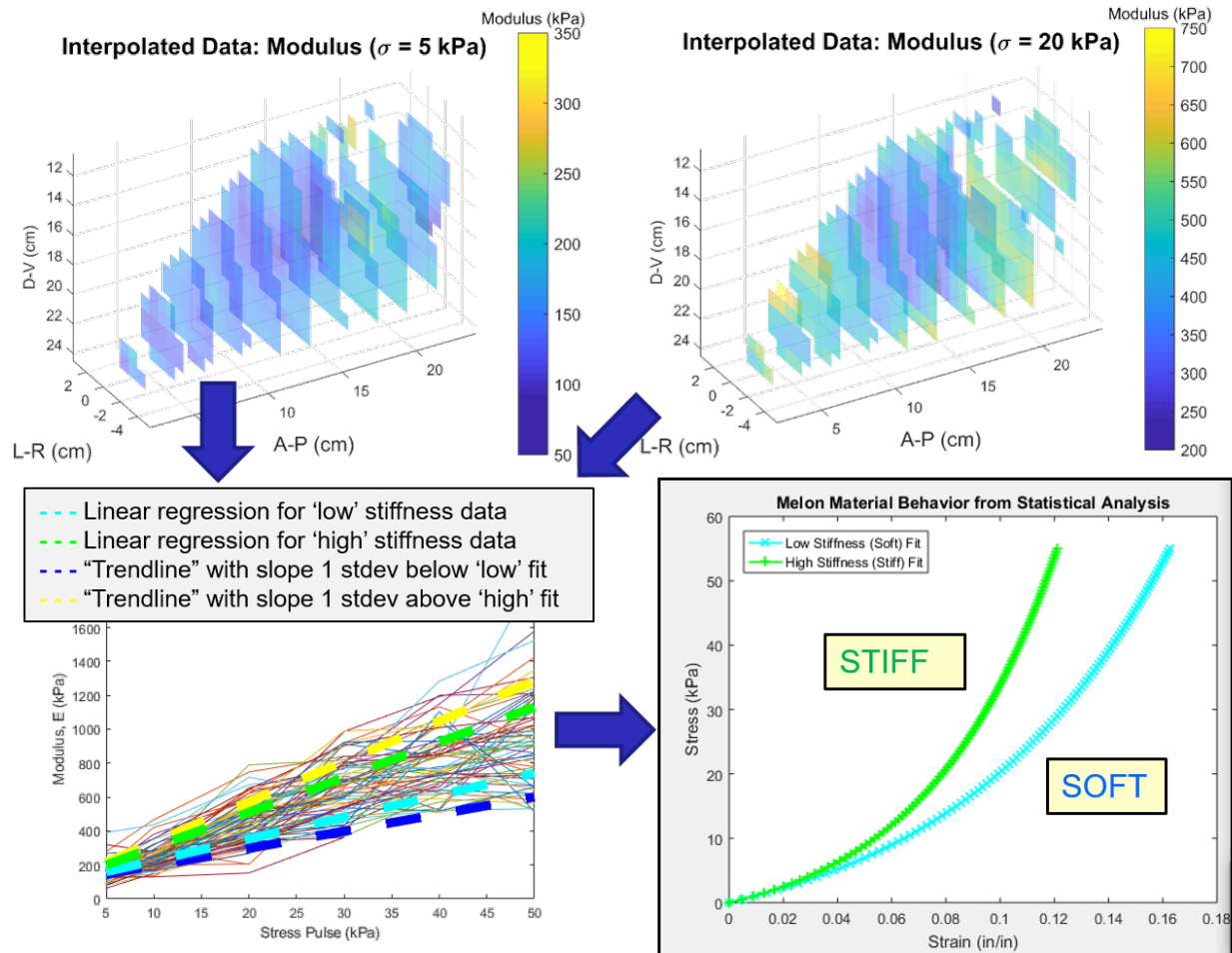


Figure 12. Schematic of process to obtain and isolate representative idealized soft and stiff melon material behavior for uniaxial compression by analyzing published test data.

Here, the 'fit' is a linear regression of the modulus vs. stress data, rather than a fit of a constitutive model to uniaxial stress vs. strain test data. This interim 'fit' is needed in order to create smooth synthetic data to represent the uniaxial compressive behavior of the idealized soft and stiff melon materials. The linear regression 'fit' quantifies an idealized mechanical response of the soft and stiff melon materials whereby both are assumed to have a modulus that varies linearly with stress. Thus, the statistical analysis provides the parameter values for the intercept

and slope that quantify this ‘best-fit’ linear modulus-stress relationship for the materials. The statistical analysis involves a constrained optimization using the LSQLIN functionality in MATLAB for soft and stiff subsets of data. Table 2 lists values for the fitted parameters. The methodology for generating the synthetic data for the idealized soft and stiff Cuvier’s beaked whale melon materials using the fitted parameters is described in full in Appendix A.

Table 2. Fitted parameters for assumed linear relationship between modulus as a function of stress for idealized soft and stiff Cuvier’s beaked whale melon materials.

	Idealized ‘Soft’	Idealized ‘Stiff’
Fitted Intercept	96 kPa	96 kPa
Fitted Slope	12.9	20.7

5.3.3 Representative Response of Soft and Stiff Melon and Artificial Flesh for Quasistatic Uniaxial Compression

Unlike the melon, the Ecoflex 0030 material is homogenous. Its homogeneity simplifies material characterization to a minimal level of testing: quasistatic uniaxial compressive testing of multiple samples with an Instron machine. Accordingly, researchers at the University of Rhode Island Dynamic Photomechanics Laboratory (URI DPML) conducted uniaxial compression tests for five samples of Ecoflex 0030. For these tests, the strain rate was 0.002/sec, giving a total test duration of 5 minutes for the Ecoflex 0030 material. Test samples were cylindrical with an average diameter of 1.12 inches (2.84 cm) and average height of 0.534 inches (1.36 cm). Figure 13 depicts a comparison of uniaxial compressive material behavior for the idealized soft and stiff Cuvier’s beaked whale melon against the Ecoflex 0030. The typical sign convention on stresses is that compressive stresses and strains are taken as negative and tensile stresses and strains as positive.

Regarding Figure 13, it is important to note that the Cuvier’s beaked whale tissue was tested at a faster strain rate (0.016-0.1/sec) than the Ecoflex 0030 (0.002/sec). Mechanical testing of adipose/skin tissue in other marine mammals (neonatal Southern Resident Killer Whales, SRKW) has shown that there is a general tendency towards strain-stiffening with increasing strain rate in these tissues. Specifically, uniaxial tension test results for dogbone samples of SRKW neonatal skin (epidermal) and blubber (hypodermal) both exhibited larger peak stress for higher crosshead speeds (Carlson et al. 2014). Thus, it is expected that the quasistatic mechanical response of the Cuvier’s beaked whale melon will likely be closer in stiffness (i.e. hyperelastic curves more similar in curvature to one another) to the Ecoflex 0030 than the as-tested low (but finite) strain rate behavior for melon tissue reported in Soldevilla et al. (2004).

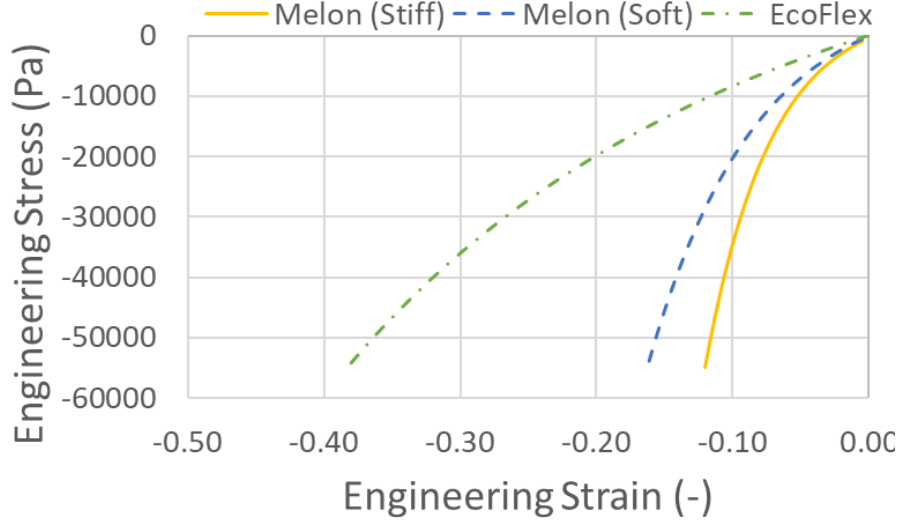


Figure 13. Comparison of uniaxial compressive material behavior for idealized soft and stiff melon vs. Ecoflex 0030, expressed as engineering stress and engineering strain.

For quasistatic compressive tests, the engineering stress and engineering strain can be converted to the corresponding values of true stress and true strain using the following conversions:

$$\varepsilon_{true} = \ln(1 + \varepsilon_{eng}) \quad (14)$$

and

$$\sigma_{true} = \sigma_{eng} \cdot (1 + \varepsilon_{eng}) . \quad (15)$$

The true stress-true strain behavior for the three materials is shown in Figure 14. It is important to be careful of signs of strains and stresses in the above conversions from engineering to true strain and stress values. For compressive tests, properly signed strains and stress are negative (i.e. $\varepsilon_{eng} < 0$ and $\sigma_{eng} < 0$), which produces $|\varepsilon_{true}| > |\varepsilon_{eng}|$ (sample is shortening during testing) and $|\sigma_{true}| < |\sigma_{eng}|$ (sample's cross-sectional area is increasing during testing). By comparing Figure 13 and Figure 14, we can confirm that we have properly converted to true stress and true strain for this compressive case since $|\varepsilon_{true}| > |\varepsilon_{eng}|$ and $|\sigma_{true}| < |\sigma_{eng}|$.

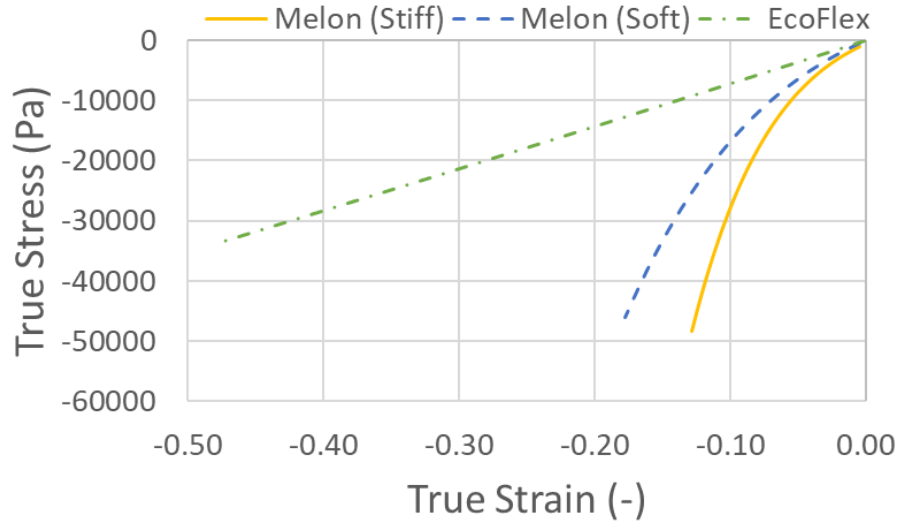


Figure 14. Comparison of uniaxial compressive material behavior for idealized soft and stiff melon vs. Ecoflex 0030, expressed as true stress and true strain.

Comparing the behavior of the three materials depicted in Figures 13 and 14 reveals that the stiffest of the three materials is the idealized stiff melon and the softest is the Ecoflex 0030. While the Ecoflex 0030 exhibits the same hyperelastic characteristic behavior as both idealized stiff and soft melon, it is softer than both. However, as previously mentioned, the Cuvier's beaked whale melon samples were tested at a higher strain rate than the Ecoflex 0030 samples. Given the tendency towards strain strengthening in SRKW blubber (Carlson et al. 2014) and in Ecoflex 0030 tested at a variety of strain rates (Liao et al. 2020), it is expected that the gap between the melon and Ecoflex 0030 responses shown in Figures 13 and 14 would be smaller if all samples had been tested at the same load rate. The limiting values of engineering compressive strain magnitude (i.e. taken as the engineering strain absolute value at the maximum common tested engineering stress of 55 kPa) for the three materials are 0.12, 0.16, and 0.38, respectively. In reality, the Ecoflex 0030 actually limits out at an engineering strain of 0.60 (at an engineering stress of 158 kPa).

5.4 HYPERELASTIC MODEL FITS TO MATERIAL UNIAXIAL COMPRESSIVE TEST DATA

5.4.1 *Cuvier's Beaked Whale*

We used the material model curve fitting capabilities of the commercially available FE software package Abaqus to obtain values for the necessary material constants for hyperelastic material behavior. As mentioned previously, we generated synthetic uniaxial compressive stress-strain data for idealized soft and stiff regions of a Cuvier's beaked whale melon, after performing a statistical analysis of published test data from Soldevilla, et al. (2004).

In order to produce a material model that behaves well for both tensile and compressive loading, we reflected the compressive stress-strain data to the tensile quadrant of stress-strain space to produce a stress-strain curve describing the material's behavior in both compression and

tension (see Figure 15). This requires the implicit assumption that the material behaves the same under both types of loading, which is a necessary assumption, given the lack of tensile test data for melon tissue and the notorious difficulty of collecting good experimental data for uniaxial tensile behavior of biological tissue.

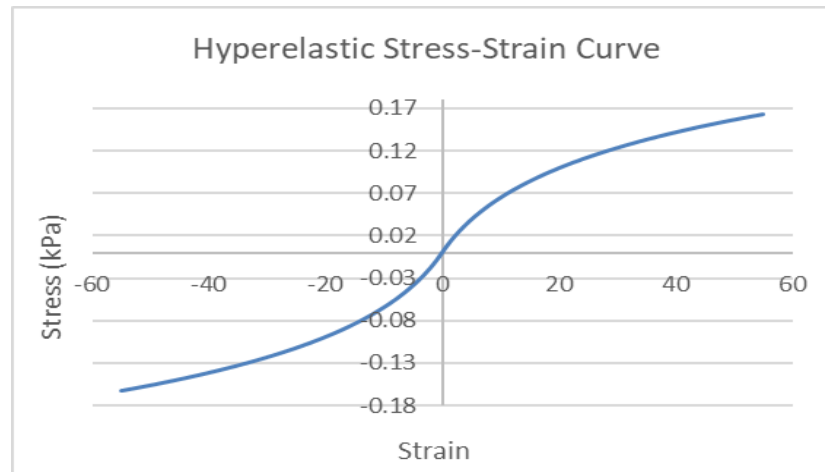


Figure 15. Sample full uniaxial data set (in engineering stress and engineering strain) to be imported into Abaqus for fitting to a hyperelastic material model.

We imported the full compressive-to-tensile stress-strain uniaxial data set into Abaqus and used the Abaqus material evaluation toolbox to perform a least-squares fit to a variety of hyperelastic material models. Figure 16 shows the ‘goodness-of-fit’ for an Ogden 3-term ($N=3$) hyperelastic fit compared to the uniaxial data. The material constants in Table 3 correspond to the Ogden three-term fit for the idealized soft and stiff material regions of the Cuvier’s beaked whale melon. The FE model of the full melon, shown in the inset of Figure 9, can then assign the hyperelastic material behavior of the soft melon material to the physical region corresponding to the melon’s soft core, assign the stiff melon hyperelastic material model to the stiffer shell region that encapsulates the core.

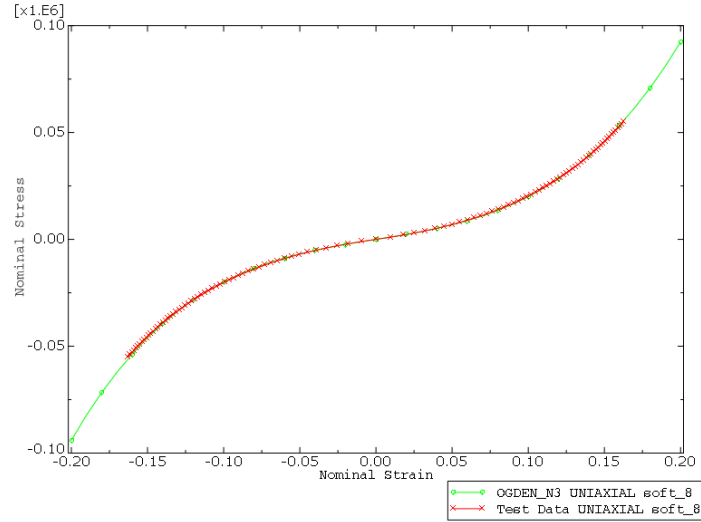


Figure 16. Example of Ogden material fit using Abaqus.

Table 3. Ogden coefficients for soft and stiff melon.

Material	μ_1 (kPa)	α_1 (-)	D_1 (kPa ⁻¹)	μ_2 (kPa)	α_2 (-)	D_2 (kPa ⁻¹)	μ_3 (kPa)	α_3 (-)	D_3 (kPa ⁻¹)
Melon – Soft	-16225	4.147	0.0	8150	8.114	0.0	8114	3.008	0.0
Melon – Stiff	-7239	4.814	0.0	4945	6.757	0.0	2333	0.713	0.0

Per Equation (11), the initial shear modulus is $\mu_o = 39 \text{ kPa}$ for both soft and stiff melon for the material parameters in Table 4. For an incompressible material (desired Poisson's ratio approaching $\nu = 0.50$), D_1 is defined to be 0 rather than being calculated from Equation (13). The initial bulk modulus can be calculated from D_1 per Equation (12). Note that the combination of $\mu_o = 39 \text{ kPa}$ and $\nu = 0.50$ can be used to calculate the elastic modulus (prior to onset of hyperelastic behavior) for the material, per Equation (7). The calculated value is $E=117 \text{ kPa}$. This value is higher than the target value of 96 kPa , per Table 2. The overestimation in stiffness stems from the selection of a finite value of $\Delta\sigma$ (instead of infinitely small $\Delta\sigma$) when creating synthetic stress, strain data from the modulus fit to Soldevilla's modulus vs. stress data.

Decreasing $\Delta\sigma$ from 0.5 to 0.1 kPa does decrease change the material parameters slightly and produces a calculated value of $E=112 \text{ kPa}$, which is closer to the target value of 96 kPa . However, plotting the synthetic stress data for both values of $\Delta\sigma$ shows that the change in overall material behavior is very tiny between these cases. Details of a convergence study with increasingly smaller values of $\Delta\sigma$ is provided in Appendix A. For our purposes, we deemed that $\Delta\sigma=0.5 \text{ kPa}$ is small enough. The overestimation in instantaneous stiffness with $\Delta\sigma=0.5 \text{ kPa}$ is likely acceptable given that the melon material data were measured with quasistatic testing but soft, rubber-like hyperelastic materials tend to stiffen (have a higher initial Young's modulus) for

high-rate load application (e.g. impact or shock loading). And the ultimate purpose of our models was accurate pre-test prediction of the sample response under impact loading.

5.4.2 Ecoflex 0030

Quasi-static compression tests performed on Ecoflex 0030 samples provided the uniaxial stress-strain test data needed to characterize the material. We imported the engineering stress and engineering strain data from the uniaxial compressive tests into the Abaqus material evaluation toolbox. The procedure described above in Section 5.4.1 provided the fitted material constants for a 3-term Ogden hyperelastic material model. The resulting material parameter values are listed in Table 4. It is important to note that the below 3-term Ogden material fit represents a preliminary model for the Ecoflex 0030, determined in the absence of uniaxial tension data for this material. For this particular fit, the material model will exhibit numerical instabilities at certain very large (in magnitude) tensile and compressive strains. However, we assumed that the material would not undergo strains over these limits and thus moved forward using these material coefficients to define the material behavior. We confirmed this assumption with our pre-test drop test simulations, but we include this note as a caveat for future research.

Table 4. Parameter values for Ogden N=3 hyperelastic model of quasistatic Ecoflex 0030.

Material	μ_1 (kPa)	α_1 (-)	D_1 (Pa ⁻¹)	μ_2 (kPa)	α_2 (-)	D_2 (Pa ⁻¹)	μ_3 (kPa)	α_3 (-)	D_3 (Pa ⁻¹)
Ecoflex 0030	74.2	-3.09	4.60e-6	17.8	8.66	0.0	-65.4	-3.58	0.0

Per Equation (11), the initial shear modulus is $\mu_o = 26.6 \text{ kPa}$ for the material parameters in Table 4. For a desired poisson's ratio of $\nu = 0.47$, D_1 is calculated from Equation (13) after an initial fit is performed with D_1 temporarily set as 0. The initial bulk modulus can be calculated from D_1 per Equation (12). Here the initial bulk modulus is $K_o = 434.5 \text{ kPa}$.

6. DROP TEST DEVELOPMENT

6.1 BACKGROUND

An impact (drop) test is a shock-like event that is transient (short time) in nature where the amount of damage imparted to a sample can be tuned by changing the main parameters of the drop test: drop height and drop weight. A properly designed drop test can provide many insights as to the mechanical response of given sample during a controlled impact event in a laboratory environment. For the type of drop tower where the impactor falls onto the sample (drop weight impact), the impactor delivers a known loading (force and pressure) to the sample that can be estimated ahead of time from the impactor weight and drop height (ASTM Standard D7136/D7136M-15, 2015).

We chose to use a drop-weight impact test as a vehicle for studying melon response to impulsive loading for a variety of reasons. For one, the in-air mechanical response of the tissue sample is essentially uncoupled from the surrounding fluid (air), unlike the case with UNDEX (water). Additionally, there are no artificial tank effects for in-air drop testing, unlike with UNDEX testing in controlled laboratory environments (pressure tanks). These conditions allow for clean measurements and observation of the dynamic behavior of melon tissue (how it moves, how energy is dissipated) during a shock event. In particular, we intended for our drop tests to deliver equivalent impulse levels to those documented in the literature as resulting in observed injury or trauma in live (U.S. Navy 2017) or dead specimens (Rye 2019). We based our drop test design on both the ASTM standard D7136/D7136M-15 and a paper that performed drop-weight impact tests on articular cartilage (ASTM Standard D7136/D7136M-15, 2015; Kaleem, Maier, Drissi, & Pierce, 2017).

6.2 DROP TEST TOWER DESIGN

This section details the design of our custom-built table-top drop tower.

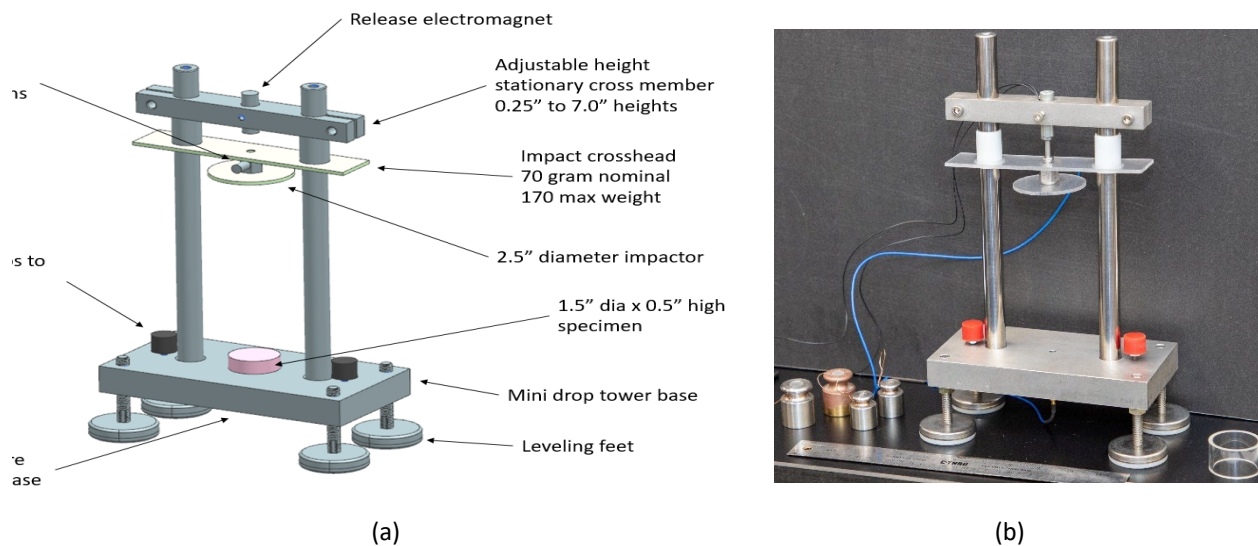


Figure 17. Custom table-top drop tower (a) design schematic and (b) actual as-manufactured hardware.

6.2.1 Impactor Height and Weight Range

Based on our pre-drop test numerical models, we determined design specifications for our proposed drop tower. For our samples and desired impulse levels, we needed the tower's load carriage to have a mass between 70 g and 170 g. We were able to add additional mass to the load carriage during creep testing since creep involves quasistatic loading and thus additional load would not risk damaging the Lexan material of the load carriage. Drop heights ranged from 0.25 inches (0.64 cm) to 5.25 inches (13.3 cm) so we designed a maximum usable drop height of 7 inches (17.8 cm) to allow for extra clearance. The as-built drop tower, shown in Figure 17, has

an impact energy range of 4 mJ to 1 J. Figure 17(a) includes the final design of the drop tower, and Figure 17(b) depicts the as-built drop tower, fabricated at NUWC Division Newport by the Code 85 Materials Laboratory.

6.2.2 *Sensors: Force and pressure*

The drop tower includes a pressure sensor at the bottom interface with the sample to determine the peak pressures propagated through the tissue. Any collected pressure data will be post-processed to determine peak pressure values and cumulative impulse during the duration of contact, both of which can be compared to established damage criteria from the literature. We expected to deliver a maximum peak pressure of 15 psi (103.4 kPa) to our samples, which led to our selection of the PCB S113B28 pressure sensor due to its adequate range and sensitivity.

We installed a force sensor within the drop tower load carriage to measure the loading (impact force) applied to a sample for the duration of a drop event. Using the recorded force-time data, we intended to calculate impactor position and velocity to compare to the calculated impact velocities from our pre-test simulations. Thus, we chose a force sensor (PCB 208C02) with a maximum range of 100 lb (444.8 N).

6.2.3 *High-Speed Data Acquisition (DAQ)*

We used a Dewetron High-Speed DAQ system courtesy of Code 85 to record pressure and force data over the duration of the drop test. Specifically, we used a Dewetron TRIONet (S/N C5160061) with two analog modules: TRION-2402-dACC and an eight-channel SMB. The maximum sampling frequency of this system is 204,800 samples/second.

6.3 DROP TEST SAMPLE SIZING

Choosing drop test sample dimensions involved a fine balance between maximizing the number of samples we could extract from our two intact melon specimens and minimizing sample height while maximizing diameter to reduce risk of buckling behavior under impact. Using Euler's column buckling theory, we aimed to determine the critical buckling load (P_{cr}) for a clamped-free end condition, or

$$P_{cr} = \frac{\pi^2 EI_a}{4L^2} \quad (16)$$

Here, E is the modulus of elasticity (which we obtain from (Soldevilla, et al., 2005)), I_a is the area moment of inertia of the cross-section, and L is the sample's height. Once the critical buckling load is calculated, we compare its value to the maximum force expected for a drop height and weight combination. To calculate the maximum impact force, F_{max} , we follow this derivation (Young, Budynas, & Sadegh, 2011; Avallone, Baumeister III, & Sadegh, 2006):

$$F_{max} = S_{impact} A \quad (17)$$

$$S_{impact} = \frac{v_i}{c_{axial}} + E \left(1 + \sqrt{\frac{W}{W_b} + \frac{2}{3}} \right) \quad (18)$$

where A is the sample's cross-sectional area, v_i is the impact velocity defined by

$$v_i = \sqrt{2gh}, \quad (19)$$

with g the gravitational constant and h the drop height, and c_{axial} is the speed of the compression wave defined by

$$c_{axial} = \sqrt{\frac{E}{\rho}}. \quad (20)$$

In these equations, W is the impactor weight, W_b is the weight of the sample, E is Young's modulus, and ρ is the mass density of the material. As a check to ensure a no-buckling condition with our sample dimensions, we compare F_{max} to P_{cr} .

To calculate the estimated delivered impulse per area, I_A , we follow this derivation:

$$I_A \approx (F_{avg} t_{contact}) / A \quad (21)$$

$$F_{avg} = \frac{1}{2} F_{max} \quad (22)$$

$$t_{contact} = \frac{L}{c_{axial}} \left(\pi \sqrt{\frac{1}{2} + \frac{W}{W_b}} - \frac{1}{2} \right). \quad (23)$$

6.3.1 Choosing Cylindrical Geometry

From the derivations above, we can see what may happen if we use cubes for our sample geometry, versus cylindrical cores, by changing the moment of inertia accordingly. For cubes, $I_{a,cube} = \frac{L^4}{12}$ and for cylinders, $I_{a,cyl} = \frac{\pi d^4}{64}$. We found that cuboid samples were more likely to buckle under the loads we were expecting to deliver and that cylinders were more stable under impact. Furthermore, we determined that we wanted to perform confined compression creep tests with the samples as well, which is best done with cylindrical geometries.

6.3.2 Sample Height and Diameter

Through trial and error using the equations in the derivation above, we initially decided on a 2-inch (5.1-cm) diameter and 0.5-inch (1.3-cm) thick cylindrical geometry for the drop tests. However, upon inspecting the size and curvature of the two melons we secured for testing, we

decided to down-size the diameter of the samples to 1.5 inches (3.8 cm) so we could comfortably excise two through-thickness cores in the center-most area of the melon. We were able to keep the 0.5-inch (1.3-cm) height and avoid buckling behavior if we kept the diameter at or above 1.5 inches (3.8 cm).

6.4 DROP TEST PRE-TEST NUMERICAL MODELING WITH ABAQUS

To determine appropriate drop heights and weights needed deliver equivalent impulses set forth by the damage criteria derived from previous cadaver UNDEX tests (Ketten 2004; Rye 2019), we constructed a series of numerical models using Abaqus. We modeled the stress and displacement of both soft and stiff estimations of the melon (based on data from Soldevilla et al. (2004)). For the EcoFlex samples, we used material fits based on data compiled by the manufacturer as well as from experiments performed by URI DPML.

To estimate impulse delivered, we averaged the vertical compressive stress for the bottom center-most 25 elements to estimate the location of the pressure sensor in the experiment. Then, we calculated the cumulative integral of the stress ($P(t)$) history over time to calculate the impulse time history ($I(t)$). The impulse delivered is then taken as the peak value of $I(t)$, or $\max(I(t))$, over the time duration of contact, which is defined to occur from time t_i to t_f .

$$I(t) = \int_{t_i}^{t_f} P(t) dt \quad (24)$$

We discretized the melon sample geometry into multiple finite elements. We used C3D8R reduced-integration 8-noded bricks. Using an implicit dynamic analysis, we applied the impact velocity to the impactor plate positioned just above the un-deformed sample. Two plastic emergency stoppers were included to prevent displacement beyond 50% of the sample's thickness, as per the actual physical experimental setup. A schematic of the numerical model setup is included in Figure 18.

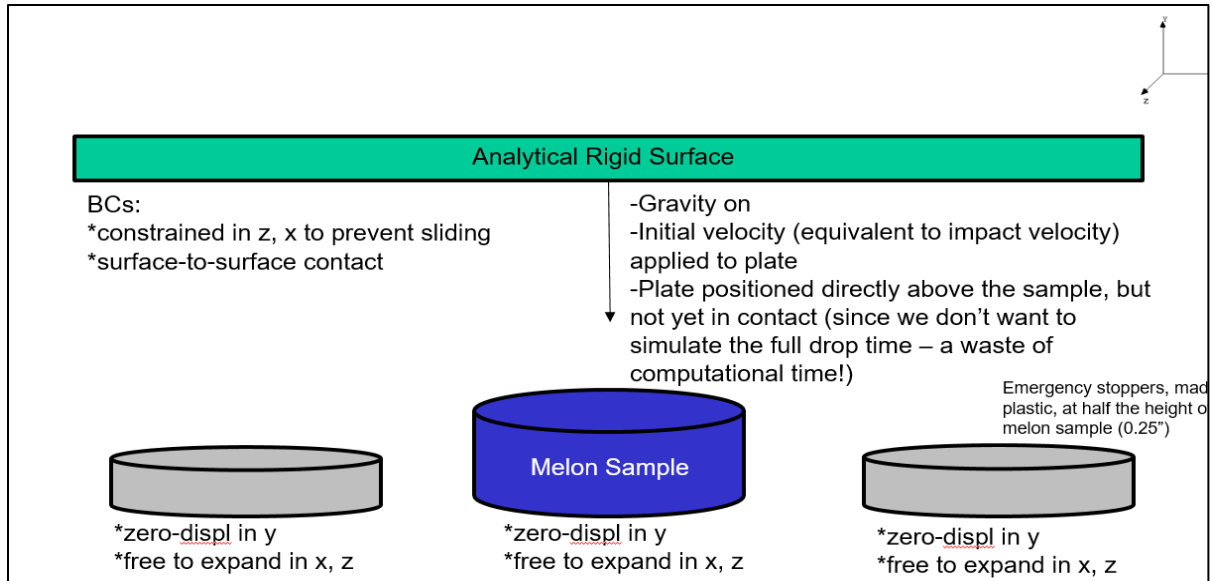


Figure 18. Schematic of numerical model setup in Abaqus.

6.4.1 Pre-Test Predictions, Soft Melon

Displacement results for a soft material fit estimation in Abaqus are shown in Figure 19.

6.4.2 Pre-Test Predictions, Stiff Melon

Displacement results for a stiff material fit estimation in Abaqus are shown in Figure 20.

6.4.3 Pre-Test Predictions, Ecoflex 0030

Displacement results for EcoFlex 0030 in Abaqus are shown in Figure 21.

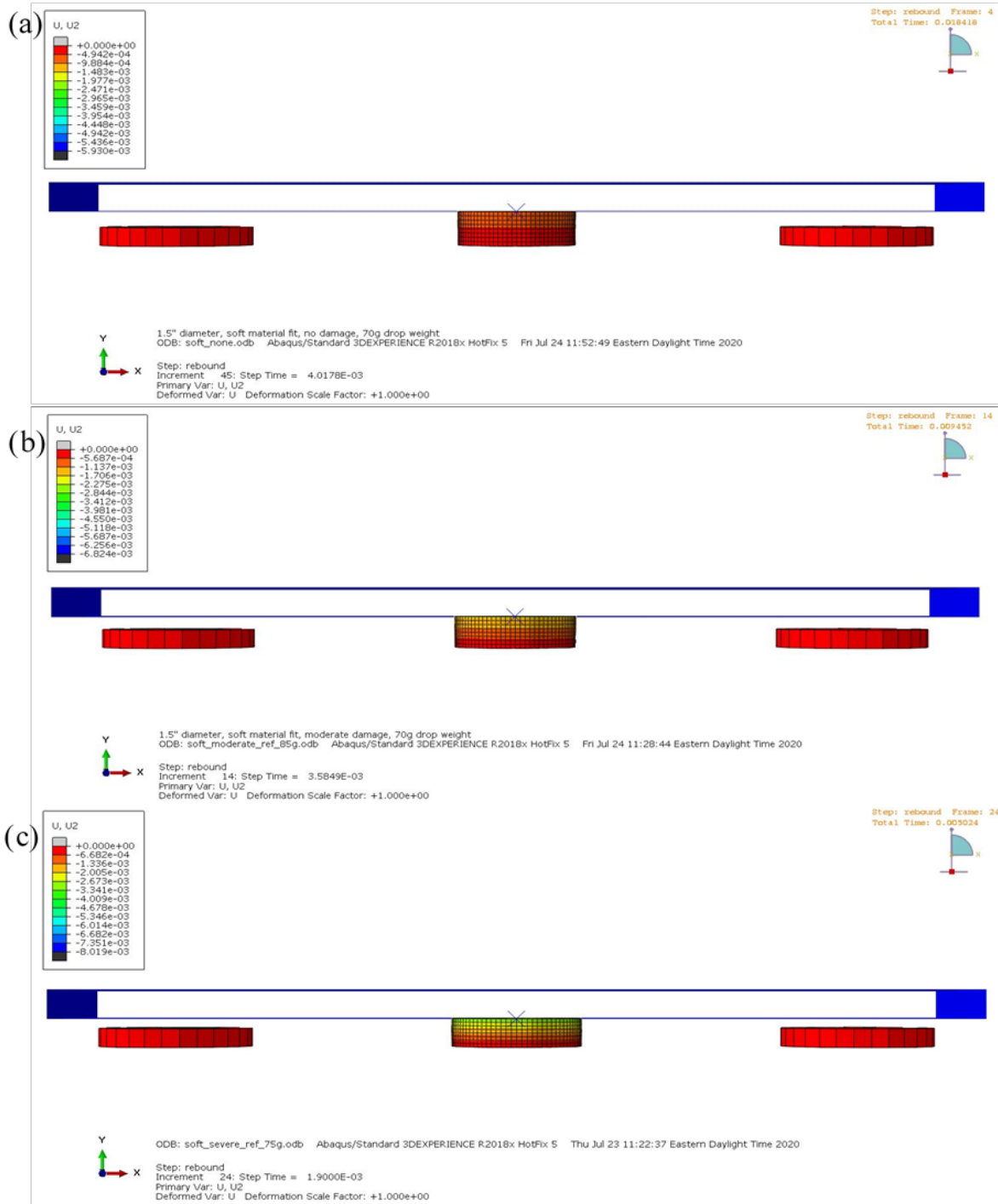


Figure 19. Displacement results for a soft material fit estimation in Abaqus for three severity levels: (a) severe, (b) moderate, and (c) no damage. Units are in meters.

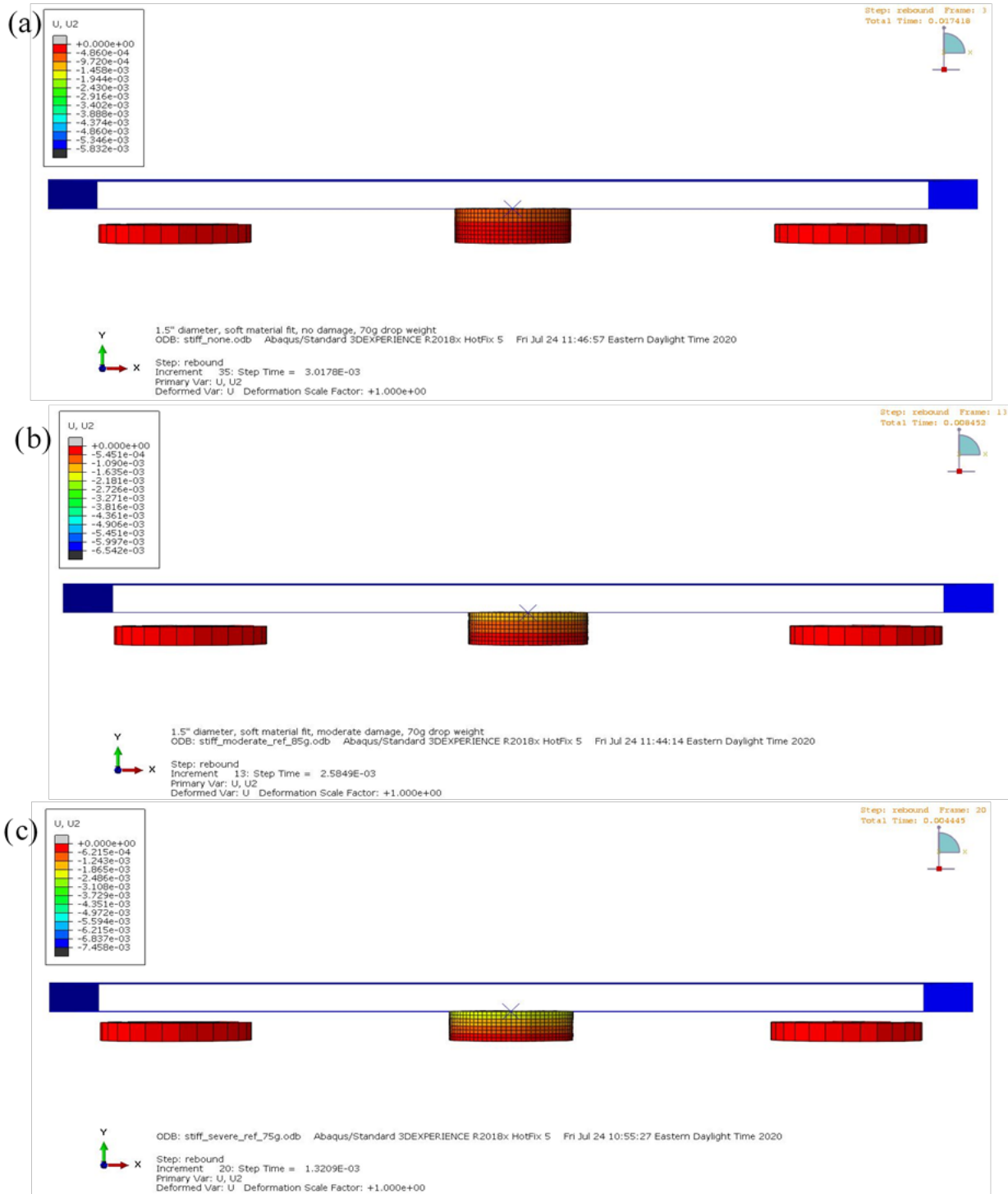


Figure 20. Displacement results for a stiff material fit estimation in Abaqus for three severity levels: (a) severe, (b) moderate, and (c) no damage. Units are in meters.

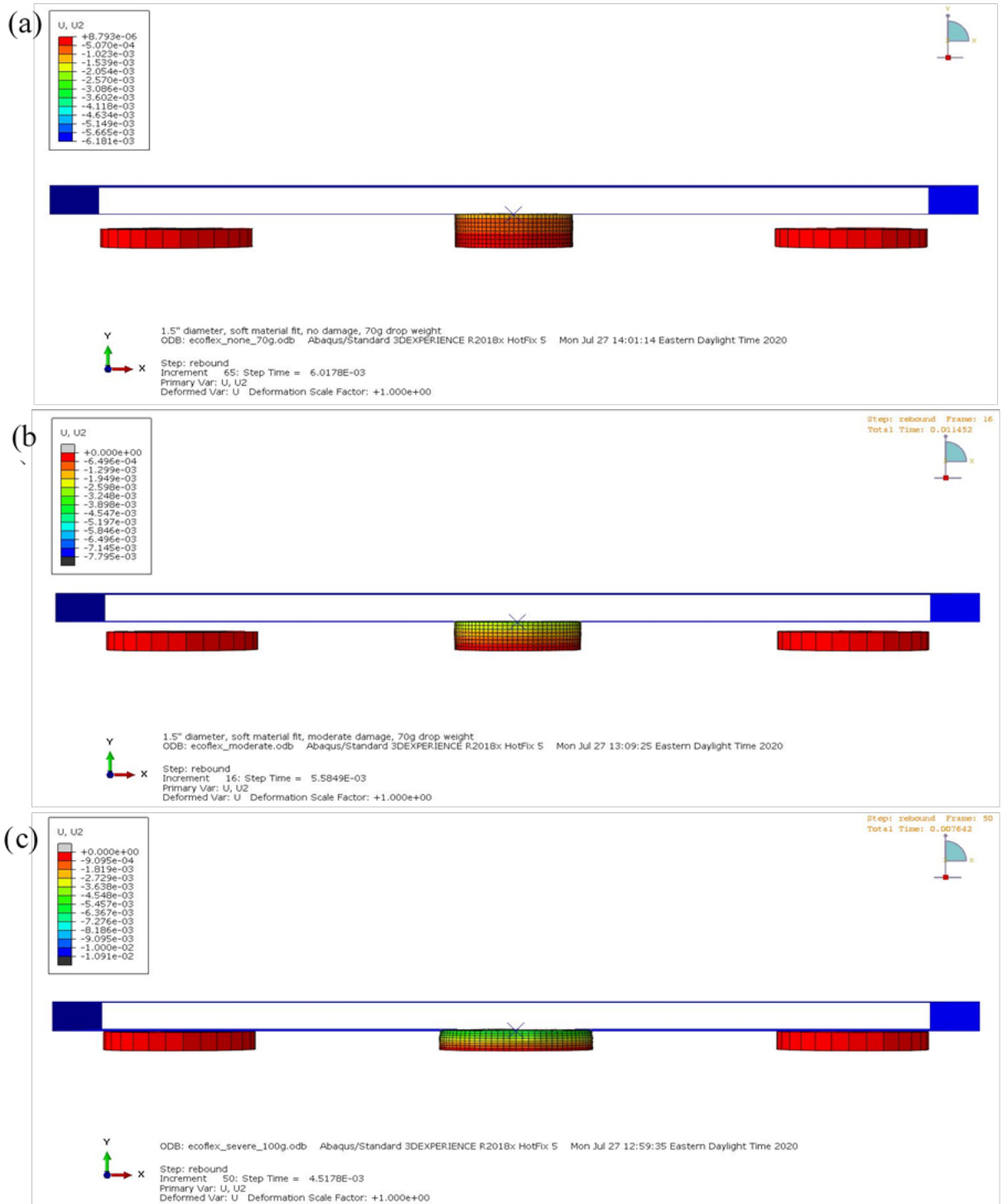


Figure 21. Displacement results for EcoFlex 0030 in Abaqus for three severity levels: (a) severe, (b) moderate, and (c) no damage. Units are in meters.

6.4.4 Summary of Proposed Drop Test Heights and Target Impulse Levels

Table 5 shows a summary table of proposed drop test height and weight pairs to achieve targeted impulse levels, all determined via pre-test predictions. For the three main cases in Table 1, corresponding to ‘None’, ‘Moderate’, and ‘Severe’ damage levels, we were able to design drop height and weight combinations for which the simulated peak impulse was within 3-6% of the desired impulse.

Table 5. Summary of proposed drop test heights and weights for target impulse levels driven from FE simulations for both soft and stiff material fits for melon material and the EcoFlex 0030 material.

EcoFlex 0030						
Damage Level	Desired Impulse (psi-ms)	Peak Impulse Delivered (psi-ms)		% Error from Desired Impulse	Drop Weight (g)	Drop Height (in.)
Mythbusters severe	110.0	41.3		62%	325	5.25
Severe	32.7	31.8		3%	100	5.25
Moderate	17.7	16.7		6%	85	1.50
None	7.30	7.1		3%	70	0.25
Melon						
Damage Level	Desired Impulse (psi-ms)	Peak Impulse Delivered (Soft Fit) (psi-ms)	Peak Impulse Delivered (Stiff Fit) (psi-ms)	% Error from Desired Impulse	Drop Weight (g)	Drop Height (in.)
Severe	32.7	31.2	33.6	3-5%	75	5.25
Moderate	17.7	17.5	18.0	1-2%	85	1.50
None	7.30	7.80	7.30	0-7%	70	0.25

A fourth category of severity was added beyond the intended range-to-effect spectrum in Table 1. This category, named ‘Mythbusters severe’, was intended to be a backup loading case that was sure to cause damage in the samples in the event that the ‘Severe’ load cases did not cause any observable damage and/or we did not achieve the target impulse values during drops. The targeted peak impulse (110 psi-ms) for ‘Mythbusters severe’ is taken from the U.S. Navy injury and mortality criteria for marine mammals potentially exposed to UNDEX (U.S. Navy 2017), and corresponds to the level at which divers exposed to UNDEX in shallow waters were experimentally observed to sustain brief paralysis of limbs and substernal pain lasting 30 minutes to several hours (Wright et al. 1950, as cited in Cudahy and Parvin 2001). We only included this damage level in our tests of Ecoflex 0030 samples, because we did not think it would be needed for the melon samples. Note that the simulated peak impulse is significantly less than the desired impulse for the ‘Mythbusters severe’ case – since this case was an add-on, it actually required a drop weight and/or drop height beyond the specifications for our design of the drop test tower.

Thus, for the ‘Mythbusters severe’ case, we ended up using the maximum height and weight for the tower to try to achieve the largest impulse possible within the constraints of our tower design.

6.5 DIGITAL IMAGE CORRELATION (DIC) FOR DROP TESTING

6.5.1 DIC Overview

During the drop tests, we employed 3D digital image correlation (DIC) to track out-of-plane deformation of the samples during impact. Unlike 2D DIC, which uses one camera, 3D DIC requires two cameras in a stereo setup to capture out-of-plane deformation even on curved sample surfaces (Shukla & Dally, 2014). DIC is powerful because it can capture through-thickness variations in deformation, and thus strain, of heterogeneous materials. We specifically chose to employ 3D DIC because our tests induce large deformations, and 2D DIC can fail when attempting to correlate large deformations.

6.5.2 Speckle Pattern Requirements

We determined the speckle pattern requirements using relations based on the camera specifications and recommended standards published by the International Digital Image Correlation Society (iDICs). First, we chose a target physical feature size, which is the physical size of each dot that the cameras and software will track. We chose the physical feature size to be nine pixels to avoid aliasing errors common with smaller feature sizes (International Digital Image Correlation Society, 2018). From here, we calculated the actual target size to be 0.18 mm based on the camera’s image scale of 20 $\mu\text{m}/\text{pixel}$:

$$\frac{\text{Physical Feature Size (in pixels)}}{\text{Image Scale}} = \text{Actual Target Size} . \quad (25)$$

We selected a frame rate of 4,000 frames per second (fps), which gives about 40 frames during a 10 ms drop (our shortest drop and thus the limiting case). We determined the drop time from the pre-test simulations previously discussed.

We estimated the subset size from an image with good contrast knowing that each subset should contain approximately 6 features in each direction (Shukla & Dally, 2014). Thus, if each feature has 9×9 pixel sampling, subsets would contain 54×54 pixels.

Table 6. Summary of DIC Speckle Pattern Requirements.

Physical Feature Size	9 pixels or 0.18 mm
Frame Rate	4,000 fps
Subset Size	54×54 pixels

6.5.3 Speckle Pattern Implementation

We iterated through several materials to apply an even speckle pattern with the correct speckle diameter range and speckle density. Ultimately, we decided to use sunscreen lotion as a base layer with graphite powder sprinkled over the sample to provide the speckles. The base material needed to (1) provide sufficient contrast, (2) cover the tissue evenly without dripping, (3) avoid diffusing into the tissue, and (4) adhere to a damp, soft tissue surface (Palanca, Tozzi, & Cristofolini, 2016).

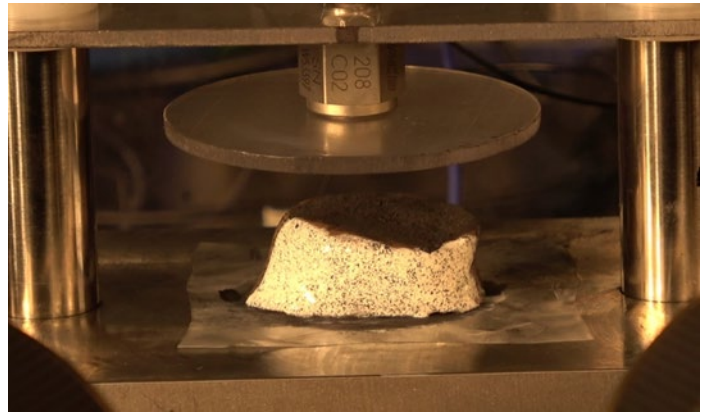
We sifted generic graphite powder through two 304 stainless steel woven sheets with known void sizes of 0.008 inch and 0.011 inch (McMaster-Carr, Elmhurst, IL) to obtain graphite speckles with the desired diameter of 0.18 mm.

Other base layer materials we tried included craft paint, cosmetic liquid foundation, spray tan, and spray leg concealer makeup. Liquid foundation, although used in previous publications on biological tissue (Bakhshae, Young, Yang, Mongeau, & Miri, 2013), produced excessive glare under the microscope lights in our setup. Spray tan did not develop noticeable coverage until it set into the tissue for about 10 minutes. Leg concealer makeup provided very even coverage, but the color choices were all too dark to provide sufficient contrast with the black graphite speckles.

We also considered spray paint as a speckling agent based on previous literature (Spencer, Siegmund, & Mongeau, 2008). However, due to the variability in spray paint dot sizes and application, we decided to use graphite powder.



(a)



(b)

Figure 22. (a) Sample of surrogate tissue with liquid foundation and graphite powder as speckling agent showed insufficient contrast under the microscope. (b) A melon sample mounted in the drop tower is speckled with sifted graphite powder over a base of sunscreen.

6.5.4 Cameras and Lenses

We used two Photron Fastcam Mini AX100 cameras (Photron USA, San Diego, CA) with 105 mm lenses courtesy of Jesse Belden (Code 8514).

Table 7. Summary of high-speed camera specifications.

Lens Type and Focal Length	105 mm macro
Minimum Distance from Sample	12.2-in.
Camera Sensor Pixel Size	20 μm /pixel
Image Size	1024 $\times$ 1024 pixels
Camera Resolution	1 megapixel

6.5.5 Final Drop Test Setup

A typical setup for the drop test experiments appears in Figure 23. Note that drop height and added mass will vary between tests, with drop height and weight combinations according to Table 5.

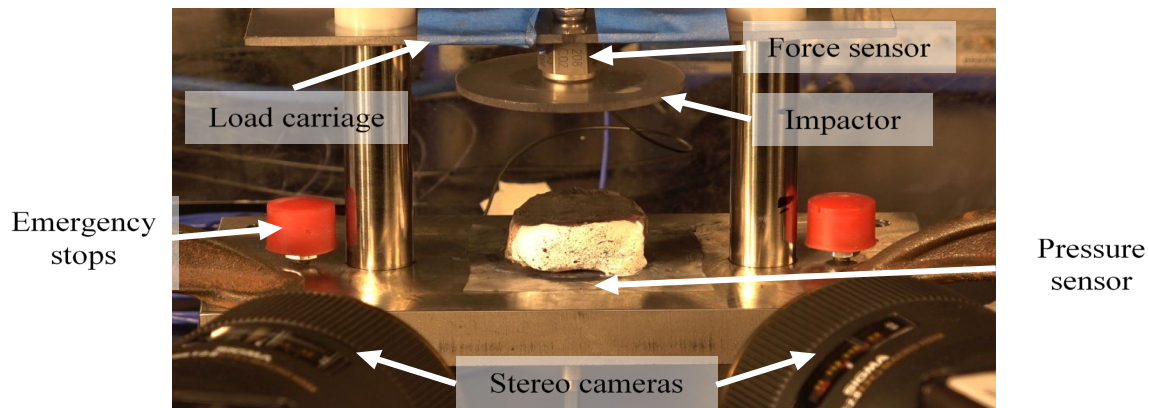


Figure 23. Final drop testing setup with melon sample loaded.

6.5.6 Final Drop Test Workflow

The final workflow for the drop test experiments, independent from the ancillary panel tests, is as follows:

1. Drop known weight from known height.
2. Impactor hits (impacts) sample.
3. Force sensor (above impactor) records impact loading time history.
4. Sample (coated with speckles) responds (“jiggles”) to impact.

5. Flush-mounted pressure sensor (below specimen) records response pressure time history.
6. High-speed cameras record video of sample response.
7. Analyst uses DIC software to study video file of a drop test experiment to quantify sample response (velocity, displacement, strain, etc. in various directions, e.g. vertical and out-of-plane).

6.6 PHYSICAL MEASUREMENTS

6.6.1 *Creep Test*

We elected to perform confined compression creep tests to obtain the tissue's bulk modulus prior to drop testing. A creep test is the static application of a known constant stress while recording the sample's displacement over time. In soft tissues, the loading rate affects the response within the elastic range (Korhonen & Saarakkala, 2011), and so one important part of characterizing a material's mechanical behavior is to investigate response for a static load application. Bulk stiffness constitutes a sample's response under confined compression, whereas in unconfined compression a combination of the shear and bulk stiffness contribute to the response. In unconfined compression, the interplay of shear and bulk stiffness can make it harder to isolate the two parameters individually (Naseri & Johansson, 2018). Thus, we chose to perform creep tests in confined compression to isolate the bulk stiffness effect.

Melon is of similar composition and structure to adipose tissue, which can be considered as incompressible under low loading rates (Comley & Fleck, 2010). Thus, bulk stiffness constitutes the response under confined compression.

To modify our drop testing tower for confined compression creep, we placed a scratch-resistant radial confinement tube of 1.5-inch inner diameter (McMaster-Carr, Elmhurst, IL) centered over the pressure sensor (Figure 24). We gently placed the sample inside the tube, and fitted an impactor loaded with the corresponding mass to apply a known stress. We determined target stress applications by selecting a range of pressures in the same order of magnitude that our pre-test simulations predicted for the "no damage" case (approximately 1 psi). We applied 670 g to the sample over a cross-sectional area of 1.77 in^2 (11.4 cm^2), resulting in an applied stress of 0.84 psi (5.77 kPa).

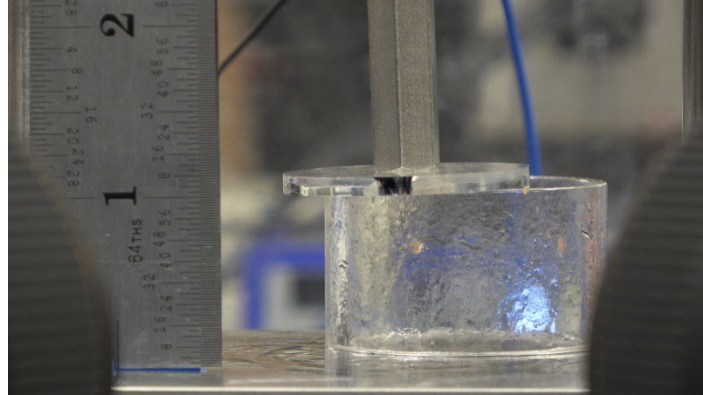


Figure 24. Detail of drop tower modified for a creep test shows radial confining tube, modified impactor plate with marker for tracking, and length measurement for calibration in post-test analysis.

To run the creep test, we attached 600 g to the load carriage (with nominal mass 70 g) using tape. While recording with a camcorder, we carefully inserted the sample in the radial confinement tube and lightly released the load carriage once it was barely in contact with the sample surface. We recorded 3 minutes of deformation based on full relaxation times in the literature of other soft biological tissues (Cai, Yu, Li, Zheng, & Zhou, 2017; Paritala, et al., 2020). Visual observations of the creep tests and recorded video of the tests confirmed that full relaxation was achieved within the 3 minutes of data recording for all samples tested. At the time of report writing, we had not yet analyzed the video stills from the creep tests to make estimates of the material bulk modulus values.

6.6.2 *Mass Density*

For each sample we leveraged Archimedes' Principle, depicted in Figure 25, to calculate the density of that sample. Following ASTM D792-13, we measured the sample mass in air, then submerged that sample in distilled water and recorded its submerged mass. We used the values for the in-air mass and submerged mass, together with the density of water at the measured temperature, to calculate sample density. All mass measurements were made with a recently calibrated electronic mass balance with a 150 g capacity, and resolution of 0.1 mg.

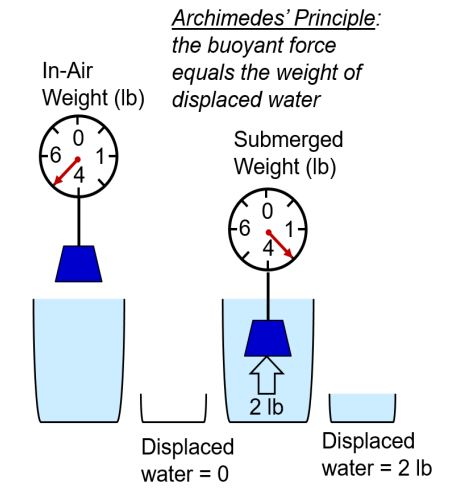


Figure 25. Relationship between buoyant force and displaced volume of water for a submerged object.

The density calculations for a given sample involved a translation of the physical principle of Figure 25 into equation form, or

$$\rho_{sample} = \frac{m_{sample,air}}{(m_{sample,air} - m_{sample,submerged})} \rho_{water} . \quad (26)$$

Here, ρ_{sample} is the calculated density of the sample, $m_{sample,air}$ is the sample's mass in air, $m_{sample,submerged}$ is the sample's submerged mass, and ρ_{water} is the density of the water in which the sample was submerged, at the temperature of that water.

In order to circumvent measurement challenges for positively buoyant samples, we designed and 3D-printed a sample basket with a sliding drawer. This basket kept positively buoyant samples below the water surface, enabling accurate submerged mass measurements. The basket geometry is depicted in Figure 26. When not in use for pre-panel or post-drop test measurements, we kept the basket submerged in its own beaker of distilled water, to minimize any experimental error from water uptake by the basket material or excessive amount of air bubbles adhered to the surfaces of the basket. Figure 27 shows a photo with all equipment used for density testing. Note that the beaker has blue tape on it, to mark the exact water fill line for use in submerged mass measurements. The basket has a stainless steel nut added to its stem, to ensure a fully submerged condition for even our most positively buoyant melon samples.

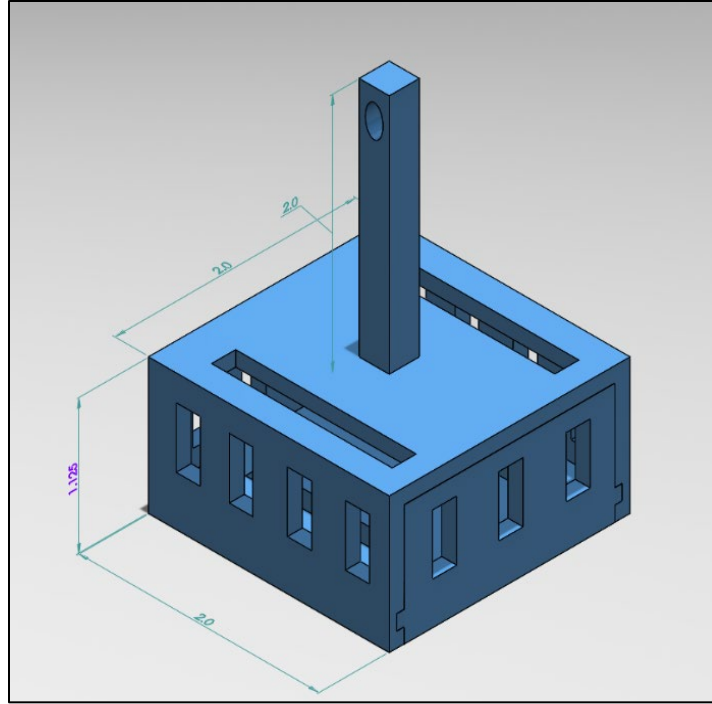


Figure 26. Geometry of basket used for submerged mass measurements (dimensions in inches).

The full apparatus and experimental setup for the submerged mass measurements is detailed in another section. The apparatus includes two subassemblies, the beaker and the ‘genie bottle’. The ‘genie bottle’ includes an enclosed volume of water with rubber stopper and metal arm. This subassembly is used as a stabilizer for the submerged mass measurements in the beaker, which is located outside of the balance enclosure. The top of the sample basket has a hole that interfaces with the end of the metal arm of the genie bottle. The beaker includes the sample basket (with or without a sample), its added mass (stainless steel nut), and distilled water. Note that the beaker water was discarded and refreshed after every submerged mass measurement, to ensure purity of the fluid medium (distilled water) for all measurements.

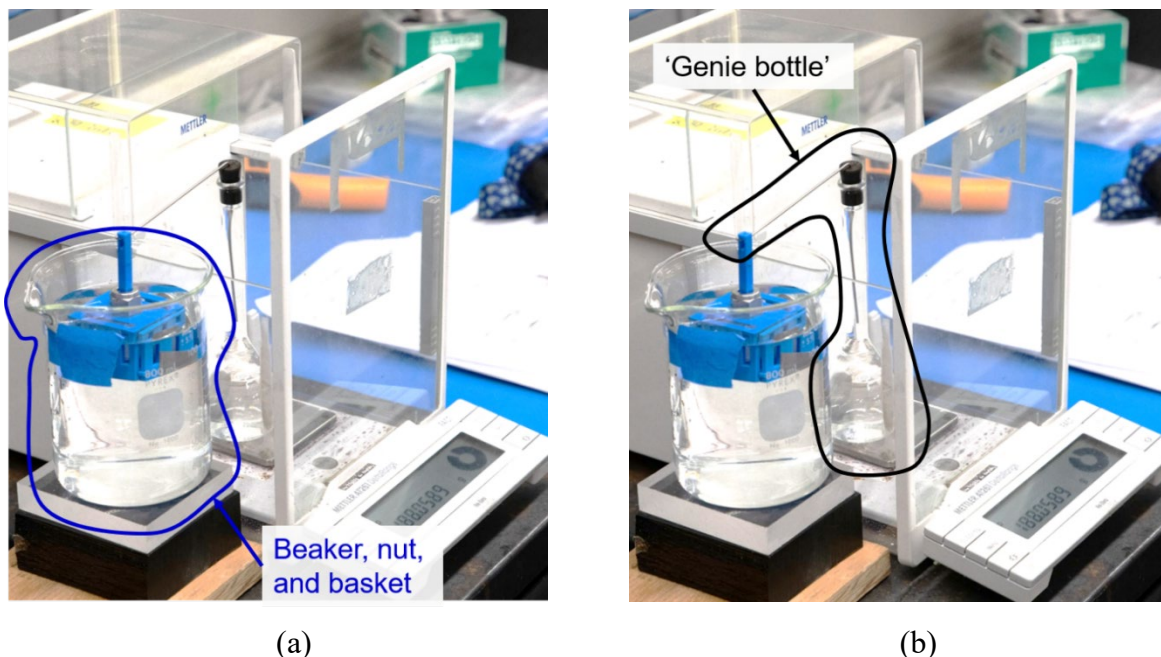


Figure 27. Equipment and main experimental setup for taking mass density measurements of drop test samples, including (a) beaker, nut, and basket and the (b) ‘genie bottle’ subassemblies.

The workflow for the density measurements involved the following steps:

1. Measure and record mass of weighing boat 1.
2. Place sample on weighing boat 1.
3. Measure and record mass of sample + weighing boat 1.
4. Measure and record ‘genie bottle’ mass.
5. Fill beaker with distilled water to tape-marked line.
6. Measure and record temperature of water in beaker.
7. Remove basket and nut from its beaker of distilled water and place in main beaker.
8. Measure and record mass of beaker + nut + basket (no sample).
9. Place sample inside basket via sliding drawer.
10. Measure and record mass of beaker + nut + basket (with sample).
11. Measure and record mass of weighing boat 2.
12. Remove sample from basket and place back in weighing boat 1.
13. Place weighing boat 2 as a cap to enclose weighing boat 1 + sample.
14. Measure and record ‘wet mass’ of weighing boat 1 + sample + weighing boat 2.
15. Empty beaker water, clean, and wipe down.

After removing samples from the basket, we re-weighed the wet samples per the above workflow. We found that we had to fully enclose the sample within two laboratory weighing boats (in a clamshell configuration) in order to prevent evaporation-related changes in mass. Figure 29 includes a typical plan view photo of a melon sample on a hexagonal weighing boat.

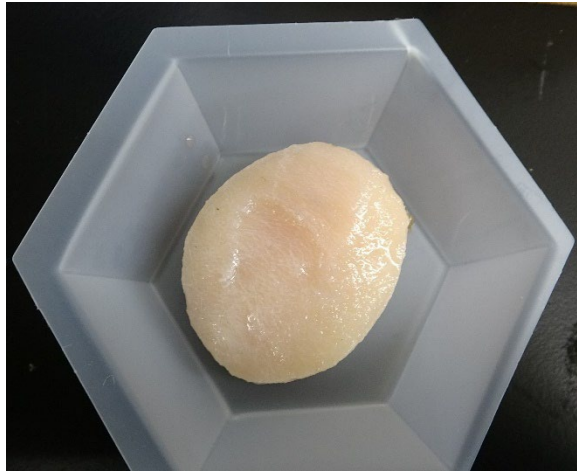


Figure 28. Melon sample on hexagonal weighing boat.

A snapshot of the density measurement workflow is shown in Figure 29.



Figure 29. In-process mass density measurements of drop test samples.

6.6.3 Sound Speed

We elected to take sound speed measurements of our samples before and after drop testing, where these measurements could be potentially useful as a non-destructive screening method for detecting impact-induced damage in the samples. We developed and employed a multi-step process, which we based on relevant methods and procedures in ASTM E494-15. The equipment used for the sound speed measurements included the following: digital calipers, an Olympus 45MG ultrasonic thickness tester, and an Olympus M109 acoustic contact transducer. Figure 30 depicts a schematic of the process for gathering sound speed data, after initial calibration of the ultrasonic thickness tester and the transducer for a given material. The M109 transducer specifications are the following: 0.5-inch (1.3-cm) sensing element diameter, 2.5-MHz frequency. We used the thickness tester in measurement Mode 1, which tracks the arrival time of the first reflected pulse received back at the tester that is caused by the reflection caused by the impedance mismatch at the bottom surface of the drop test sample when resting on the lab bench.

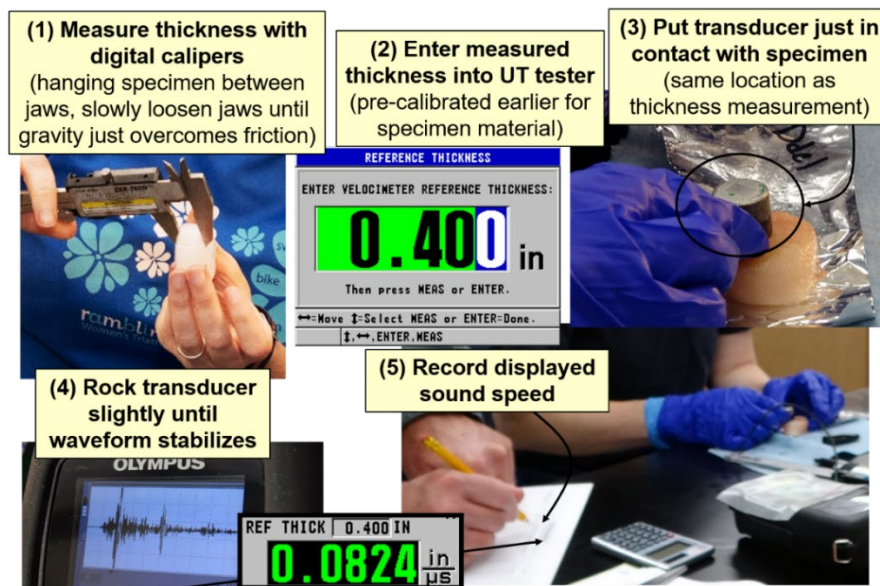


Figure 30. Schematic of process for measuring sound speed within drop test samples using an ultrasonic thickness tester (Olympus 45MG) and acoustic transducer (Olympus M109).

Prior to any measurements of sound speed related to the drop test experiments, we needed to calibrate the Olympus 45MG to similarly sized samples of melon tissue to ensure accurate sound speed measurements. When the 45MG is in velocity mode, it is necessary to perform a two-point thickness calibration to properly set the zero offset for the transducer being used. To do this, we took a cube of melon tissue, measured the thickness in two different directions, and calibrated our material profile within the 45MG to these measurements. Upon removal from the fridge, the melon cube measured 0.35 inch $\times$ 0.495 inch $\times$ 0.54 inch (0.89 cm $\times$ 1.26 cm $\times$ 1.37 cm). After an hour of handling, the cube dimensions reduced to 0.31 inch $\times$ 0.490 inch $\times$ 0.49 inch (0.79 cm $\times$ 1.24 cm $\times$ 1.24 cm). Final material profile settings are in Table 8 for the melon and Table 9 for the Ecoflex 0030.

Table 8. Ultrasonic thickness tester settings for Mode 1 measurement of sound speed in melon drop test samples.

Sound Velocity	0.0767 in/microsec
Zero	2416
Pulser Power	200 V
Max Gain	69.3 dB
Initial Gain	2.9 dB
TDG Slope	11.61 dB/microsec
MB Blank	1.6 microsec
Echo Window	150 microsec
Echo Detection	+Slope

Table 9. Ultrasonic thickness tester settings for Mode 1 measurement of sound speed in Ecoflex 0030 drop test samples.

Sound Velocity	0.0395 in/microsec
Zero	1123
Pulser Power	110 V
Max Gain	75.1 dB
Initial Gain	39.2 dB
TDG Slope	1.85 dB/microsec
MB Blank	0.87 microsec
Echo Window	200 microsec
Echo Detection	-Slope

Measured Mode 1 signals for solid Ecoflex 0030 and melon, respectively, are shown in Figure 31.

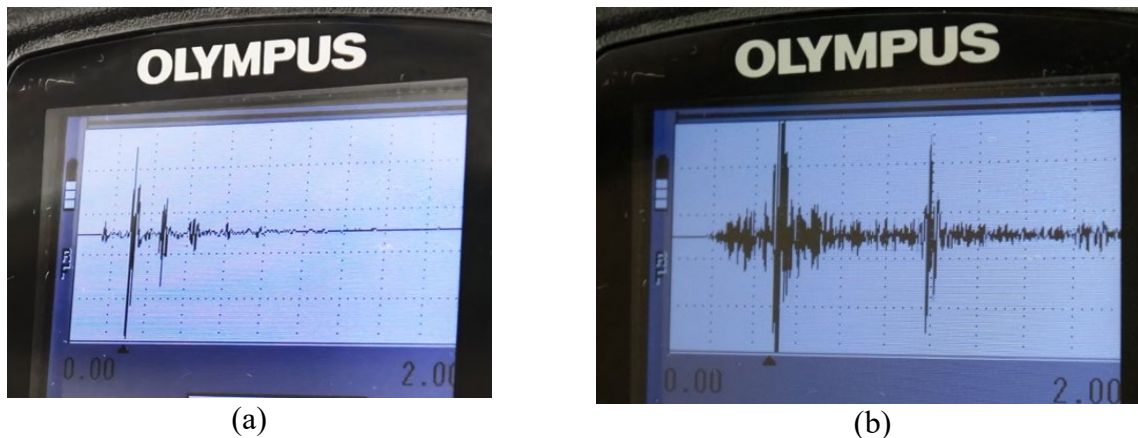


Figure 31. Measured Mode 1 signals for (a) Ecoflex 0030, and (b) melon, using Olympus 45MG thickness tester and M109 transducer with typical drop test samples prior to drop testing.

6.6.4 *Microscopy*

In an attempt to visualize any structural changes at the cellular level of tested samples, we employed two types of microscopes described in detail below. The purpose of this was to determine if the drop testing had somehow altered the structural composition of the melon (e.g., had it been “damaged”).

There are significant challenges to working with post-mortem tissue when attempting to quantify damage as a function of applied loading to a biological specimen. According to Ressel et al. (2006):

1. “Histologically, postmortem abrasions lack vital reactions”.
2. “...inflammation does not proceed in a dead animal”.
3. “Postmortem blunt trauma should in theory not induce bruising because of the lack of blood pressure”.

However, the same authors do point out that special stains, such as MSB or Perl’s Prussian blue, can be useful when examining tissues with moderate postmortem changes (Ressel et al., 2006). As such, prior to the actual drop test experiments, we conducted benchmark lab tests to investigate the efficacy of a variety of potential stains to be able to visualize defects within our samples. Given the lack of access to university veterinary pathology labs during the height of the COVID-19 pandemic, we improvised by employing blue food coloring as contrast agents for optical microscopy.

Following drop testing and post-drop panel tests, we sacrificed specific samples to microscopy, which was destructive, for qualitative evaluation. We used a Nova Compound Microscope (Nova-Tech International, Kingwood, TX) at 100X magnification courtesy of Code 15 and a second compound microscope with a camera attachment courtesy of Code 34 (manufacturer unknown). The compound microscope’s (with the camera attached to it) magnification was controlled by moving the camera unit up and down. Thus, the exact magnification level was subjective based on the height of the camera unit and not necessarily a set magnification level. However, this microscope, even at its highest magnification, was not sensitive enough to view the cellular components of the tissue samples and was not used. Instead, we used the Nova Compound Microscope and then used the lens of a camera placed over one of the eyepieces of the microscope to take images. As mentioned above, we presoaked samples, post drop testing, prior to microscopic examination. The soak consisted of diluted solution of blue food coloring and water, to provide contrast when visualizing the tissue under the microscope. We sliced samples across their diameter to assess any internal changes. For the melon, we looked for cellular structure changes and for the EcoFlex samples, we closely examined the integrity of the vascularization (Figure 32).

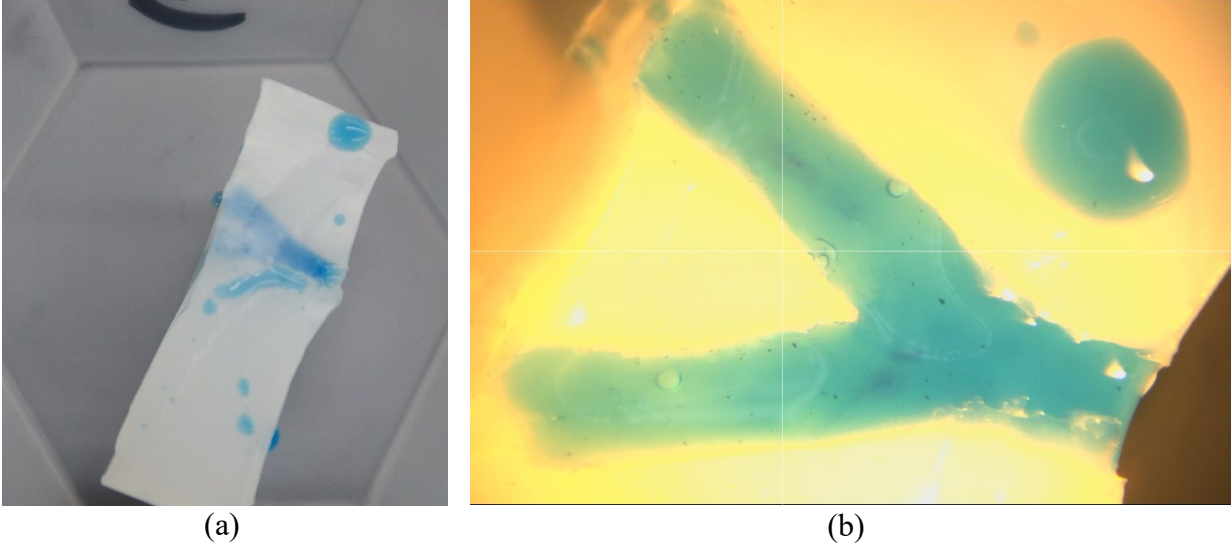


Figure 32. Vascularized EcoFlex sample sliced along diameter for microscopy in (a) full view and (b) magnified view shows vascularization through-the-thickness sufficient dye uptake.

6.6.5 Using Physical Measurements as Non-Destructive Damage Screening Tools

Our intent in taking mass density and sound speed measurements before and after drop tests was to explore the potential for using these measurements together as potential non-destructive damage screening tools. Our hypothesis was that the compressive wave sound speed might change due to the process of impact (as compared to a pre-test sound speed measurement made on the same sample), and that this change might be a potential indicator of damage. The full rationale for trying out this technique for this application is outlined in Figure 33.

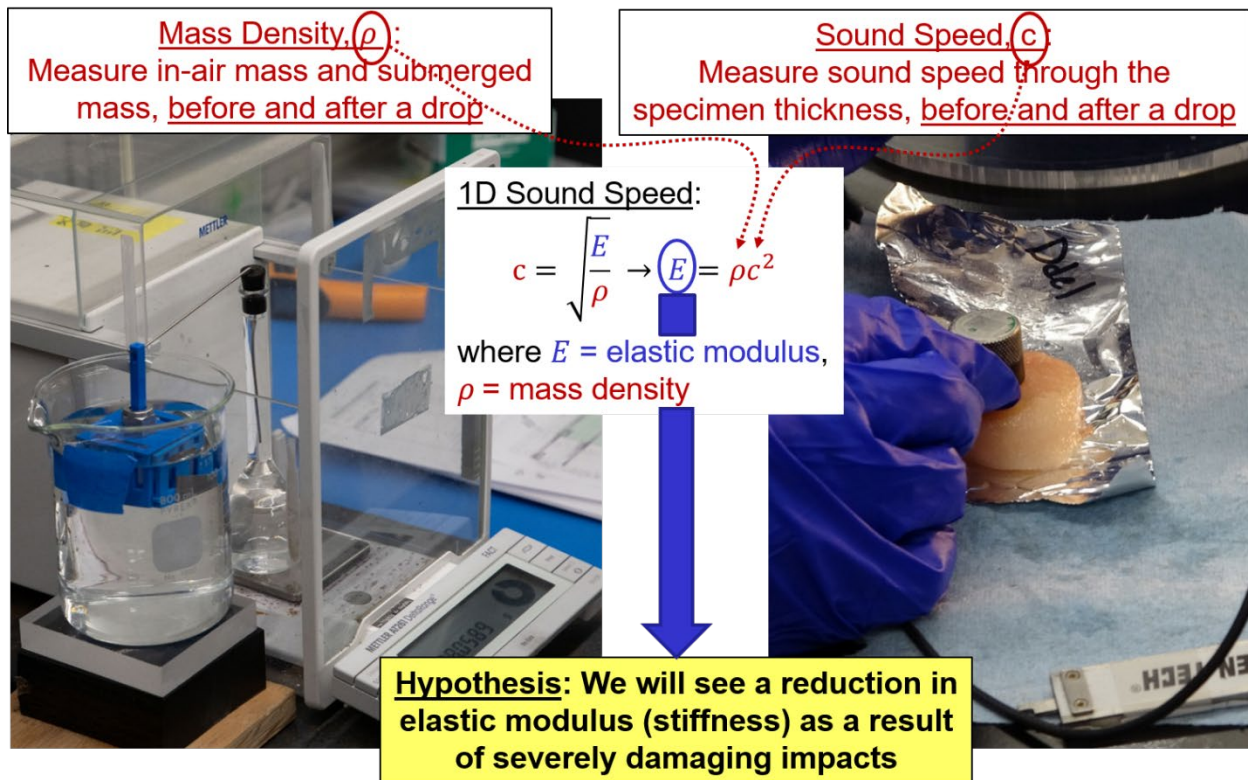


Figure 33. Rationale for comparing pre-test and post-test measurements of sound speed in drop test samples as a potential metric for drop-test damage.

Note that the above hypothesis assumes that sample density does not change appreciably as a result of the drop test. If this assumption is correct, then we are led to the conclusion that any change in sound speed as a result of a drop test could be used to quantify any loss of specimen stiffness (tissue degradation for more severe drop cases) that may have resulted from the impact.

7. SPECIMEN EXTRACTION/CREATION FOR DROP TESTS

7.1 CHALLENGES WITH MELON SAMPLE EXTRACTION

There are several unique challenges associated with extracting melon samples for use in drop testing. Extraction had to be carefully planned, to ensure maximal sample integrity and surface smoothness (for DIC), while at the same time maximizing the number of usable samples for use in drop testing.

All of the intact melons were either previously frozen when they were collected from IFAW and Mystic Aquarium or were frozen immediately after the chain of custody was transferred to NUWC Division Newport (under DeAngelis' permit). Sampling completely frozen tissue is not recommended, as it can shear or tear the tissue itself even with the sharpest instruments (e.g., reduces surface smoothness for DIC). However, sampling "fresh" melon tissue

(not frozen) also poses challenges because the tissue loses some of its shape when it is not supported by the skull. The skin does provide some support during the sampling process, but not enough to reduce shear, and certainly not throughout the entire melon, as skin is only present on the outermost surface. Therefore, samples were extracted when the frozen melons had been allowed to thaw for no longer than 10 minutes. Melons were kept on ice during the sampling process to maintain temperatures that varied no more than 5 degrees Fahrenheit. Once samples were extracted from the melon, these small pieces of melon tissue were then placed in individual plastic Whirl-pak sample bags, labeled, and then placed in a gallon sized Ziploc bag before being placed in a freezer. This reduced the chances of freezer burn and ensured the samples did not stick to each other.

Before the process of excising the sampling started, it is important to prepare the sampling area. Personal protective equipment (gloves, boots, face shield, mask, etc.) should be worn at all times. In the absence of a laboratory dedicated for biological sampling (e.g., hood and metal table with a drainage system on the floor), a table covered in plastic, with a nearby sink designated for biological samples, in a well-ventilated area is sufficient. The following is a list of the minimum types of equipment needed when extracting melon samples: razor blades, metal scalpel, metal tweezers, sampling tool, ice in a chest/bucket/or access to a freezer, thermometer (for ice chest), Whirl-pak sample bags, permanent marker, pen, metal ruler, diluted bleach, sink (soap and water to wash equipment), paper towels, garbage bags to discard soiled towels or biological samples, cutting board, and a dedicated notebook (because it will get soiled).

7.2 MELON SPECIMEN DIMENSIONS

For drop testing, melon samples were extracted from the common dolphin and harbor porpoise melons using a custom-built coring tool, described subsequently and per Figure 34. Each cored sample was 1.5 inch (3.8 cm) in diameter by 2 inch (5.1 cm) tall. If any skin was present on the cored sample, it was removed using a razor blade. Figure 35 is a visual representation of where melon samples were extracted from relative to the assumed melon composition (shell, mixed, or core). Multiple cores (edges marked in red in Figure 35) were taken from each melon specimen. Each core was sliced into multiple individual drop test samples, as described in a previous section.

7.3 SAMPLING TOOL DESIGN

The design of the sampling tool focused on the tool's ability to extract precisely shaped cylindrical specimens with a smooth surface, for use in the drop test experiments. Extraction needed to be achieved with minimal tearing of tissue, to achieve as smooth a surface as possible on the curved surfaces of the cylindrical specimens, to maximize quality of DIC measurements. A schematic of the extraction workflow is included in Figure 34.

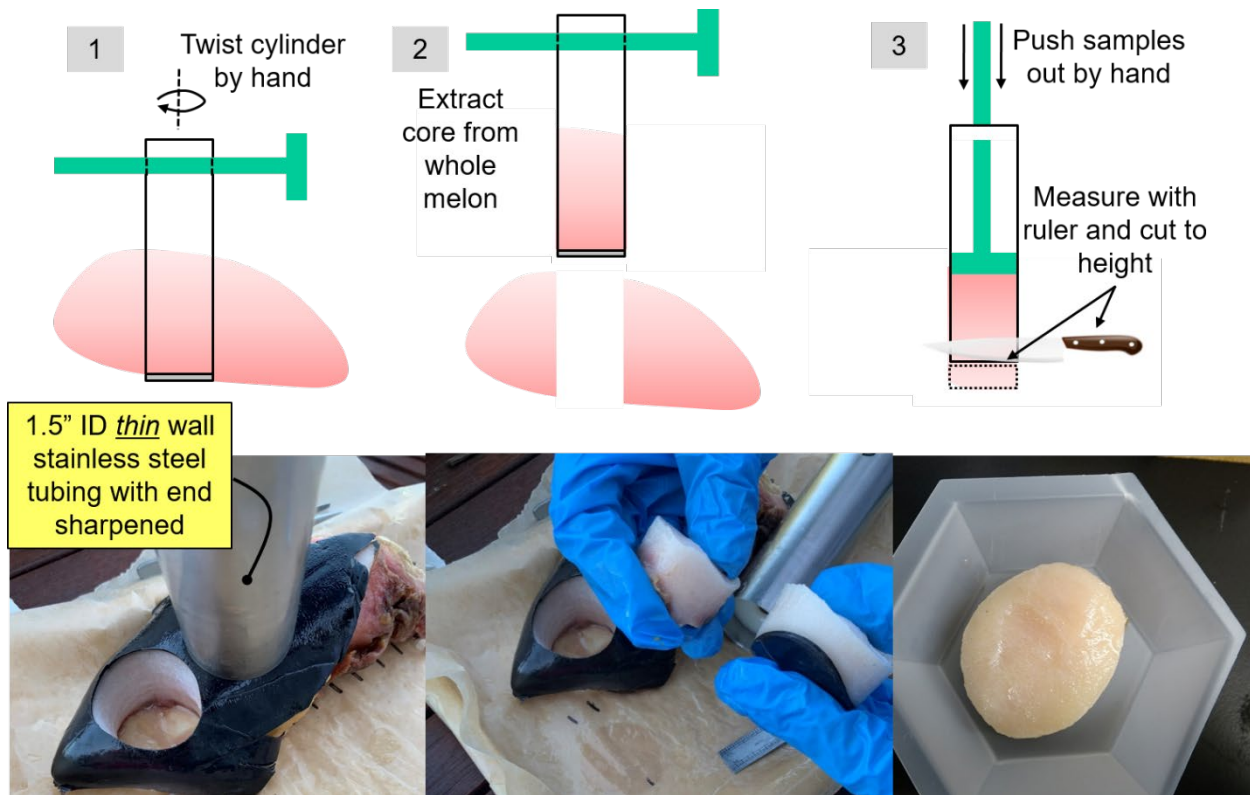


Figure 34. Schematic and associated photos of melon sample extraction.

7.4 EXTRACTED MELON SAMPLES

Once melon samples were extracted, and prior to being placed in the Whirl-Pak sample bag, we took note of the approximate location of the sample location (Table 10). Figure 35 is a visual representation of where melon samples were extracted relative to the assumed melon composition (shell, mixed, or core). We excised multiple cores (edges marked in red in Figure 35) from each melon specimen. By proceeding in this manner, we could infer the relative composition of the sample—shell, core, or a mix of shell and core and/or surrounding connective tissue.

Table 10. Example of sample location for *Delphinus delphis* (Ddel) and *Phocoena phocoena* (Pphoc), anterior (ANT), middle (MID), posterior (POST).

Sample ID	Relative Location and Description
Ddel 001 ANT MEL	Dorsal with skin
Ddel 002 ANT MEL	Ventral
Ddel 003 MID MEL	Dorsal with skin
Ddel 004 MID MEL	Middle
Ddel 005 MID MEL	Ventral
Ddel 006 POST MEL	Dorsal with skin
Ddel 007 POST MEL	Ventral

Sample ID	Relative Location and Description
Pphoc_001_ANT_MEL	½ Dorsal (with skin), ½ Ventral
Pphoc_002_POST_MEL	Dorsal with skin
Pphoc_003_POST_MEL	Ventral

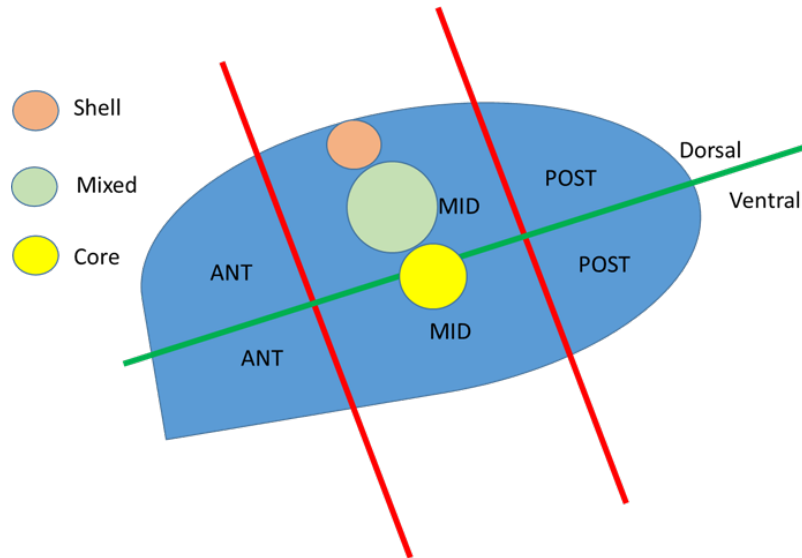


Figure 35. Schematic of sample extraction locations from the melon and associated tissue types (not to scale).

7.5 ECOFLEX SAMPLE PREPARATION

We manufactured both solid and vascularized Ecoflex 0030 samples for testing in the drop test tower.

7.5.1 Solid

Manufacturing solid samples of Ecoflex 0030 is a fairly straightforward process. The workflow is pictured in Figure 36: stir two liquid components separately, mix together, de-gas mixture with vacuum sealer, pour mixture in molds by layer, wait several hours for a given layer to cure, then separate successive poured layers with aluminum foil.

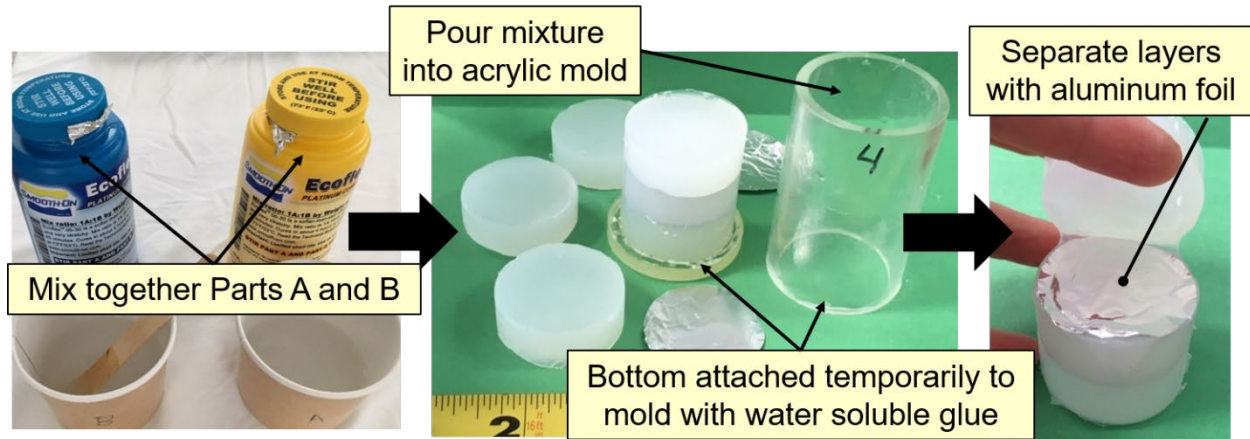


Figure 36. Workflow for fabrication of solid Ecoflex 0030 drop test samples.

7.5.2 Vascularized

Manufacturing the vascularized Ecoflex 0030 samples involved the same steps as the solid Ecoflex 0030 samples, except for a significant additional pre-step, which involved 3D printing dissolvable models of idealized vasculature. We developed the geometry for the idealized vasculature per Nowak et al. 2003 and Sohrabi et al. 2014, which both describe the well-known Weibull model for describing the geometry of idealized lung vasculature.

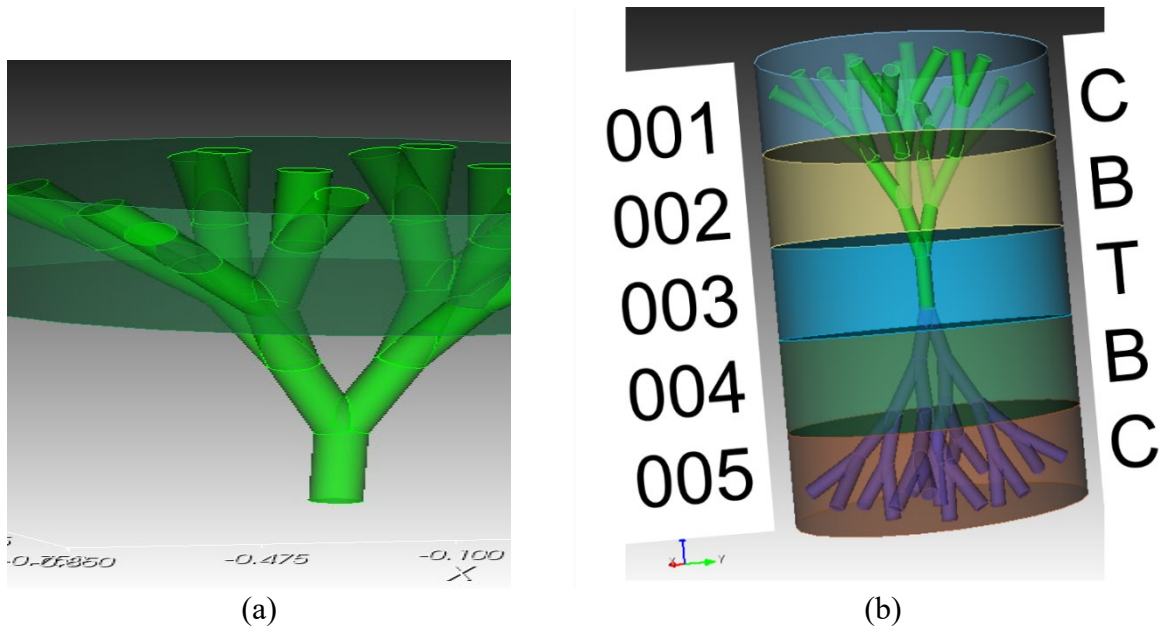


Figure 37. Geometry of idealized vasculature in vascularized Ecoflex 0030 samples, for (a) canopy sample, and (b) canopy (C), branching (B), and trunk (T) samples within a single mold.

The pre-step for fabrication of the vascularized Ecoflex 0030 samples is represented in Figure 38, with the 3D printed idealized vasculature placed in the mold in the first step, and successive layers of Ecoflex 0030 poured one at a time.

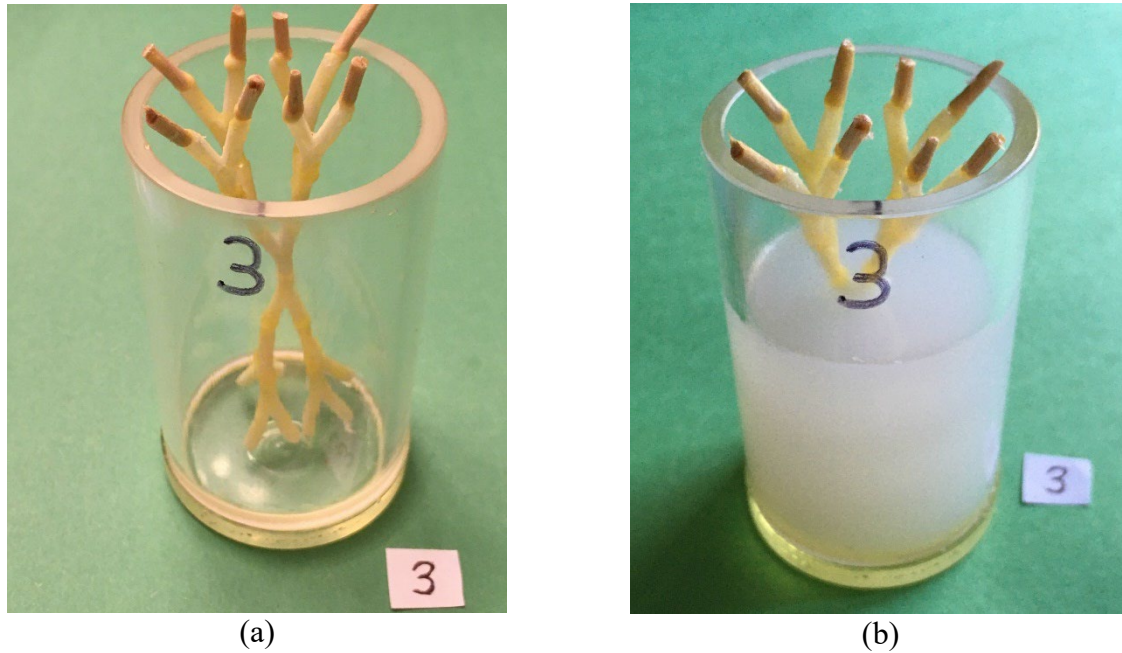


Figure 38. Vascularized Ecoflex 0030 sample fabrication, (a) prior to pouring any Ecoflex material, and (b) after three of five planned layers have been poured into the mold.

8. DROP TEST - PRELIMINARY RESULTS

8.1 FINAL TEST MATRICES

8.1.1 *Ecoflex 0030*

8.1.1.1 *Solid*

The first series of drop tests focused on solid Ecoflex 0030 samples because these samples involved the simplest handling procedures of all of our specimens. Additionally, we assumed that the isotropy and homogeneity of these specimens should lead to the most uncomplicated responses for impact loading, making these ideal ‘training’ samples for refining all of our laboratory and test procedures. The final as-executed test matrix for the solid Ecoflex 0030 samples is shown in Table 11, with the corresponding severity levels listed in Table 12. While the severity level categories are common to all drop tests, the drop height and weight combinations to achieve these severity levels varies by specimen type, as shown previously in Table 5.

Each sample is subjected to at most two drop tests, denoted by the blue columns in the table. Unless otherwise noted, a given sample is subjected to a series of pre-test panel tests (“Pre-Test #A Panel Tests: Y/N?”) prior to the initial drop test, Drop Test #A. Then Drop Test #A is conducted following the listed Severity Level for Drop Test #A. If Post-Test #A panel tests were conducted, these were carried out immediately following Drop Test #A. If Post-Test #A microscopy was performed, a second drop test (Drop Test #B) is not possible, as the microscopy procedure involves cutting the drop test sample in half to extract a slice in the through-thickness direction of that cylindrically shaped sample. For some samples, a second drop test was planned ahead of time, e.g. Drop Test E2B. However, for other samples, the second drop test was only conducted if the post-test panel results differed from the pre-test panel results, e.g. Drop Test E3B. For this type of contingent drop test, the project leads sometimes decided to conduct the second drop test anyway for various reasons, but mostly because the microscopy could be time-consuming and did not always produce remarkable results.

To fully decipher the drop test matrix, it is best to give an example. For sample ID EcoFLX0030_006_NONE:

1. Pre-test panel tests are conducted prior to drop test #A, then...
2. Drop Test #A, labeled E3A, is conducted at severity level 3 (weight of 100 g dropped from a height of 5.25 inches, per Table 5).
3. After Drop Test #A, post-test panel tests are performed on the damaged sample.
4. Post-test #A microscopy is declined.
5. Pre-test #B panel tests are executed.
6. Drop Test #B, labeled E3B, is carried out at severity level 4 (weight and drop height per Table 5).
7. After Drop Test #B, post-test panel tests are performed.

Post-test #B microscopy is elected, so the drop test sample is cut in half (into two half-cylinders), a slice is cut along the rectangular face of one of the half-cylinders, and this slice is examined under various microscopes.

Table 11. As-executed test matrix, solid Ecoflex 0030 samples.

Drop Test #	Sample ID	Degree of Vasc. (N/T/B/C)	Pre-Test #A Panel Tests: Y/N?	Drop Test #A Severity Level	Post-Test #A Panel Tests: Y/N?	Post-Test #A Microscopy: Y/N?	Drop Test #	Pre-Test #B Panel Tests: Y/N?	Drop Test #B Severity Level	Post-Test #B Panel Tests: Y/N?	Post-Test #B Microscopy: Y/N?
E1A	EcoFLX0030_001_N ONE	N	Y	1	Y	Y	---	n/a	n/a	n/a	n/a
E2A	EcoFLX0030_003_N ONE	N	Y	1	Y	N					
							E2B	Y	3	Y	Y
E3A	EcoFLX0030_006_N ONE	N	Y	3	Y	Y if post-test panel differs vs. pre-test	---	n/a	n/a	n/a	n/a
						N if post-test panel like pre-test	E3B	Y	4	Y	Y

N/T/B/C - None/Trunk/Branches/Canopy

Table 12. Severity levels for all drop tests.

Severity	Intended Damage Level
1	None
2	Moderate
3	Severe
4	Mythbusters severe

Prior to drop testing, we measured the sound speed in all samples in their virgin state. For solid Ecoflex 0030, we measured an average sound speed equal to 0.0401 in/microsec (1020 m/s) with a standard deviation of 1%, or 0.00028 in/microsecond (7 m/s). As a sanity check, we compared this value to published sound speed results for pure Ecoflex 0020 samples, shown as an average value of 0.0383 in/microsec (972.7 m/s) (Cafarelli et al., 2016). Notably, the nominal elastic modulus (at 100% strain) for Ecoflex 0020 is 8 psi (55.16 kPa) and is 10 psi (68.95 kPa) for Ecoflex 0030 (Smooth-On, Inc., Macungie, PA). Given that these two materials have similar densities and the compressive wave speed of a solid is proportional to (the square root of) the elastic modulus and inversely proportional to (the square root of) the density, per Equation (20) and Figure 33, then the sound speed for Ecoflex 0030 should be somewhat higher than for Ecoflex 0020.

Table 13. Comparison of Ecoflex 0030 sound speed against published sound speed values for a similar, but slightly softer, grade of Ecoflex.

	Ecoflex 0020	Ecoflex 0030
Measured compressive wave sound speed (m/s)	973±1	1020±7
Measured mass density (kg/m ³)	1063	1070
Nominal elastic modulus at 100% strain (psi)	8	10

8.1.1.2 Vascularized

The second series of drop tests involved the vascularized Ecoflex 0030 samples, which were a little more complicated to work with than the solid Ecoflex 0030 samples, but still far easier to handle as compared to biological tissue samples.

Table 14. As-executed test matrix, vascularized Ecoflex 0030 samples, part 1 of 2.

Drop Test #	Sample ID	Degree of Vasc. (N/T/B/C)	Pre-Test #A Panel Tests: Y/N?	Drop Test #A Severity Level	Post-Test #A Panel Tests: Y/N?	Post-Test #A Microscopy: Y/N?	Drop Test #	Pre-Test #B Panel Tests: Y/N?	Drop Test #B Severity Level	Post-Test #B Panel Tests: Y/N?	Post-Test #B Microscopy: Y/N?
EV1 A	EcoFLX0 030_010_VASC-C	C	Y	1	Y	Y	---	n/a	n/a	n/a	n/a
EV2 A	EcoFLX0 030_021_VASC-C	C	Y	1	Y	N					
							EV2B	Y	3	Y	Y
EV3 A	EcoFLX0 030_011_VASC-C	C	Y	4	Y	Y if post-test panel differs vs. pre-test	---	n/a	n/a	n/a	n/a
						N if post-test panel like pre-test	EV3B	Y	4	Y	Y
16C	EcoFLX0 030_016_VASC-C	C	Y	3	Y	Y	N/A	n/a	n/a	n/a	n/a
EV4 A	EcoFLX0 030_001_VASC-C	C	Y	4	Y	N	---	n/a	n/a	n/a	n/a
EV5 A	EcoFLX0 030_004_VASC-B	B	Y	1	Y	Y	EV5B	n/a	n/a	n/a	n/a
EV6 A	EcoFLX0 030_007_VASC-B	B	Y	1	Y	N	EV6B	Y	3	Y	Y
EV7 A	EcoFLX0 030_017_VASC-B	B	Y	4	Y	Y if post-test panel differs vs. pre-test	---	n/a	n/a	n/a	n/a
						N if post-test panel like pre-test	EV7B **	Y	4	Y	Y

N/T/B/C - None/Trunk/Branches/Canopy

**Go to severity level 4 single hit: if no damage seen in single hit severity level 4 test or in 1-2 punch test of similar sample type after hit with severity level 3

Table 15. As-executed test matrix, vascularized Ecoflex 0030 samples, part 2 of 2.

Drop Test #	Sample ID	Degree of Vasc. (N/T/B/C)	Pre-Test #A Panel Tests: Y/N?	Drop Test #A Severity Level	Post-Test #A Panel Tests: Y/N?	Post-Test #A Microscopy: Y/N?	Drop Test #	Pre-Test #B Panel Tests: Y/N?	Drop Test #B Severity Level	Post-Test #B Panel Tests: Y/N?	Post-Test #B Microscopy: Y/N?
9B	EcoFLX0030_009_VASC-B	B	N	4	N	N	N/A	n/a	n/a	n/a	n/a
14B	EcoFLX0030_014_VASC-B	B	N	4	N	N	N/A	n/a	n/a	n/a	n/a
EV8 A	EcoFLX0030_018_VASC-T	T	Y	1	Y	Y	EV8B	n/a	n/a	n/a	n/a
EV9 A	EcoFLX0030_013_VASC-T	T	Y	1	Y	N	EV9B	Y	4	Y	Y
EV10 A	EcoFLX0030_023_VASC-T	T	Y	4	Y	Y if post-test panel differs vs. pre-test	---	n/a	n/a	n/a	n/a
						N if post-test panel like pre-test	EV10 B**	Y	4	Y	Y

N/T/B/C - None/Trunk/Branches/Canopy

**Go to severity level 4 single hit: if no damage seen in single hit severity level 4 test or in 1-2 punch test of similar sample type after hit with severity level 3

8.1.2 *Melon*

8.1.2.1 *Common Dolphin*

The test matrix for our common dolphin (*Delphinus delphis*) melon samples is shown in Table 16.

Table 16. As-executed test matrix, common dolphin melon samples.

Drop Test #	Sample ID	Assumed Tissue Type (C,S,M)++	Pre-Test #A Panel Tests: Y/N?	Drop Test #A Severity Level	Post-Test #A Panel Tests: Y/N?	Post-Test #A Microscopy: Y/N?	Drop Test #	Pre-Test #B Panel Tests: Y/N?	Drop Test #B Severity Level	Post-Test #B Panel Tests: Y/N?	Post-Test #B Microscopy: Y/N?
MD1 A	Ddel_007_POST_ME_L	C/M (Ventral)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MD1 B	Y	3	Y	Y
MD2 A	Ddel_005_MID_ME_L	M (Ventral)	Y	3	Y	Y	---	n/a	n/a	n/a	n/a
MD3 A	Ddel_002_ANT_ME_L	C/M (Ventral)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MD3 B	Y	3	Y	Y
MD4 A	Ddel_001_ANT_ME_L	S (Dorsal)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MD4 B	Y	2	Y	Y
MD5 A	Ddel_003_MID_ME_L	S/M (Dorsal)	Y	2	Y	N					
							MD5 B	Y	3	Y	Y
MD6 A	Ddel_006_POST_ME_L	S/M (Dorsal)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MD6 B	Y	3	Y	Y
MD7 A	Ddel_004_MID_ME_L	C (Middle)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MD7 B	Y	3	Y	Y

++C=Core, S=Shell, M=Mixed, C/M=Mixed, mostly core, S/M=Mixed, mostly shell

8.1.2.2 Harbor Porpoise

The final drop test series featured the harbor porpoise (*Phocoena phocoena*) melon samples. Since the harbor porpoise melon was so much smaller than the common dolphin melon, we had far fewer samples from this species, and thus even less margin for error for these than for the common dolphin samples. The executed test matrix is depicted in Table 17. Note that for sample ID Pphoc_001_ANT_MEL, microscopy was not conducted and a second drop test was not conducted.

Table 17. As-executed test matrix, harbor porpoise melon samples.

Drop Test #	Sample ID	Assumed Tissue Type (C,S,M)++	Pre-Test #A Panel Tests: Y/N?	Drop Test #A Severity Level	Post-Test #A Panel Tests: Y/N?	Post-Test #A Microscopy: Y/N?	Drop Test #	Pre-Test #B Panel Tests: Y/N?	Drop Test #B Severity Level	Post-Test #B Panel Tests: Y/N?	Post-Test #B Microscopy: Y/N?
MP1 A	Pphoc_003_MID_MEL	C/M (Ventral)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MP1 B	Y	3	Y	Y
MP2 A	Pphoc_002_MID_MEL	S/M (Dorsal)	Y	2	Y	Y	---	n/a	n/a	n/a	n/a
MP3 A	Pphoc_001_ANT_MEL	C/M (Ventral)	Y	1	Y	N	---	n/a	n/a	n/a	n/a
							MP3 B	Y	3	Y	Y

++C=Core, S=Shell, M=Mixed, C/M=Mixed, mostly core, S/M=Mixed, mostly shell

8.2 DATA FROM DROP TEST SENSORS

This section includes tables with key information obtained from post-processing of raw data collected from the drop tower sensors. While several seconds of data were recorded for both the impactor force sensor and the drop tower table flush-mounted pressure sensor, it is useful to narrow the window of investigation to the ~0.5 seconds of time that includes the initial impact/contact event.

Figure 39 includes the force time history for the first drop test conducted with a melon specimen, MD1A. The force data has been shifted to zero (using an offset equal to the average of the first 1000 data points), and slightly smoothed using a moving average scheme over a very small time window. (Note that the ‘smoothdata’ function was used in MATLAB 2018a, with a smoothing factor of 0.005 for data signals that were typically 8-10 seconds long and sampled every 5 microseconds, corresponding to a sampling frequency of 200,000 samples/second). The contact window is established by finding the window of data that meets the criteria of exceeding an initial threshold value and falling below a final threshold value. The initial time is defined as the first time at which the measured data exceeds a given threshold, generally specified as the maximum of the 75% (melon) and the 95% (Ecoflex) confidence interval. The final time is taken as the first time after the initial data peak at which the measured data falls below the 50% (melon) confidence interval maximum value or 0% (Ecoflex) confidence interval maximum value, i.e. mean of the data set.

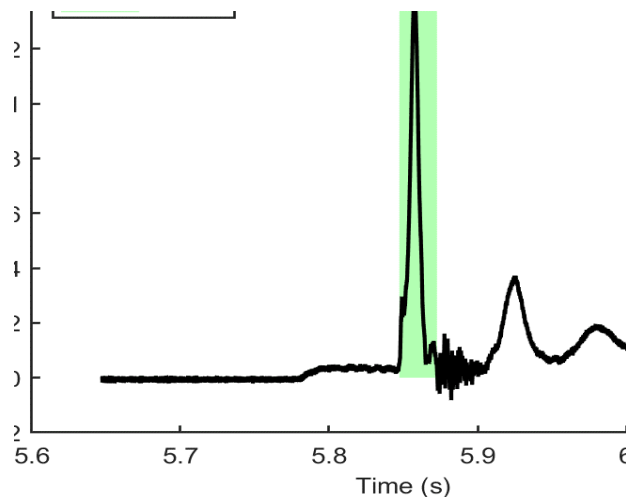


Figure 39. Force time history for drop test MD1A, with contact time window marked.

The equations and calculations in this section are derived from Money (1988) and ASTM D7136/D7136M-15. Major assumptions in this derivation are the following:

1. Frictionless contact between the impactor plate and the guide rails (zero energy dissipation).
2. Rigid body kinematics for the load carriage assembly (zero compliance in this system, which is an important assumption for displacement equations).

The impactor velocity, displacement, and energy can be derived from the force data per a well-known series of equations used for drop weight impact analysis. The equation of motion in the direction of travel of the impactor (positive downwards) is as follows:

$$m_{impactor}g - F(t) = m_{impactor} \frac{dv(t)}{dt}. \quad (27)$$

where $F(t)$ is the force measured by the force sensor and the product $(m_{impactor}g)$ is the weight of the impactor, acting on the sample (g is the gravitational constant and $m_{impactor}$ is the mass of the impactor). Here, $v(t)$ is the velocity of the impactor at any time, t . Rearranging terms and integrating over the time duration of the impact/contact event yields the equation for the velocity of the impactor per this equation:

$$v(t) = v_i + g(t - t_i) - \frac{1}{m_{impactor}} \int_{t_i}^{t_f} F(t)dt, \quad t_i < t < t_f. \quad (28)$$

Here, v_i is the impact velocity defined by $v_i = \sqrt{2gh}$ per Equation (19 and the time limits on the integration are the initial time of contact initiation, t_i , and the final time of the contact event, t_f . Since $\frac{dx(t)}{dt} = v(t)$, the impactor velocity equation can be integrated over the contact duration to obtain the impactor displacement at any time, t :

$$x(t) = v_i(t - t_i) + \frac{g(t - t_i)^2}{2} - \frac{1}{m_{impactor}} \int_{t_i}^{t_f} \int_{t_i}^{t_f} F(t)dt, \quad t_i < t < t_f. \quad (29)$$

The energy of the impactor $E_{impactor}$ can be derived starting with typical work-energy principles, or:

$$dE_{impactor}(t) = F(t)dx(t) = F(t) \frac{dx(t)}{dt} = F(t)v(t)dt. \quad (30)$$

Integrating this equation over the contact event gives the following:

$$E_{impactor}(t) = v_i \int_{t_i}^{t_f} F(t)dt + g \int_{t_i}^{t_f} tF(t)dt - \frac{1}{2m_{impactor}} \left(\int_{t_i}^{t_f} F(t)dt \right)^2. \quad (31)$$

The energy imparted by a drop (Figure 42) is simply the sum of the impactor energy with the initial potential energy from the impactor mass dropping over a known height, h , or:

$$E_{imparted}(t) = E_{impactor}(t) + m_{impactor}gh. \quad (32)$$

Theoretically, the energy absorbed by a sample should equal the calculated energy imparted, if all the listed assumptions for an ideal drop test are met. However, significant bending of the impactor crosshead (Figure 17) was observed in the drop test experiments, and so it is likely that the calculated energy imparted is equal to the energy absorbed by the sample and

(unmeasured, and unaccounted for) bending energy in the impactor crosshead, i.e.
 $E_{imparted}(t) > E_{absorbed}(t)$.

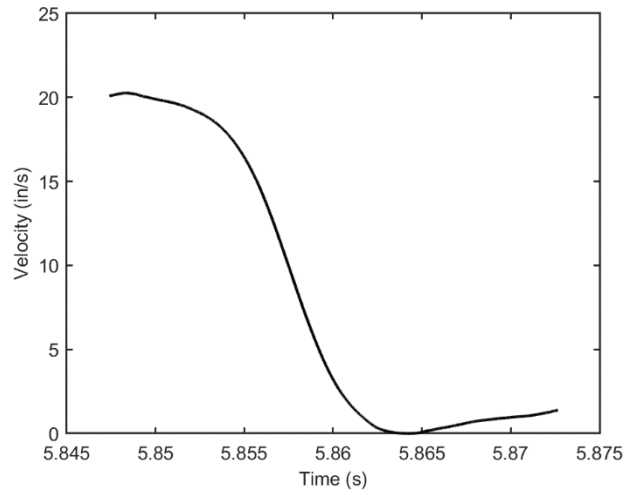


Figure 40. Velocity time history (from force data) for test MD1A during initial contact.

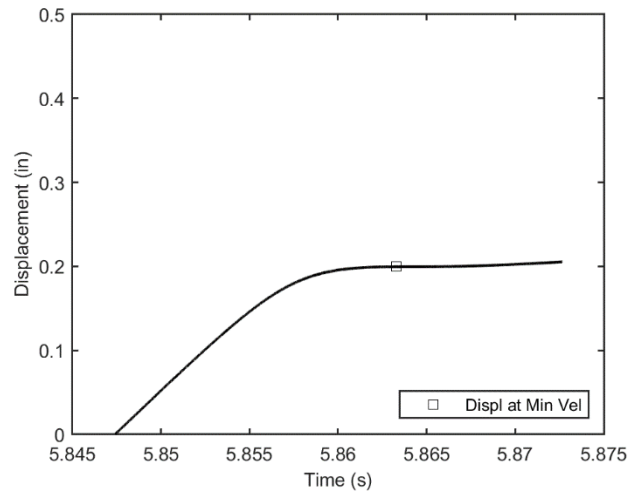


Figure 41. Displacement time history (from force data) for test MD1A during initial contact.

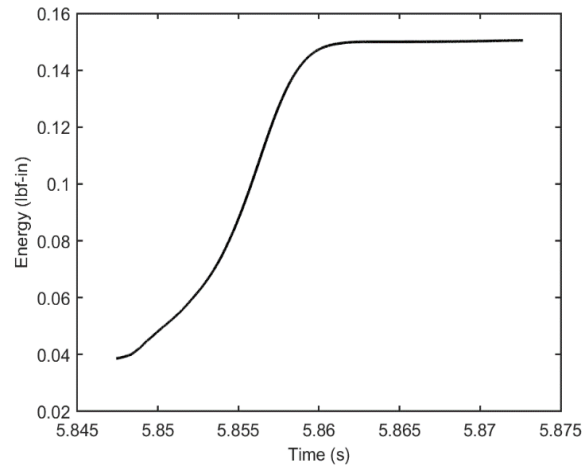


Figure 42. Energy imparted by drop (from force data) for test MD1A during initial contact.

Figure 43 depicts the pressure data that corresponds to the force data in Figure 39, for test MD1A. Similar to the force data, the pressure data has been shifted to zero (using an offset equal to the average of the first 1000 data points), and slightly smoothed with the same algorithm and smoothing parameter as the force time history. The contact duration is taken to be the same as for the force data, since the DAQ synchronized the timing for both sensors.

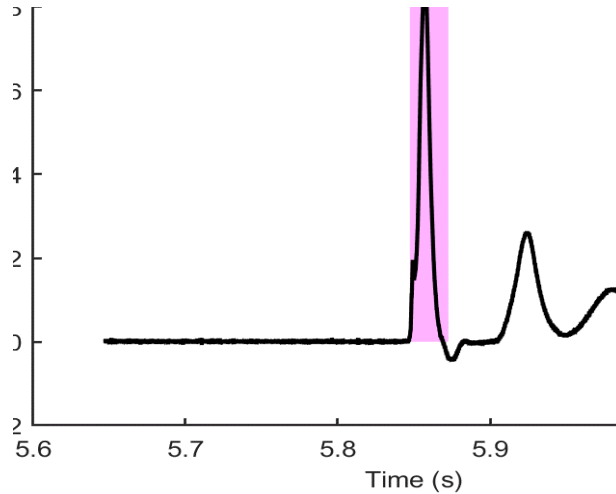


Figure 43. Pressure data for test MD1A, with contact time window marked.

The pressure data $P(t)$ is integrated over the contact duration to obtain the impulse time history $I(t)$, per the below:

$$I(t) = \int_{t_i}^{t_f} P(t) dt . \quad (33)$$

Figure 68 shows the impulse time history as calculated from the pressure data shown in Figure 43.

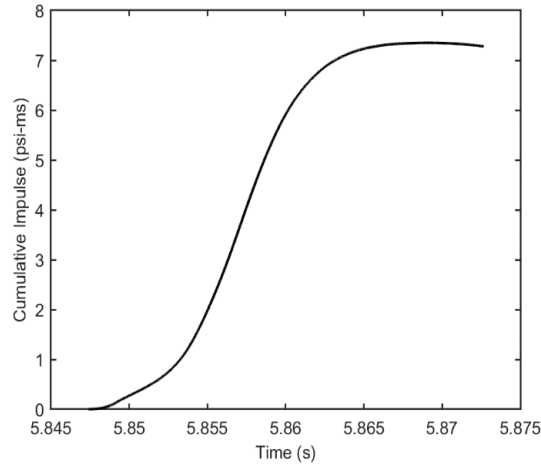


Figure 44. Impulse time history (from pressure data) for test MD1A during initial contact.

Table 20 summarize the key values obtained from post-processing of the drop test sensor data. Note that the reported maximum pressure is for the data prior to smoothing, as any smoothing would adjust the peak value. Due to small irregularities in sample surface flatness/smoothness and constraints on the precision of our distance measurements, the drop heights in the calculations needed to be adjusted slightly in most cases to ensure that the minimum velocity was indeed zero. Drop test MP2A was notable in that the drop height adjustment was 0.27-in (0.69 cm), an 18% increase on the nominal drop height. This may account for the large difference between the measured max impulse (39.2 psi-ms) and the nominal (estimated) max impulse (17.7 psi-ms) for this test. Note that very small adjustments in drop heights have a large effect on the derived displacement of the impactor at minimum impactor velocity, due to the $v_i(t - t_i)$ term in the displacement equation, $d(t)$. Also note that the nominal impulse values for these drop heights were predicted using average material properties, from quasistatic testing. Thus, the rate-dependence of material mechanical response (for both melon and Ecoflex) and the spatial variation (for the melon samples) of material stiffness and density is not accounted for in the nominal max impulse values reported below.

Table 18. Key values obtained via post-processing of drop test sensor data, common dolphin melon tests.

Drop Test #	Severity Level	Nominal Max Impulse (psi-ms)	Actual Max Impulse (psi-ms)	Diff%, Max Impulse	Contact Duration (ms)	Max Press. (psi)	Displ. of Impactor at Min. Vel. (in.)	Drop Height Adjust. (in.)	Energy Imparted (in.-lbf)
MD1A	1	7.3	7.4	1%	25.4	0.9	0.20	0.05	0.15
MD1B	3	32.7	14.3	-56%	9.7	4.0	0.26	-0.08	1.58
MD2A	3	32.7	42.9	31%	10.6	11.8	0.33	-0.03	1.67
MD3A	1	7.3	12.9	77%	41.6	0.7	0.22	-0.02	0.09
MD3B	3	32.7	39.2	20%	9.2	13.6	0.29	-0.09	1.57
MD4A	1	7.3	8.6	17%	19.2	0.7	0.12	-0.02	0.08
MD4B	3	32.7	25.3	-23%	7.7	11.4	0.19	-0.13	1.52
MD5A	2	17.7	5.3	-70%	10.8	1.3	0.19	-0.08	0.48
MD5B	3	32.7	10.0	-70%	7.7	4.5	0.21	-0.25	1.43
MD6A	1	7.3	7.6	4%	35.6	0.8	0.17	-0.05	0.07
MD6B	3	32.7	16.4	-50%	10.0	5.9	0.31	-0.06	1.61
MD7A	1	7.3	6.3	-13%	24.2	0.7	0.17	0.01	0.12
MD7B	3	32.7	35.4	8%	8.3	10.0	0.22	-0.19	1.47

Table 19. Key values obtained via post-processing of drop test sensor data, harbor porpoise melon tests.

Drop Test #	Severity Level	Nominal Max Impulse (psi-ms)	Actual Max Impulse (psi-ms)	Diff%, Max Impulse	Contact Duration (ms)	Max Press. (psi)	Displ. of Impactor at Min. Vel. (in.)	Drop Height Adjust. (in.)	Energy Imparted (in.-lbf)
MP1A	1	7.3	6.8	-7%	41.3	0.5	0.29	-0.001	0.12
MP1B	3	32.7	18.3	-44%	11.4	4.6	0.37	-0.04	1.66
MP2A	2	17.7	39.2	121%	9.2	13.6	0.25	0.27	0.90
MP3A	1	7.3	5.1	-31%	35.0	0.3	0.15	-0.01	0.09
MP3B	3	32.7	10.7	-67%	9.2	3.3	0.27	-0.03	1.66

Table 20. Key values obtained via post-processing of drop test sensor data, solid Ecoflex 0030 tests.

Drop Test #	Severity Level	Nominal Max Impulse (psi-ms)	Actual Max Impulse (psi-ms)	Diff%, Max Impulse	Contact Duration (ms)	Max Press. (psi)	Displ. of Impactor at Min. Vel. (in.)	Drop Height Adjust. (in.)	Energy Imparted (in.-lbf)
E1A	1	7.3	8.4	15%	17.9	1.1	0.17	0.03	0.13
E2A	1	7.3	6.0	-18%	15.1	0.9	0.16	0.07	0.15
E2B	3	32.7	29.2	-11%	10.7	5.4	0.37	0.08	2.71
E3A	1	7.3	25.7	-22%	11.4	7.3	0.38	0.08	2.70
E3B	4	115.0	68.2	-41%	20.0	7.0	0.67	0.03	8.58

For more detail on post-processing, the reader is referred to Appendix B.

8.3 DATA FROM PANEL TESTS

The tables below include the density data for all of the melon samples. The Ecoflex 0030 density data are not included because the changes in density were unremarkable and/or statistically insignificant for the majority of drop tests with this material. Note that a few density data points are not included, mostly for the earliest drop tests with the common dolphin samples. These were omitted due to suspected errors in data transcription and/or procedure (e.g. not filling the water exactly to the marked location in Figure 27).

Table 21. Measured density, common dolphin melon tests.

Drop Test #	Severity Level	Submerged Mass, Sample Only (g)	Wetted Mass (in Air), Sample Only (g)	Density (g/cc)	Submerged Mass, Sample Only (g)	Wetted Mass (in Air), Sample Only (g)	Density (g/cc)	Diff%, Density
MD1A	1	-1.399	12.067	0.89	-1.444	11.979	0.89	-0.4%
MD1B	3	-1.444	11.979	0.89	--	12.030	--	--
MD2A	3	0.477	9.135	1.05	--	9.144	--	--
MD3A	1	--	15.780	--	-0.175	15.497	0.98	--
MD3B	3	-0.175	15.497	0.98	-0.360	15.236	0.97	-1.2%
MD4A	1	-0.345	15.724	0.97	-0.505	15.399	0.96	-1.0%
MD4B	3	-0.505	15.399	0.96	--	15.215	--	--
MD5A	2	-0.851	12.427	0.93	-0.793	12.163	0.93	0.3%
MD5B	3	-0.793	12.163	0.93	-0.868	11.962	0.93	-0.7%
MD6A	1	-1.098	16.959	0.94	-1.215	16.730	0.93	-0.7%
MD6B	3	-1.215	16.730	0.93	-1.273	16.738	0.93	-0.3%
MD7A	1	-0.957	13.126	0.93	-1.079	12.967	0.92	-0.9%
MD7B	3	-1.079	12.967	0.92	-1.075	12.922	0.92	0.0%

Table 22. Measured density data, harbor porpoise melon tests.

Drop Test #	Severity Level	Submerged Mass, Sample Only (g)	Wetted Mass (in Air), Sample Only (g)	Density (g/cc)	Submerged Mass, Sample Only (g)	Wetted Mass (in Air), Sample Only (g)	Density (g/cc)	Diff%, Density
MP1A	1	-0.858	15.483	0.94	-0.737	10.665	0.93	-1.3%
MP1B	3	-0.737	10.665	0.93	-0.675	10.681	0.94	0.6%
MP2A	2	0.698	19.973	1.03	0.708	19.818	1.03	0.1%
MP3A	1	-0.879	17.638	0.95	-0.812	17.628	0.95	0.4%
MP3B	3	-0.812	17.628	0.95	-0.792	17.480	0.95	0.1%

The melon density data do not appear to follow any trends of statistical significance. Our conclusion is that the sample densities did not change appreciably as a result of drop testing.

The tables below include the sound speed data for all of the melon samples. The Ecoflex 0030 sound speed data is not included because the changes in sound speed were unremarkable and/or statistically insignificant for the majority of drop tests with this material.

Table 23. Measured sound speed and associated thickness data, common dolphin melon tests.

Drop Test #	Hit #, for Sample	AVG, Pre-Test Thick. (in.)	AVG, Orig. Sound Speed (m/s)	STDERR, Orig. Sound Speed (% of AVG)	AVG, Post-test Sound Speed (m/s)	STDERR, Post-test Sound Speed (% of AVG)	Diff%, Sound Speed	Damage? (1=yes, 0=no)
MD1A	1	0.36	1736	2%	1465	2%	-16%	1
MD1B	2	0.34	1736	2%	1405	2%	-19%	1
MD2A	1	0.33	1719	1%	1211	7%	-30%	1
MD3A	1	0.48	1651	1%	1643	1%	-1%	0
MD3B	2	0.43	1651	1%	1499	7%	-9%	1
MD4A	1	0.46	1744	1%	1693	1%	-3%	0
MD4B	2	0.49	1744	1%	1507	4%	-14%	1
MD5A	1	0.38	1693	1%	1693	1%	0%	0
MD5B	2	0.43	1693	1%	1549	5%	-9%	1
MD6A	1	0.56	1676	1%	1355	2%	-19%	1
MD6B	2	0.53	1676	1%	1355	1%	-19%	1
MD7A	1	0.41	1685	1%	1549	1%	-8%	1
MD7B	2	0.43	1685	1%	1422	2%	-16%	1

Table 24. Measured sound speed and associated thickness data, harbor porpoise melon tests.

Drop Test #	Hit #, for Sample	AVG, Pre-Test Thick. (in.)	AVG, Orig. Sound Speed (m/s)	STDERR, Orig. Sound Speed (% of AVG)	AVG, Post-test Sound Speed (m/s)	STDERR, Post-test Sound Speed (% of AVG)	Diff%, Sound Speed	Damage? (1=yes, 0=no)
MP1A	1	0.36	1270	4%	982	1%	-23%	1
MP1B	2	0.34	1270	4%	1075	3%	-15%	1
MP2A	1	0.33	1947	2%	1431	9%	-27%	1
MP3A	1	0.48	1405	2%	1422	2%	1%	0
MP3B	2	0.43	1405	2%	1211	4%	-14%	1

Each data point in the table marked with ‘AVG’ is an average (mathematical mean) of three independent measurements, either thickness measurements (with digital calipers) or sound speed measurements (with the ultrasonic thickness tester). Data columns marked ‘STDERR’ represent standard error calculations derived from the raw data, expressed as a percentage of the average value of the respective population of measurements. Standard error, SE, is calculated according to the following equation:

$$SE = \frac{\sigma}{\sqrt{N}} = \frac{1}{\sqrt{N}} \cdot \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1}} \quad (34)$$

where N is the number of measurements (3 in this case), and $\bar{x}$ is the mean (average) value of that group of measurements. The standard error as a percentage of the mean (SE%) is

$$SE\% = \frac{SE}{\bar{x}} \cdot 100\% \quad (35)$$

Additionally, the column marked ‘Diff%’ is the difference between the post-test and original sound speed of a sample, expressed as a percentage of the original sample sound speed value, or

$$Diff\% = \frac{(\bar{c}_{orig} - \bar{c}_{post})}{\bar{c}_{orig}} \cdot 100\% \quad (36)$$

Here, $\bar{c}_{orig}$ is the original mean sound speed of a sample and $\bar{c}_{post}$ is the post-test mean sound speed of that sample. The last column of data for both Table 23 and Table 24 concerns a delineation between ‘Yes Damage’ and ‘No Damage’. Our criteria for damage was that damage was deemed to have occurred for cases where the sound speed reduction was greater than two times the maximum standard error of the original untested sample, i.e. –8%. Where to draw the line to delineate a positive vs. negative result is always a matter of debate; however, in this case, there are no data points resulting in a sound speed reduction between –3 and –8%, giving us confidence that a damage delineation value of –8% is defensible for this data set.

For some of the drop test series, we observed a significant reduction in sound speed after the initial or second drop test. Examples for select cases for all three types of materials are shown in Figure 45.

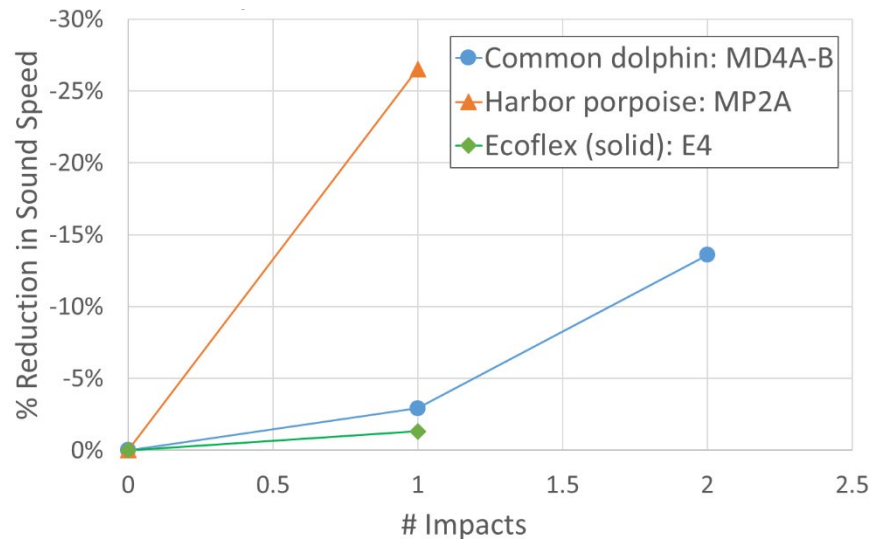


Figure 45. Examples of significant reduction in sound speed as a result of damaging impacts.

The reduction in sound speed was not always observed on the first drop vs. the second drop, as seen in Figure 46. Here, there are two data series, one marked as ‘Yes Damage’ and the other delineated ‘No Damage’, following the values in the last column of Table 23 and Table 24. When looking at Figure 46, it is important to note that our test matrices did not include any planned low-severity tests for the second drop test on a given sample, by design. Essentially, we assumed that a sample could be potentially compromised after a single drop. Since our goal was to obtain test data with as clear a story as possible, we did not attempt any low-severity hits with samples that had already been impacted once.

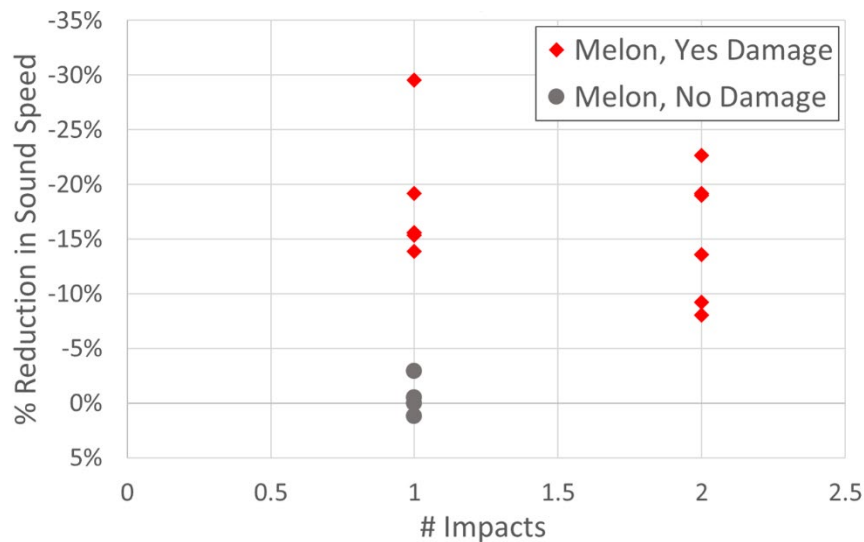


Figure 46. Examples of significant reduction in sound speed as a function of number of impacts.

8.4 VISUALIZATION OF SPATIAL VARIATION IN TISSUE PROPERTIES OF DROP TEST SAMPLES

The subsequent figures include schematic visualizations of the spatial variation in tissue type, measured density, and measured sound speed for the melon drop test samples. Note that these figures are not to scale, but rather are intended to show the variation across individual samples for observed and measured tissue properties. Given our drop test sample sizing constraints, which yielded cylindrical specimens 1.5-inch diameter and 0.5-inch height, our sampling scheme is extremely coarse across an entire melon specimen. However, the intent of our sampling scheme was to produce ideal drop test samples rather than to pinpoint the exact location of the core vs. shell tissue types in each melon specimen.

8.4.1 Spatial Variation in Tissue Properties, Harbor Porpoise

Figure 47 includes a schematic of the drop test samples as extracted from the harbor porpoise (*Phocoena phocoena*) melon specimen. Each individual drop test sample is represented by a pink rectangle with solid black borders. Figure 48 shows the same grid of samples as Figure 47 but here the samples are labeled with observed tissue types and we have marked the assumed boundary of the melon core with solid black lines. Anatomical directions are marked with parentheses, as in (D) for dorsal, (V) for ventral, (A) for anterior and (P) for posterior.

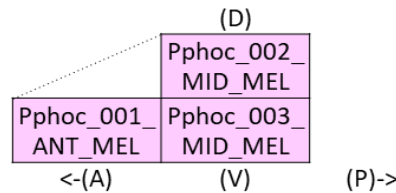


Figure 47. Visualization of spatial variation of drop test sample ID over a sagittal slice (not to scale), with individual drop test sample boundaries marked by solid lines, *Phocoena phocoena*.

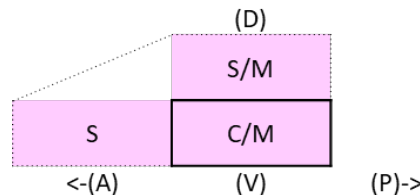


Figure 48. Visualization of spatial variation in observed tissue type over a sagittal slice (not to scale), with assumed core boundary marked by solid lines, *Phocoena phocoena*.

Figure 49 and Figure 50 show the spatial variation in measured density and sound speed across the three drop test samples taken from the harbor porpoise melon. These do exhibit the expected lower density and lower sound speed in the core as compared to surrounding shell and mixed tissue.

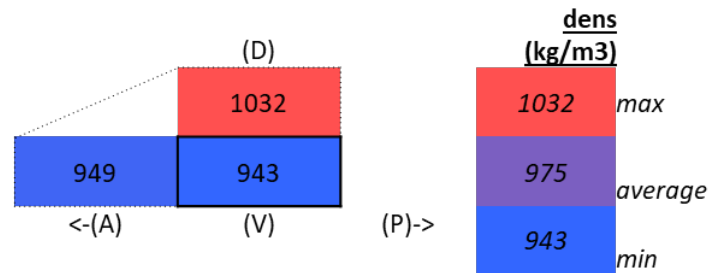


Figure 49. Visualization of spatial variation in measured density over a sagittal slice (not to scale), with assumed core boundary marked by solid lines, *Phocoena phocoena*.

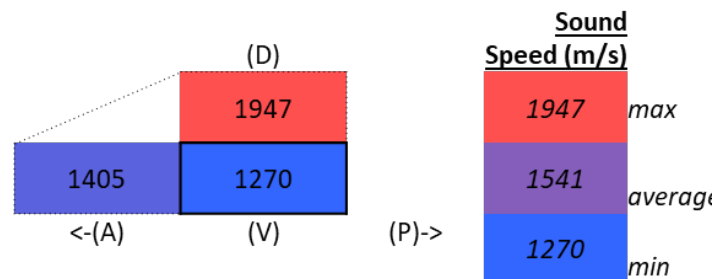


Figure 50. Visualization of spatial variation in measured sound speed over a sagittal slice (not to scale), with assumed core boundary marked by solid lines, *Phocoena phocoena*.

8.4.2 Spatial Variation in Tissue Properties, Common Dolphin

Figure 51 depicts a schematic of the drop test samples taken from the full common dolphin melon (*Delphinus delphis*) melon specimen. Here, each drop test sample is depicted by a pink rectangle with solid black borders. Anatomical directions are marked with parentheses, as in (D) for dorsal, (V) for ventral, (A) for anterior and (P) for posterior. Figure 50 shows the same grid of samples as Figure 51 but here the samples are labeled with observed tissue types and the assumed boundary of the melon core is marked with solid black lines.

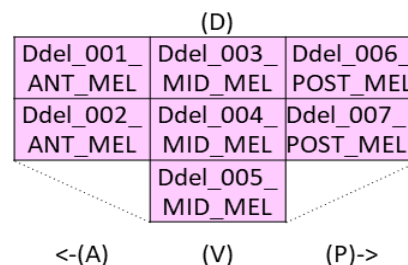


Figure 51. Visualization of spatial variation of drop test sample ID over a sagittal slice (not to scale), with individual drop test sample boundaries marked by solid lines, *Delphinus delphis*.

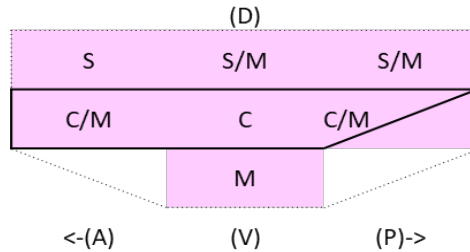


Figure 52. Visualization of spatial variation in observed tissue type over a sagittal slice (not to scale), with assumed core boundary marked by solid lines, *Delphinus delphis*.

Figure 53 and Figure 54 include the measured density and sound speed data for the common dolphin, respectively. In Figure 51, sample ID Ddel_007_POST_MEL is observed to be C/M, or Core/Mixed, tissue type but the melon core (solid line) is assumed to only pass through part of this sample. This particular drop test sample exhibited a very mixed composition, with low density and high sound speed, which leads us to believe that it has several different tissue types (including core) contained in its volume. Other than this sample, the other core samples exhibited the expected lower density and lower sound speed than shell and mixed/connective tissue samples.

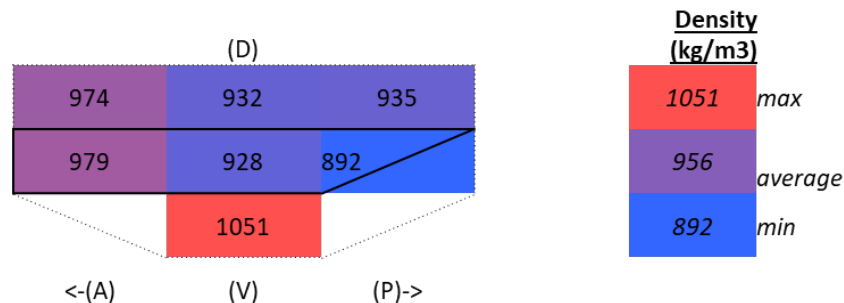


Figure 53. Visualization of spatial variation in drop test measured density over a sagittal slice (not to scale), with assumed core boundary marked by solid lines, *Delphinus delphis*.

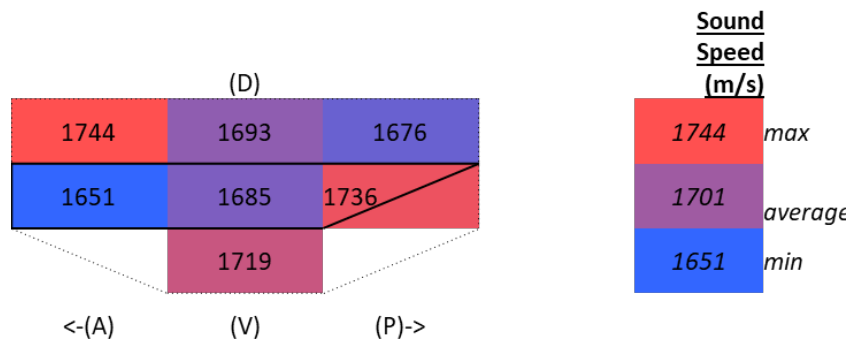


Figure 54. Visualization of spatial variation in drop test measured sound speed over a sagittal slice (not to scale), with assumed core boundary marked by solid lines, *Delphinus delphis*.

8.5 CROSS-COMPARISON BETWEEN PANEL TEST MEASUREMENTS AND POST-PROCESSED DROP TEST SENSOR DATA

We cross-referenced imparted impulse with post-drop-test measurements of specimen sound speed per the workflow in Figure 55. Note that melon samples from both species demonstrated the full range of intended imparted impulse and exhibited a reduction in sound speed for select cases.

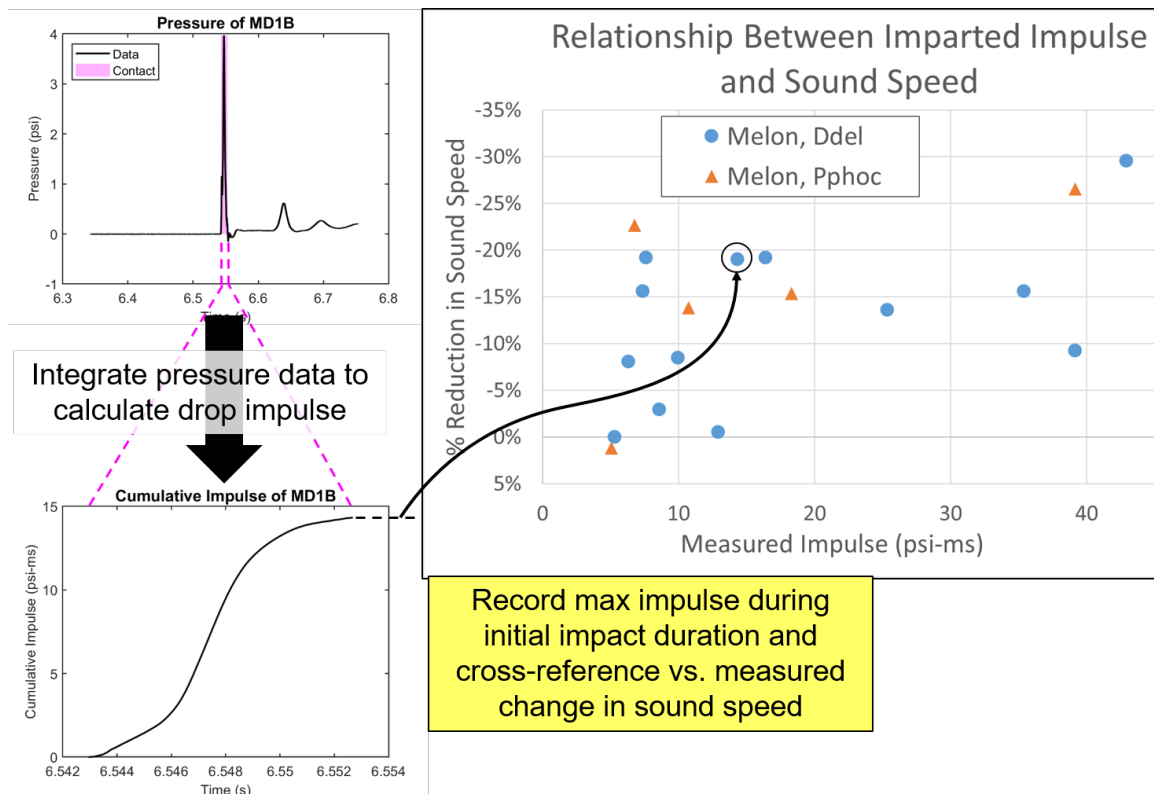


Figure 55. Workflow to post-process measured pressure data to obtain maximum impulse values during impact and cross-plot peak values against recorded reduction in sound speed.

We cross-plotted peak (maximum) pressure with maximum measured impulse for all of our cases, as seen in Figure 56. The data fall in a roughly linearly proportional band since the load type is the same for all cases (drop weight impact with a flat impactor). This means that the peak pressure and peak impulse pairs scale in proportion to input drop energy (drop height and mass). Most importantly, Figure 56 indicates that the drop tests successfully imparted impulse levels to the melon samples in the intended range-to-effect range of 7.3 to 32.7 psi-ms (Table 1 and Table 5), though the drop tests tended to be slightly more severe than intended. Note that in the figure, the data are cross-referenced against assumed tissue type for that individual drop test sample. The data in the figure show a trend towards higher peak pressures seen for similar impulse levels in the drop test samples comprised of shell tissue as compared to core tissue. The dichotomy in material behavior, i.e. between the way that shell and core tissue transmit impact-driven compressive stress waves, is clearly evident in this plot.

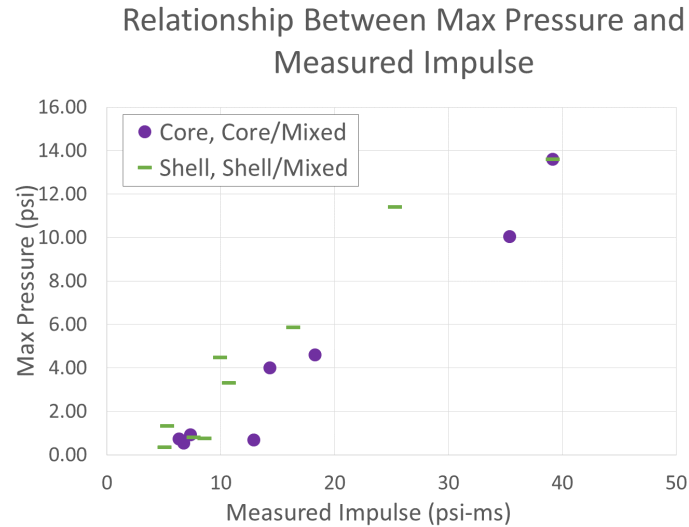


Figure 56. Relationship between maximum pressure and maximum measured impulse imparted to the drop test sample, cross-referenced against tissue type.

Figure 57 is a replot of Figure 56, but with the data delineated by assumed damage status rather than tissue type. Sound speed data and damage status are per Table 23 and Table 24, and the cutoff for damage is a sound speed data reduction of 8% in magnitude.

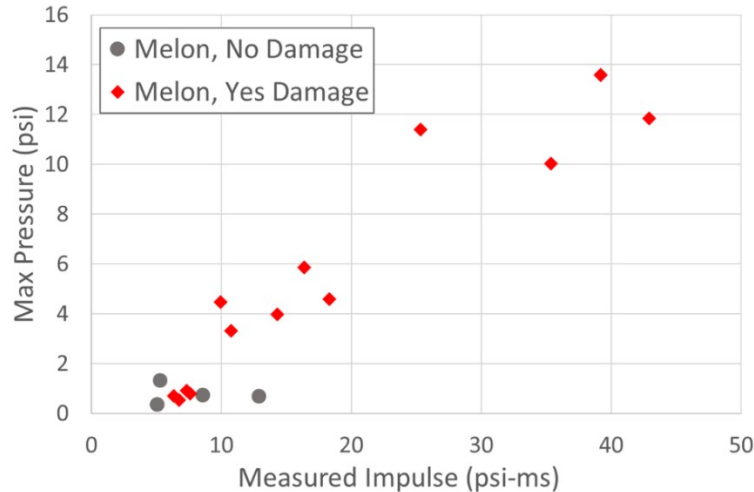


Figure 57. Relationship between maximum pressure and maximum measured impulse imparted to the drop test sample, cross-referenced against damage status.

As previously discussed, in a series of UNDEX tests with instrumented harbor porpoises of similar mass, Ketten 2004 reported that moderate damage occurred to the melon at 200 psi (peak impulse of 17.7 psi-ms, (Rye, 3 April 2019 and 13 September 2019)) and severe damage was seen in the melon at 300 psi (peak impulse of 32.7 psi-ms (Rye, 3 April 2019 and 13 September 2019)). Additionally, no damage was seen in the same UNDEX vs. harbor porpoise

cadaver (25-29 kg mass) series for the same size and depth of charge, but larger standoff, where the peak pressure was nominally 100 psi and peak positive-phase impulse was 7.3 psi (Rye, 3 April 2019 and 13 September 2019).

Figure 58 depicts the reduction of sound speed as a function of impulse calculated from the pressure data measured at the bottom face of the sample. The plot shows that tests resulting in very small changes in sample sound speed (denoted ‘No Damage’ cases) are associated with small values of measured impulse.

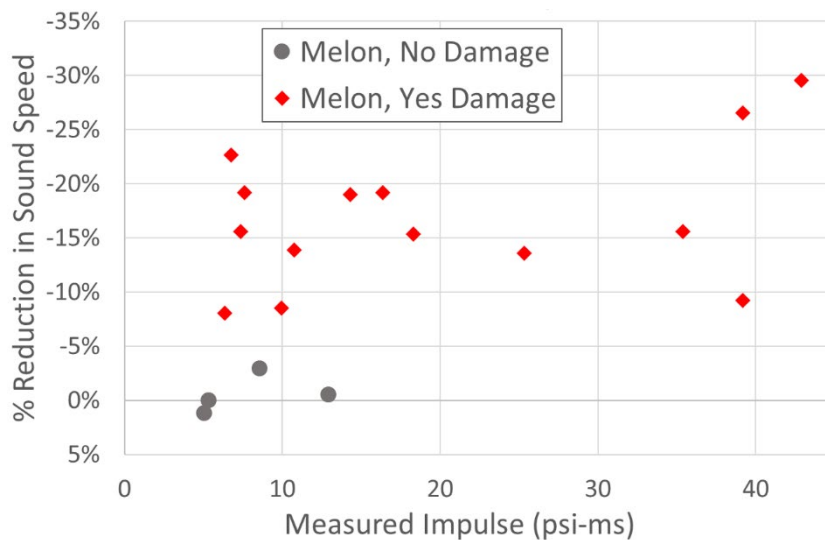


Figure 58. Relationship between sound speed reduction and maximum impulse imparted to the specimen.

In Figure 59, the observed reductions in sound speed are plotted against the energy imparted in each drop test, calculated from the force data recorded by the sensor attached to the impactor plate in the drop test tower. The abscissa data are less scattered for Figure 59 as compared to Figure 58, which makes sense given that the impulse measurement involves the compressive wave propagation through the sample and pressure measurement at the flush-mounted pressure sensor on the drop tower table, in addition to the energy imparted to the sample. Figure 59 includes vertical error bar depictions on the sound speed data that are associated with the standard error values included in Table 23 and Table 24. Note that the zero and slightly positive (+1%) data points for reduction in sound speed, Tests MD5A and MP3A respectively, are acceptable after adding in the context of the error bars to this figure.

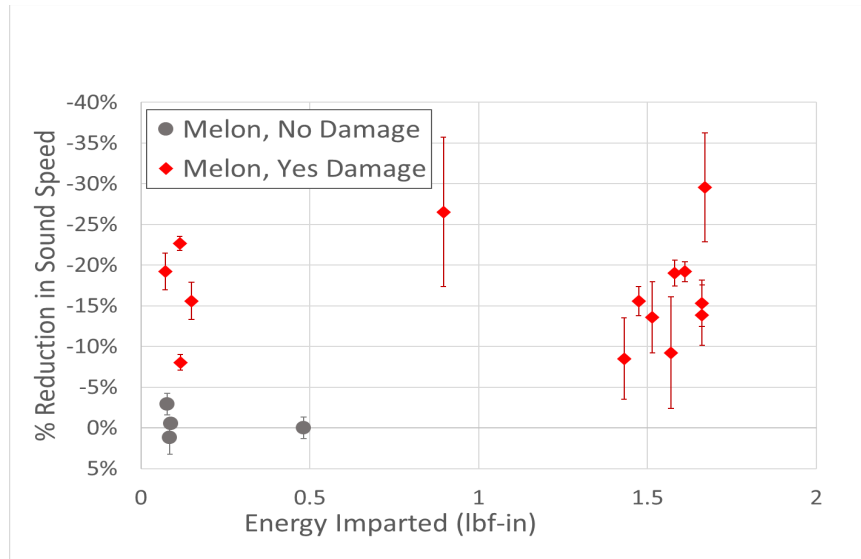


Figure 59. Relationship between sound speed reduction and energy imparted during impact, with error bars.

Figure 60 is a replot of Figure 59, but with the data series marker shapes separated by tissue type (shell vs. core).

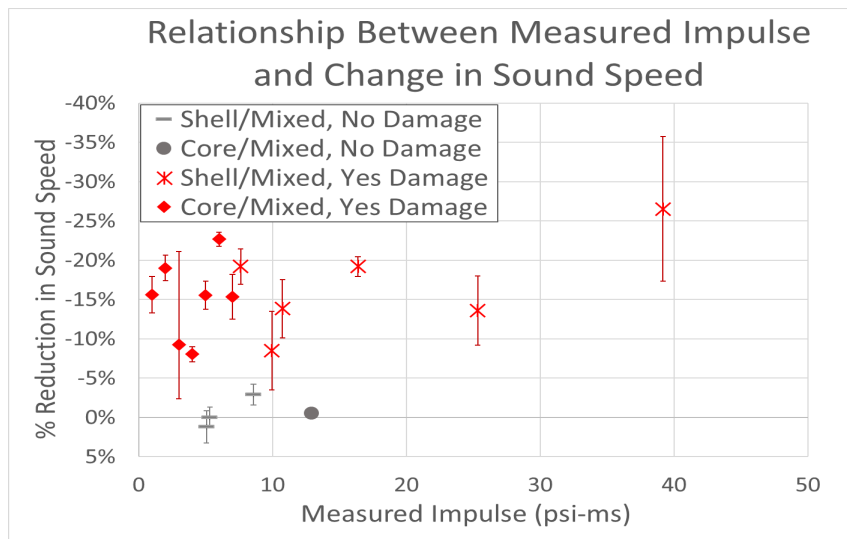


Figure 60. Relationship between sound speed reduction and maximum impulse imparted to the specimen during impact, with error bars.

8.6 PRELIMINARY DIGITAL IMAGE CORRELATION (DIC) RESULTS

To date, we have only conducted preliminary digital image correlation analyses. Our focus for these was to obtain out-of-plane (OOP) displacement, which is the hallmark result from stereo (3D) DIC camera setups. The following series of figures depict an overlay of DIC results for OOP at key snapshots in time: during the initial downswing of the impactor plate (Figure 61), at maximal compression of the sample (Figure 62), and during the initial upswing of the impactor plate (Figure 63). Displacement values are colored by contour, with the colorscale range set from -0.2 to 1.2 mm (-0.08 to 0.47 in.).

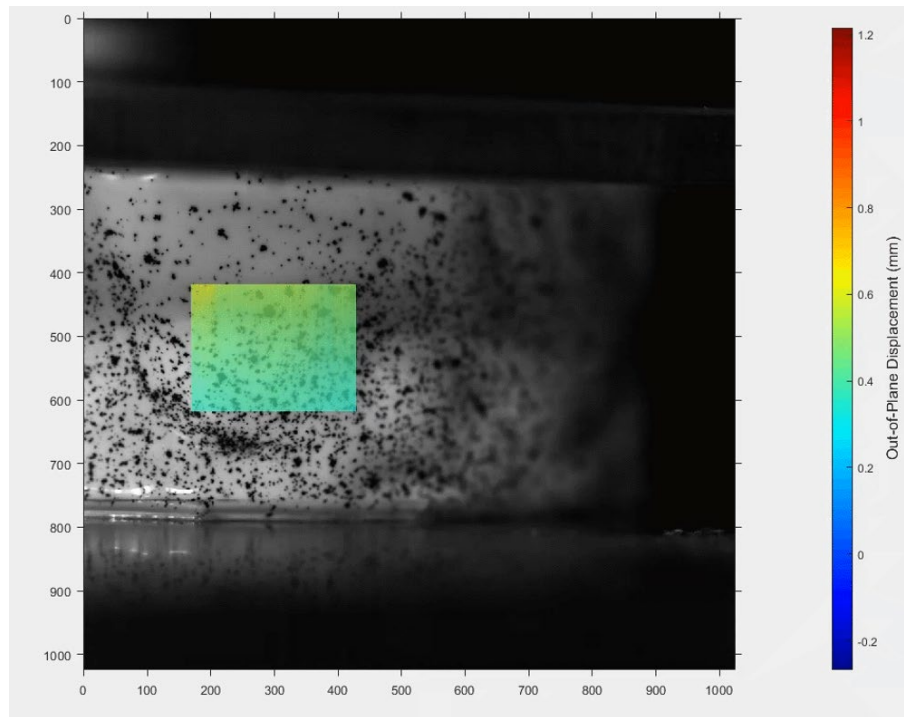


Figure 61. Preliminary DIC result for Ecoflex 0030 - OOP displacement, time snapshot during the initial downswing of the impactor plate.

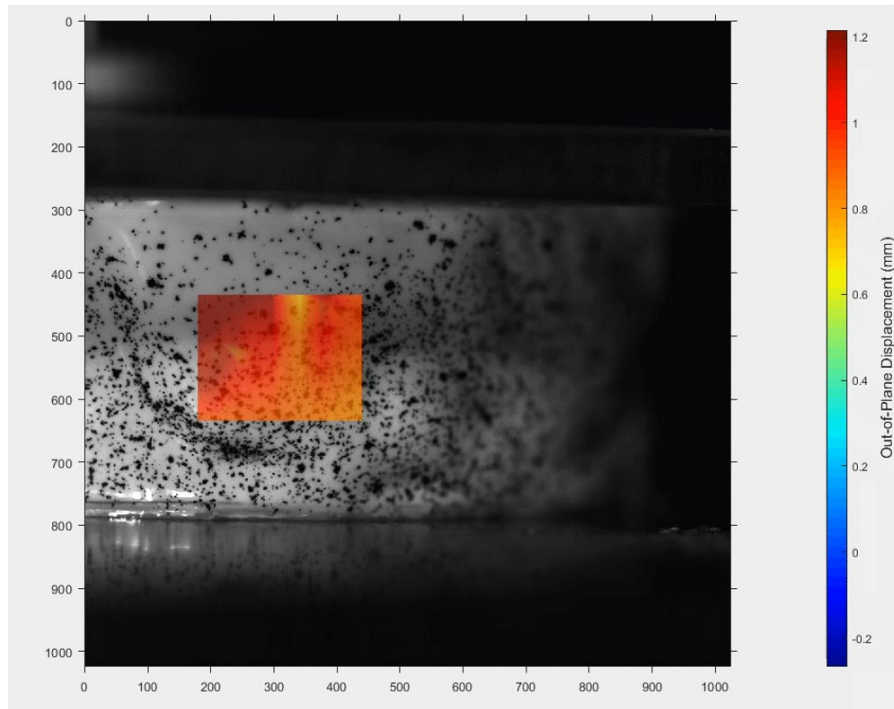


Figure 62. Preliminary DIC result for Ecoflex 0030 - OOP displacement, time snapshot at maximal sample compression.

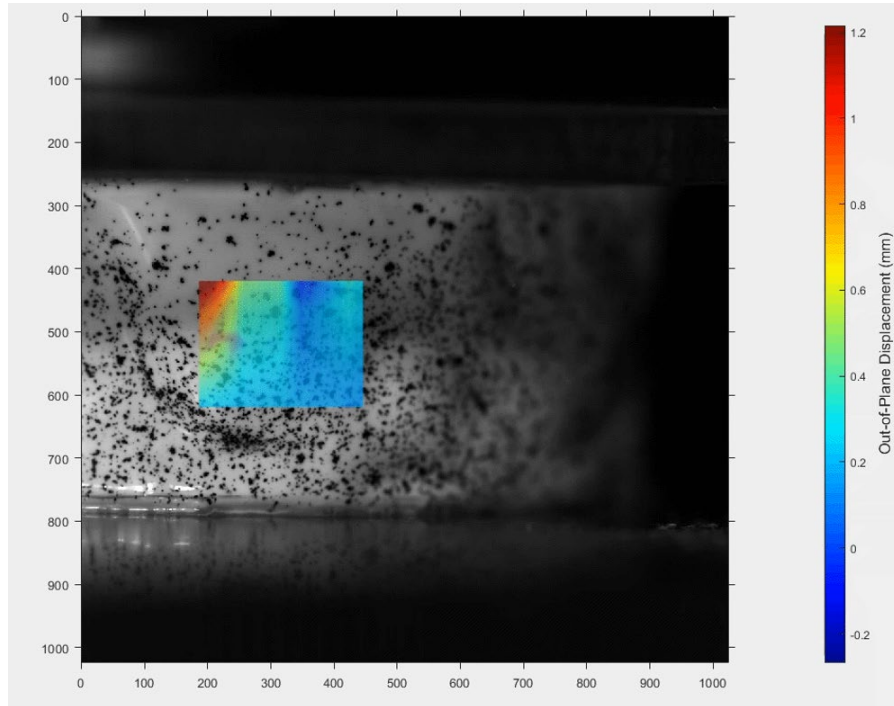


Figure 63. Preliminary DIC result for Ecoflex 0030 - OOP displacement, time snapshot during the initial upswing of the impactor plate.

9. CONCLUSIONS AND FUTURE WORK

Modeling is a proactive solution to evaluate UNDEX and current non-auditory marine mammal injury and mortality criteria (protection and mitigation). Given the inability to ethically and legally conduct UNDEX experiments on live marine mammals, it is prudent to pursue FE models instead, to simulate melon response to various UNDEX threats. However, FE model results should not be used to make any conclusions about potential damage from a given loading unless the FE model has been verified or validated against a known benchmark or experimental data set.

The drop testing experiments described herein have been designed to produce validation data for marine mammal melon samples subjected to a substitute shock-like event in a controlled laboratory environment. Data collected from the drop tower sensors can be used to fully characterize the loading imparted to a specimen (impulse imparted and displacement, velocity, and energy of the impactor) during these experiments. Also, 3D DIC measurements characterize the in-plane displacement and strains and out-of-plane displacement response.

Beyond gathering data on the mechanical response of the melon samples to drop weight impact, we developed a novel screening method for identifying potential damage in the melon samples. By taking sound speed measurements (with a handheld thickness tester, acoustic transducer, and digital calipers) before and after the drop weight impact tests, we observed that measurable changes in specimen sound speed correlated with high levels of imparted impulse. We plan to pursue this technique further, in case it is beneficial and practical to recommend inclusion of the method (and associated handheld equipment) for necropsy protocols.

Future work will focus on revising pre-test FE models of drop tests and comparing post-test simulated results with experimental data from the drop tests. It is our intent that further development of material models of melon tissue and FE models of entire melon organs will lead to scientifically defensible simulations of dynamic response of melon FE models to various UNDEX threats, for various species of Odontocetes.

APPENDIX A — SUPPLEMENTARY MATERIAL FOR STATISTICAL ANALYSIS

A.1 GENERATING SYNTHETIC UNIAXIAL COMPRESSIVE TEST DATA TO REPRESENT IDEALIZED SOFT AND STIFF CUVIER'S BEAKED WHALE MELON MATERIALS

We used the linear regression results for idealized soft and stiff Cuvier's beaked whale melon to create synthetic uniaxial compressive test data over the range of stresses tested by Soldevilla et al. (2004). To do this, first note that the tangent to a curve is the limit of its slope at a point over a vanishingly small increment, where the limits of the increment are symmetric about that point, i.e. the point is at the midpoint between the limits. Thus, when converting modulus as a function of stress to an appropriate stress-strain curve (to create the synthetic uniaxial compressive stress-strain data), it is necessary to use an incremental equation where the increments are appropriately sized. The incremental equation is used to calculate strain, ε , at a given stress, σ , knowing that the modulus, E , is assumed to be of a linear form that varies with σ , i.e. $E(\sigma)$. The relationship between modulus and stress can be written as follows:

$$E(\sigma) = E_0 + \sigma \cdot \frac{dE}{d\sigma} \quad (37)$$

Where E_0 is the fitted intercept from Table 2 and $\frac{dE}{d\sigma}$ is the fitted slope from the same table. The increment in strain, $\Delta\varepsilon_n$, corresponding to the increment in uniaxial compressive stress state between the $(n-1/2)^{\text{th}}$ to $(n+1/2)^{\text{th}}$ stress state is as follows:

$$\Delta\varepsilon_n = \Delta\varepsilon(\sigma_n) = \varepsilon(\sigma_{n+1/2}) - \varepsilon(\sigma_{n-1/2}) \quad (38)$$

We use a midpoint difference approximation, i.e. from $(n-1/2)^{\text{th}}$ to $(n+1/2)^{\text{th}}$ states, rather than a forward or backward difference approximation, to maximize numerical accuracy. For a case where the modulus varies linearly with stress, the increment in strain at the n^{th} stress state is

$$\Delta\varepsilon_n \approx \frac{\sigma_{n+1/2} - \sigma_{n-1/2}}{E(\sigma_n)} \quad (39)$$

Combining these equations, we obtain the strain ε_n at the n^{th} stress state, σ_n , as

$$\varepsilon_n = \varepsilon(\sigma_n) \approx \frac{\sigma_{n+1/2} - \sigma_{n-1/2}}{E_0 + \sigma_n \cdot \frac{dE}{d\sigma}} \quad (40)$$

Here, E_0 is the fitted intercept from Table 2, $\frac{dE}{d\sigma}$ is the fitted slope from the same table, σ_n is the current stress under consideration, and $\sigma_{n+1/2}$ and $\sigma_{n-1/2}$ are the values of stress at the extrema of a very small increment in stress, $\Delta\sigma_n$, that is symmetric about σ_n , i.e.

$$\Delta\sigma_n = \sigma_{n+1/2} - \sigma_{n-1/2} \cdot \quad (41)$$

In order to generate synthetic data that is representative of the material fit to the linear relationship between modulus and stress, it is important to select a stress increment that is small enough to avoid introducing any kind of discretization error. Figure 64 includes multiple sets of synthetic data produced using different $\Delta\sigma$ values. As $\Delta\sigma \rightarrow 0$, the results converge to a single curve, as one would expect from the definition of a tangent as the limit of the slope at a point as $\Delta\sigma \rightarrow 0$. We found that a constant stress increment of $\Delta\sigma = 0.5$ kPa produces synthetic stress-strain data that represents a good balance between the amount (size) of the synthetic data produced and the accuracy of that data set's representation of the assumed linear relationship between modulus and stress.

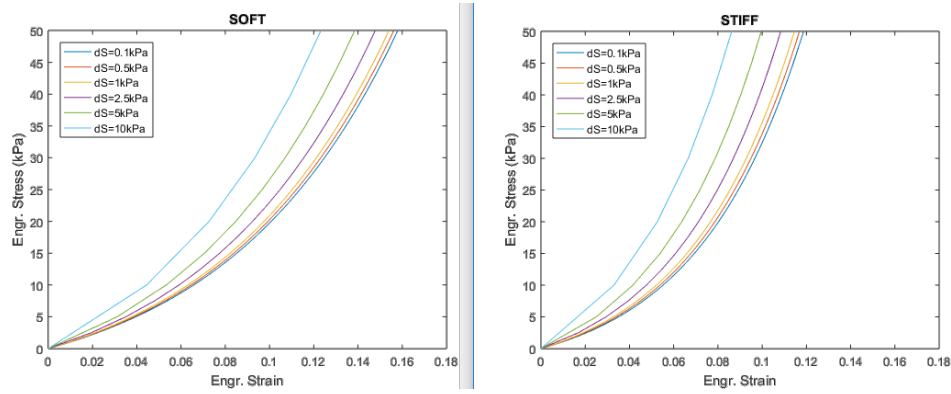


Figure 64. Results of convergence study to determine appropriately small stress increment to create synthetic uniaxial compressive data from fitted intercept and slope values

APPENDIX B — SUPPLEMENTARY MATERIAL RELATED TO DROP TOWER SENSOR DATA AND POST-PROCESSING

This appendix includes details of post-processing of data collected for all drop tests from the drop tower force and pressure sensors. Also included are all force and impulse plots.

B.1 MATLAB ANALYSIS CODE TO POST-PROCESS DATA FROM DROP TOWER FORCE AND PRESSURE SENSORS FOR A SINGLE DROP TEST

The below code allows the user to plot data from the force and pressure sensors from the drop tower. Additionally it finds the contact duration for a given drop test by finding the first time at which the force data exceeds a specified threshold value, then the first time after this when the force data falls below threshold. The code calculates cumulative impulse during the contact duration by integrating the pressure data only during this interval. The code calculates impactor velocity during the contact duration by integrating the force data only during this interval and setting the sum of forces equal to the product of impactor mass and acceleration. Finally, the code graphically depicts the smoothed pressure, cumulative impulse, smoothed force, and impactor velocity plots, and saves these in document-friendly and PowerPoint-friendly formats.

```
function main_postproc_sensorsdata_force_adjusth_tcontact()
%% Main function to post-process drop test sensor data
% Date: 18mar21
% Author: C. Eno
% Rev: E. Guzas

%% Main script

% Variables for data smoothing
smooth_p=0.005; % [0-1] smoothing factor to apply to raw pressure data
smooth_f=0.005; % [0-1] smoothing factor to apply to raw force data
t_pre = 0.2; % sec: duration of time to plot prior to contact
t_post = 0.2; % sec: duration of time to plot after to contact

% Drop test names and filenames
...Melon - dDel
Drop_Test='MD1A';
filename='pressure-force-sensor-
data/melon/MD1A_20200807_105509.dmd_export_20200807_105620.mat';
severity = 1;
makeplots(Drop_Test,filename,smooth_p,smooth_f,t_pre,t_post,severity);

%...other blocks for each melon data set

% ...Ecoflex - solid
Drop_Test='E1A'; % very tricky data
filename='pressure-force-sensor-data/ecoflex-
solid/E1A_20200804_104317.dmd_export_20200804_104536.mat';
severity = 1;
makeplots(Drop_Test,filename,smooth_p,smooth_f,t_pre,t_post,severity);

%...other blocks for each Ecoflex data set
end %end: main_postproc_sensorsdata_force_adjusth_tcontact()
```

```

%% Subfunction to make and save main plots from drop test sensor data
function makeplots(Drop_Test,filename,smooth_p,smooth_f,t_pre,t_post,...
    severity)

% Initial variables - general
thick = 0.5; %in, nominal thickness of sample
grav = 386.1; % gravity, in/sec2
g_to_lbm = 0.0022046/grav; %convert mass to British inches/lbs units
lbfin_to_joule = 0.1129848; %energy from lbf-in to Joules
eps_vel = 0.1; %in/sec, tolerance on velocity for potential drop height
    % adjustments. Smallest height=0.25", so 1% of that
    % velocity is 0.01*sqrt(2*386.1*0.25) = 0.139 in/sec

%%
% load data and display variable names/information
load(filename);
%whos; %comment to see all variables in test data
disp(' ');
fprintf('For Drop Test Case %s\n',Drop_Test);

% Assign drop weight and height by severity and material
switch severity
    case 1
        mass_drop = 70; %grams
        h_drop = 0.25; %in
    case 2
        mass_drop = 85; %grams
        h_drop = 1.5; %in
    case 3
        if strcmp(Drop_Test(1),'M')
            mass_drop = 75; %grams
        end
        if strcmp(Drop_Test(1),'E')
            mass_drop = 100; %grams
        end
        h_drop = 5.25; %in
    case 4
        mass_drop = 325; %grams
        h_drop = 5.25; %in
    otherwise
        error('ERROR: Severity = 1,2,3, or 4');
end
mass_drop = mass_drop * g_to_lbm;

%% ... force data post-processing
% percentages (confidence interval ratios) to use for thresholding of
% sensor data (by some % CI above mean) to find and isolate initial 'spike'
% in pressure or force data, where this 'spike' corresponds to 1st impact
if strcmp(Drop_Test,'MD3A') || strcmp(Drop_Test,'MD6A') || ...
    strcmp(Drop_Test,'MD4A') || strcmp(Drop_Test,'MP1A') || ...
    strcmp(Drop_Test,'MP3A')
    pct_i = 0.85; %need higher thresholds for these cases
    pct_f = 0.75;
else
    pct_i = 0.75; %these thresholds work well for all the rest
    pct_f = 0.50;
end

% Set higher thresholds for Ecoflex (needed due to rebounding)
if strcmp(Drop_Test(1),'E')
    pct_i = 0.95;
    pct_f = 0.0; %reboundiness of Ecoflex=>need much lower final threshold

```

```

end
if strcmp(Drop_Test, 'EV5A')
    pct_i = 0.95;
    pct_f = 0.95; %need much higher final threshold for this case
end

% load and smooth data
tf = ch_Force_TIME_interval_1;
f2= ch_Force_interval_1;
f2 = f2 - mean(f2(1:1000)); %subtract init. offset as calc'ed from 1000 pts
f=smoothdata(f2, 'SmoothingFactor', smooth_f);

% find max force, using manual adjustment to force data smoothing for cases
% that are especially noisy
[fmax,indx_fmax] = max(f);
if strcmp(Drop_Test, 'E3A') || strcmp(Drop_Test, 'E3B')
    smooth_f = 0.025;
    f=smoothdata(f2, 'SmoothingFactor', smooth_f);
    fprintf('SPECIAL...smooth_f: %f\n', smooth_f);
    [fmax,indx_fmax] = max(f);
end

% find contact duration by performing a search to find when FORCE
% values are above and below some threshold above the mean
% start with finding initial contact time
threshold_f_i=sqrt(2)*erfinv(pct_i)*(std(f)); % _% confidence interval
fprintf('...Mean(f): %f\n', mean(f));
[indx] = find(f>threshold_f_i+mean(f));
indx_init = indx(1); %index of 1st value above threshold
if indx_init > indx_fmax
    error('ERROR: did not catch correct initial time for contact event');
end

% now find end contact time
threshold_f_f=sqrt(2)*erfinv(pct_f)*(std(f)); % _% confidence interval
[indx] = find(f(indx_init:end)<threshold_f_f+mean(f));
indx_end = indx(1)+indx_init; %index of 1st pressure above threshold

% address case where indx_end is too early (prior to peak value)
% try 2x of jumping ahead slightly
if indx_end < indx_fmax
    indx_end = indx_end + 10;
    [indx] = find(f(indx_end:end)<threshold_f_f+mean(f));
    indx_end = indx(1)+indx_end; %index of 1st pressure above threshold
end
if indx_end < indx_fmax
    indx_end = indx_end + 10;
    [indx] = find(f(indx_end:end)<threshold_f_f+mean(f));
    indx_end = indx(1)+indx_end; %index of 1st pressure above threshold
end
% if still can't find the right location, use a manual reset past peak
if indx_end < indx_fmax
    indx_end = indx_fmax;
    [indx] = find(f(indx_end:end)<threshold_f_f+mean(f));
    disp('WARNING: manual reset of index to find peak force');
    indx_end = indx(1)+indx_end; %index of 1st pressure above threshold
end

% plot smoothed force for selected time window of data capture
figure(3); clf;
indx_subtract = t_pre/(tf(2)-tf(1));
indx_add = t_post/(tf(2)-tf(1));
if indx_init-indx_subtract <= 0

```

```

    indx_subtract = indx_init - 1;
end
if indx_end+indx_add > length(tf)
    indx_add = length(tf)-indx_end;
end

% find and plot rectangular/trapezoidal window of actual impulse calc
vert = [ tf(indx_init) 0;...
        tf(indx_end) 0;...
        tf(indx_end) fmax;...
        tf(indx_init) fmax];
face = [1,2,3,4];
h1 = patch('Faces',face,'Vertices',vert,'FaceColor','green','FaceAlpha',...
    0.3,'Edgecolor','none');
hold on;
% plot force
h2 = plot(tf(indx_init-indx_subtract:indx_end+indx_add),...
    f(indx_init-indx_subtract:indx_end+indx_add),'k-','linewidth',1.5);
hold off;
% label plot
legend([h2 h1],'Data','Contact','location','northwest');
title(sprintf('Force of %s', Drop_Test));
ylabel('Force (lbf)');
xlabel('Time (s)');

% save plot in format for MS Powerpoint (*.ppt), then Word (*.doc)
fname=sprintf('%s_force-time_ppt.png', Drop_Test);
savefigpngrev5(fname,'ppt',[],[],[]);
fname=sprintf('%s_force-time_doc.png', Drop_Test);
savefigpngrev5(fname,'doc',[],[],[]);
clf; close all;

%% ...pressure data post-processing
% open pressure data, smooth, find max, and display max to user
t = ch_Pressure_TIME_interval_1;
p2= ch_Pressure_interval_1;
p2 = p2 - mean(p2(1:1000)); %subtract init. offset as calc'ed from 1000 pts
[pmax,indx_pmax]=max(p2); %max of raw data
fprintf('Max unsmoothed pressure (psi): %.4f\n',pmax);
p=smoothdata(p2,'SmoothingFactor',smooth_p);
[pmax,indx_pmax]=max(p); %max of smoothed data
fprintf('Max smoothed pressure (psi): %.4f\n',pmax);
figure(10); plot(t,p2); hold on; plot(t,p);

% plot smoothed pressure for selected time window of data capture
figure(3); clf;
indx_subtract = t_pre/(t(2)-t(1));
indx_add = t_post/(t(2)-t(1));
if indx_init-indx_subtract <= 0
    indx_subtract = indx_init - 1;
end
if indx_end+indx_add > length(t)
    indx_add = length(t)-indx_end;
end

% find and plot rectangular/trapezoidal window of actual impulse calc
vert = [ t(indx_init) 0;...
        t(indx_end) 0;...
        t(indx_end) 1.*pmax;...
        t(indx_init) 1.*pmax];
face = [1,2,3,4];

```

```

h1 =
patch('Faces',face,'Vertices',vert,'FaceColor','magenta','FaceAlpha',.3,'Edgecolor','none');
hold on;
% plot pressure
h2 = plot(t(indx_init-indx_subtract:indx_end+indx_add),...
    p(indx_init-indx_subtract:indx_end+indx_add),'k-','linewidth',1.5);
hold off;
% label plot
legend([h2 h1],'Data','Contact','location','northwest');
title(sprintf('Pressure of %s', Drop_Test));
ylabel('Pressure (psi)');
xlabel('Time (s)');

% save plot in format for MS Powerpoint (*.ppt), then Word (*.doc)
fname=(sprintf('%s_press-time_ppt.png', Drop_Test));
savefigpngrev5(fname,'ppt',[],[],[]);
fname=sprintf('%s_press-time_doc.png', Drop_Test);
savefigpngrev5(fname,'doc',[],[],[]);
clf; close all;

%% ...impulse data post-processing
ti=ch_Pressure_TIME_interval_1.*10^3; %sec to ms, for impulse calc
time_contact_only = ti(indx_init:indx_end); %time values of contact event
fprintf('Contact duration (ms): %.1f\n',time_contact_only(end)-time_contact_only(1));
fprintf('...Contact start (s): %.4f\n',time_contact_only(1)/1000);
fprintf('...Contact end (s): %.4f\n',time_contact_only(end)/1000);

% calculate cumulative impulse during contact duration
i_contact = cumtrapz(time_contact_only,p(indx_init:indx_end));
imax=max(i_contact);
fprintf('Max impulse during contact (psi-ms): %.4f\n',imax);

% plot cumulative impulse during contact duration
figure(1);
plot(time_contact_only/10^3,i_contact,'k-','linewidth',1.5);
title(sprintf('Cumulative Impulse of %s', Drop_Test));
ylabel('Cumulative Impulse (psi-ms)');
xlabel('Time (s)');

% save plot in format for MS Powerpoint (*.ppt), then Word (*.doc)
fname=(sprintf('%s_impuls-time_ppt.png', Drop_Test));
savefigpngrev5(fname,'ppt',[],[],[]);
fname=(sprintf('%s_impuls-time_doc.png', Drop_Test));
savefigpngrev5(fname,'doc',[],[],[]);

%% ... velocity (from force) post-processing
% calc integral of Force(time), only during contact
time_contact_only = time_contact_only/1000; %ms to sec
t = time_contact_only - time_contact_only(1); %relative time
f = f(indx_init:indx_end); % force, for just contact event
integral_of_f = cumtrapz(t,f);

% velocity(time) = v_init + grav*time - integral of
% Force(time)/mass (during contact only)
v_init = sqrt(2*grav*h_drop);
v_total = v_init + grav*(t) - integral_of_f/mass_drop; %total impactor vel

% look for 1st min impactor vel after max impactor velocity => at this
% time, impactor should be stationary (or almost stationary), i.e. vel=0
[v_max, indx_vmin] = max(v_total);
[v_min, indx_vmin] = min(v_total(indx_vmin(1):end));

```

```

% shift velocity curve (to adjust min velocity to 0, i.e. impactor arrest ).
% Use error tolerance on logic testing to avoid excessive adjustments
% (avoid floating point precision issues and windowing approximation errors).
% Underestimation of drop height: vel_min < 0- => increase h_drop
fprintf('Nominal drop height (in): %.2f\n',h_drop);
if v_min < -eps_vel
    v_total = v_total - v_min;
    v_init = v_total(1); % must reset initial velocity after shift
    fprintf('...Addition to drop height (in): %.3f\n',0.5*v_min^2/grav);
end
% Overestimation of drop height: vel_min > 0+ => decrease h_drop
if v_min > eps_vel
    v_total = v_total - v_min;
    v_init = v_total(1); % must reset initial velocity after shift
    fprintf('...Reduction to drop height (in): -%.3f\n',0.5*v_min^2/grav);
end

% plot velocity history and label
figure(1);
plot(t + time_contact_only(1), v_total,'k-','linewidth',1.5);
title(sprintf('Impactor Velocity for %s', Drop_Test));
ylabel('Velocity (in/s)');
xlabel('Time (s)');

% save plot in format for MS Powerpoint (*.ppt), then Word (*.doc)
fname=(sprintf('%s_velocity-time_ppt.png', Drop_Test));
savefigpngrev5(fname,'ppt',[],[],[]);
fname=(sprintf('%s_velocity-time_doc.png', Drop_Test));
savefigpngrev5(fname,'doc',[],[],[]);

%% ... displacement (from force) post-processing
% calc double integral of integral of Force(time), only during contact
doub_integral_of_f = cumtrapz(t, integral_of_f );

% displ(time) = h_drop + v_init*time + 0.5*grav*time^2
% - double integral of Force(time)/mass (during contact only)
d_total = h_drop + v_init*(t) + 0.5*grav*(t).^2 ...
    - doub_integral_of_f/mass_drop; %total impactor displacement
d_impactor = d_total - d_total(1);

% print displacement at time of 1st min impactor vel after max impactor
% velocity => assume separation likely happens right after this
fprintf('Displacement of impactor at min velocity (in): %.4f\n',...
    d_impactor(indx_vmin));

% plot impactor displacement
figure(1);
h1 = plot(t + time_contact_only(1), d_impactor,'k-','linewidth',1.5);
title(sprintf('Impactor Displacement for %s', Drop_Test));
hold on;
h2 =
plot(t(indx_vmin)+time_contact_only(1),d_impactor(indx_vmin),'ks','markersize',7);
hold off;
legend(h2,'Displ at Min Vel','location','southeast');
ylabel('Displacement (in)');
xlabel('Time (s)');
if strcmp(Drop_Test(1),'M')
    ylim([0, thick]);
end
if strcmp(Drop_Test(1),'E')
    ylim([0, 1.5*thick]);
end

```

```

% save plot in format for MS Powerpoint (*.ppt), then Word (*.doc)
fname=(sprintf('%s_displ-time_ppt.png', Drop_Test));
savefigpngrev5(fname,'ppt',[],[],[]);
fname=(sprintf('%s_displ-time_doc.png', Drop_Test));
savefigpngrev5(fname,'doc',[],[],[]);

%% ... energy (from force) post-processing
% Perform energy analysis via conservation of energy: assume all impactor's
% potential energy (PE) and kinetic energy (KE) (at all time data points
% during the contact event) gets imparted by specimen. Impactor plate
% is assumed to be rigid!

% energy imparted by specimen
energy_imparted = 0.5*mass_drop * (v_init^2 - v_total.^2)...
    + mass_drop *grav*d_total; %in-lbf, imparted to specimen

% alternative energy equation
energy = v_init * integral_of_f + grav*cumtrapz(t,t.*f)...
    - 0.5/mass_drop * integral_of_f.^2; %in-lbf, without initial E=m*g*h

% plot imparted energy
figure(1);
plot(t + time_contact_only(1),...
    energy_imparted,'k-','linewidth',1.5);
title(sprintf('Imparted Energy of %s', Drop_Test));
ylabel('Energy (lbf-in)');
xlabel('Time (s)');

% save plot in format for MS Powerpoint (*.ppt), then Word (*.doc)
fname=(sprintf('%s_energy-time_ppt.png', Drop_Test));
savefigpngrev5(fname,'ppt',[],[],[]);
fname=(sprintf('%s_energy-time_doc.png', Drop_Test));
savefigpngrev5(fname,'doc',[],[],[]);

% display energy values
fprintf('Energy at contact = 0.5*m*v_i^2: %.3f lbf-in (%.1f mJ)\n',...
    0.5*v_total(1)^2*mass_drop,...
    0.5*v_total(1)^2*mass_drop*lbfin_to_joule*1000);
fprintf('Sample energy imparted at initial contact: %.3f lbf-in (%.1f mJ)\n',energy_imparted(1),...
    energy_imparted(1)*lbfin_to_joule*1000);
fprintf('Energy from alt. calc at min impactor vel: %.3f lbf-in (%.1f mJ)\n',...
    energy(indx_vmin), energy(indx_vmin)*lbfin_to_joule*1000);
fprintf('Sample energy imparted at min impactor vel: %.3f lbf-in (%.1f mJ)\n',...
    energy_imparted(indx_vmin),energy_imparted(indx_vmin)*lbfin_to_joule*1000);
end %end: makeplots()

function [x]=savefigpngrev5(filename,format,classification,tag_ul,tag_ll)
% This function sets various figure parameters & saves as a *.png file
% with a specified resolution (dpi). Parameters include grid, window size,
% axes tick label fontsize, axes label fontsize, title fontsize (if
% applicable), and legend fontsize.
% It does NOT set linewidths or markersizes of data series.
%
%Execution:
% savefigpng_rev5(filename,format,classification,tag,tag2);
%
%Inputs are:
%--filename: [string] path & name for saved file,
%            e.g. (file in subfolder 'fig')

```

```

%          'fig/press_fnc-n_dys_implos_fig1_(U)'
%--format:  [string] 'doc' for report format, else for viewgraph format
%--classification: [string] classification tag at lower right corner of plot
%--tag:      [string] tag for upper left corner of plot
%--tag2:     [string] tag for lower left corner of plot
%
%--Author:   Emily L. Guzas
%--Modified: Joseph M. Ambrico
%--Date:     2014-10-04
%--Rev2:     2016-Apr-21
%--Rev4:     2017-Oct-10
%--Rev5:     2018-Jan-9

%Size the figure appropriately
if strcmp(format,'article')==1
    rect = [1 1 8.0 6.0]; %size: 80 W x 60mm H (2x2 in *doc @ 100%)
else
    rect = [1 1 12.952 9.711]; %size: 130 W x 97mm H (2x2 in *ppt @ 100%)
end
figure(gcf);
set(gcf, 'PaperPositionMode', 'manual','paperunits','centimeters');
set(gcf, 'PaperUnits', 'centimeters', 'PaperPosition', rect);
set(gcf, 'Units', 'centimeters', 'Position', rect); %[lft bott width hgt]
set(gcf, 'PaperPosition', rect);

%Set axes props & labels
if exist('format')==1 % if format exists as a variable
    if strcmp(format,'doc')==1 % if document format
        fnt = 10;
        fntleg = fnt;
        title('');
    elseif strcmp(format,'article')==1
        fnt = 10;
        fntleg = 8;
        title('');
    elseif strcmp(format,'ppt')==1 % if powerpoint format
        fnt = 12;
        fntleg = fnt;
    else
        fnt = 12;
        fntleg = fnt;
    end % if strcmp format
else % make viewgraph format plots
    fnt = 12;
end % if exist format

%...rev4: deal with colorbars AND potential for struct data structures
AxesInFig_Cbar = findall(gcf,'type','axes','Tag','Colorbar');
AxesInFig_allbutCbar = findall(gcf,'type','axes','Tag','');
if isempty(AxesInFig_Cbar)
    set(gca, 'fontsize', fnt, 'linewidth', 1.0, 'box', 'on', 'visible', 'on'); %axes props
    set(get(gca, 'XLabel'), 'fontsize', fnt); %default is 10
    set(get(gca, 'YLabel'), 'fontsize', fnt); %default is 10
    set(get(gca, 'title'), 'fontsize', fnt+2); %default is 10
else
    set(AxesInFig_allbutCbar, 'fontsize', fnt, 'linewidth', 1.0, 'box', 'on', 'visible', 'on');
    if ~iscell(get(AxesInFig_allbutCbar, 'XLabel'))
        set(get(AxesInFig_allbutCbar, 'XLabel'), 'fontsize', fnt); %default is 10
    else
        tmp = get(AxesInFig_allbutCbar, 'XLabel');
        for i=1:length(tmp);
            set(tmp{i}, 'fontsize', fnt);
        end
    end
end

```

```

        end
    end
    if ~iscell(get(AxesInFig_allbutCbar, 'YLabel'))
        set(get(AxesInFig_allbutCbar, 'YLabel'), 'fontsize', fnt); %default is 10
    else
        tmp = get(AxesInFig_allbutCbar, 'YLabel');
        for i=1:length(tmp);
            set(tmp{i}, 'fontsize', fnt);
        end
    end
    if ~iscell(get(AxesInFig_allbutCbar, 'title'))
        set(get(AxesInFig_allbutCbar, 'title'), 'fontsize', fnt+2); %default is 10
    else
        tmp = get(AxesInFig_allbutCbar, 'title');
        for i=1:length(tmp);
            set(tmp{i}, 'fontsize', fnt+2);
        end
    end
    end
    % (Re)set colobar axes
    set(AxesInFig_Cbar, 'fontsize', fnt-2);
end

if exist('classification')==1 % if classification exists as a variable
    if isempty(classification)==0 % if classification is not empty
        %h = text(0.99,0.03,classification,'units','normalized');
        h = text(0.99,0.01,classification,'units','normalized'); %rev5
        set(h, 'HorizontalAlignment', 'Right', 'FontSize', fnt, 'fontweight', 'bold');
        set(h, 'VerticalAlignment', 'bottom'); %rev5
    end % if isempty
end % if exist classification

if exist('tag_ul')==1 % if tag exists as a variable
    if isempty(tag_ul)==0 % if tag is not empty
        h = text(0.02,0.98,tag_ul,'units','normalized');

        set(h, 'HorizontalAlignment', 'Left', 'VerticalAlignment', 'top', 'FontSize', fnt, 'Background
        dColor', [1 1 1], 'EdgeColor', [0 0 0]);
    end % if isempty
end % if exist tag

if exist('tag_ll')==1 % if tag2 exists as a variable
    if isempty(tag_ll)==0 % if tag2 is not empty
        h = text(0.02,0.065,tag_ll,'units','normalized');
        set(h, 'HorizontalAlignment', 'Left', 'FontSize', fnt, 'BackgroundColor', [1 1 1]);
    end % if isempty
end % if exist tag

%Set legend fontsize
chk = findobj(gcf, 'Legend', 'visible');
if ~isempty(chk)
    gcl = legend;
    set(gcl, 'fontsize', fntleg); %default is 10
end

%Save
print('-dpng', '-r200', filename); %print fig to *.png format @ 200dpi
end %end: savefigpngrev5()

```

Sample output from the above code follows this paragraph. It is saved in one file as 'main_postproc_sensorsdata_force_adjusth_tcontact.m':

```
>> main_postproc_sensorsdata_force_adjusth_tcontact;
```

```
For Drop Test Case MD1A
```

```
...Mean(f): 0.010906
```

```
Max unsmoothed pressure (psi): 0.9171
```

```
Max smoothed pressure (psi): 0.9046
```

```
Contact duration (ms): 25.2
```

```
...Contact start (s): 5.8474
```

```
...Contact end (s): 5.8727
```

```
Max impulse during contact (psi-ms): 7.3499
```

```
Nominal drop height (in): 0.25
```

```
...Addition to drop height (in): 0.050
```

```
Displacement of impactor at min velocity (in): 0.1995
```

```
Energy at contact =  $0.5*m*v_i^2$ : 0.081 lbf-in (9.1 mJ)
```

```
Sample energy imparted at initial contact: 0.039 lbf-in (4.4 mJ)
```

```
Energy from alt. calc at min impactor vel: 0.111 lbf-in (12.6 mJ)
```

```
Sample energy imparted at min impactor vel: 0.150 lbf-in (16.9 mJ)
```

B.2 ALL DATA FROM DROP TOWER FORCE AND PRESSURE SENSORS

This section includes graphs of the data collected from the drop tower sensors. Post-processing is per the MATLAB script.

B.2.1 Melon, Common Dolphin (*Delphinus delphis*)

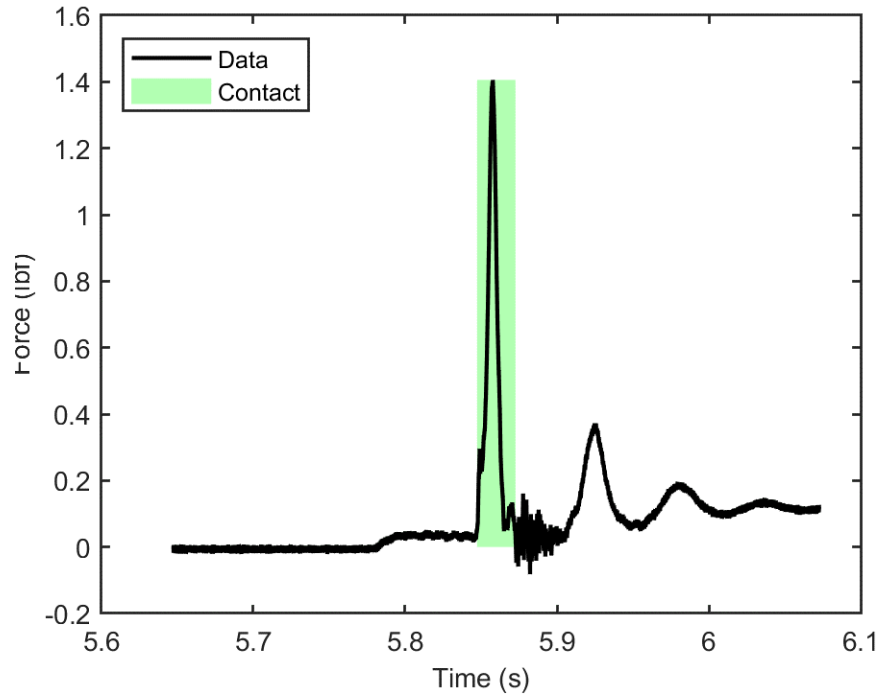


Figure 65. Force time history for drop test MD1A, with contact time window marked.

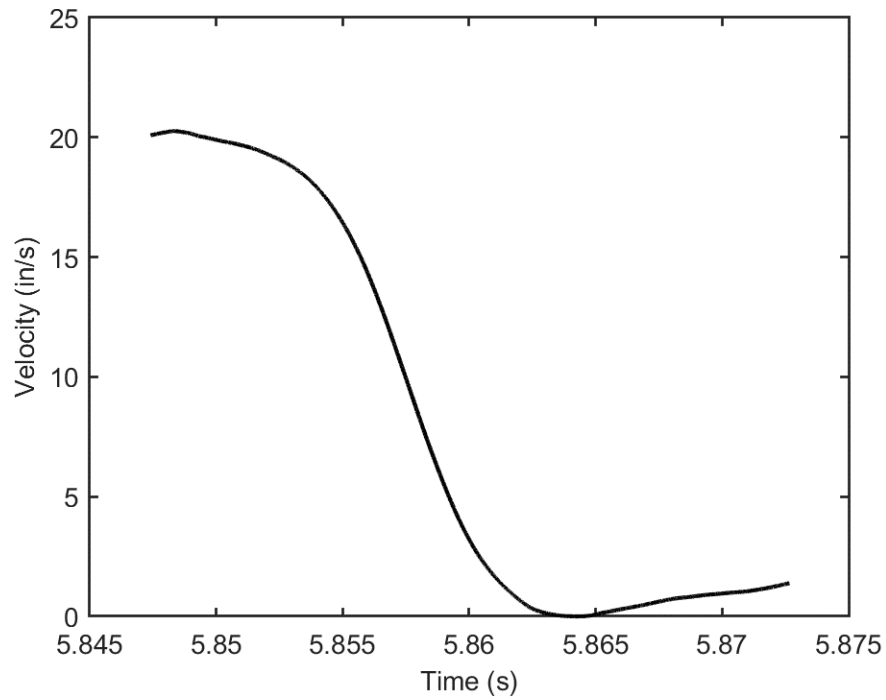


Figure 66. Velocity time history (from force data) for test MD1A during initial contact.

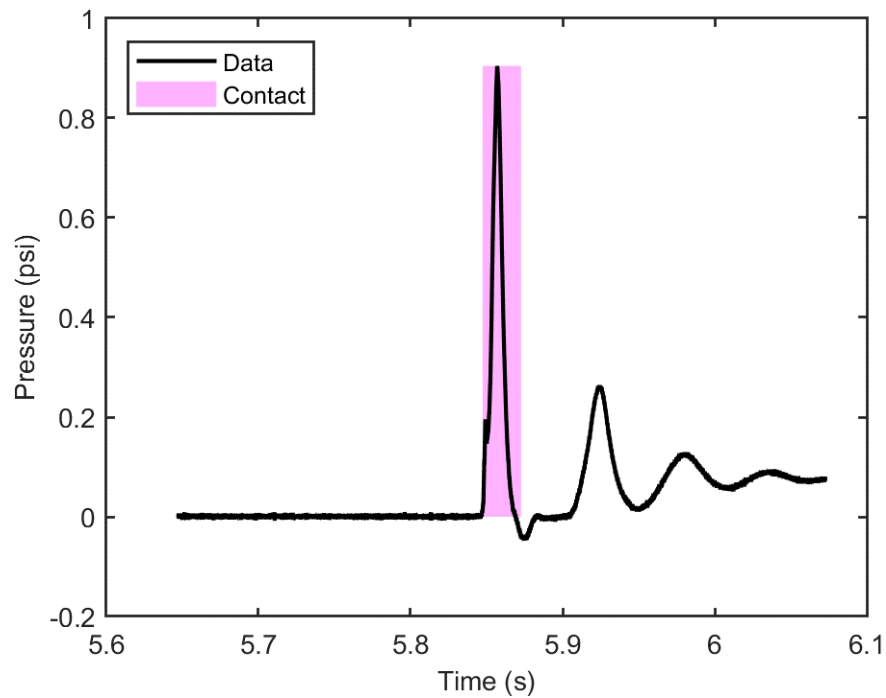


Figure 67. Pressure data for test MD1A, with contact time window marked.

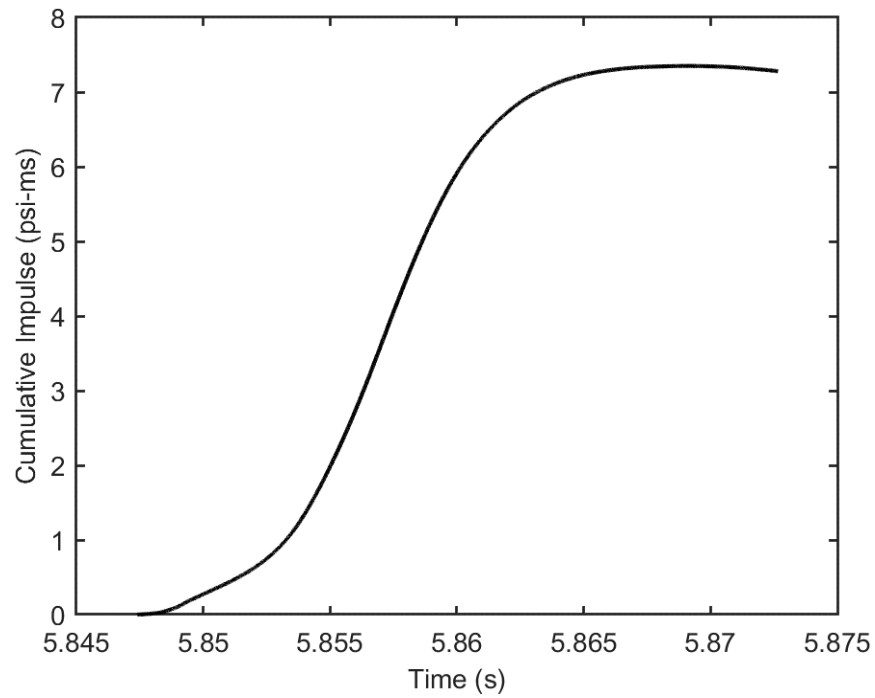


Figure 68. Impulse time history (from pressure data) for test MD1A during initial contact.

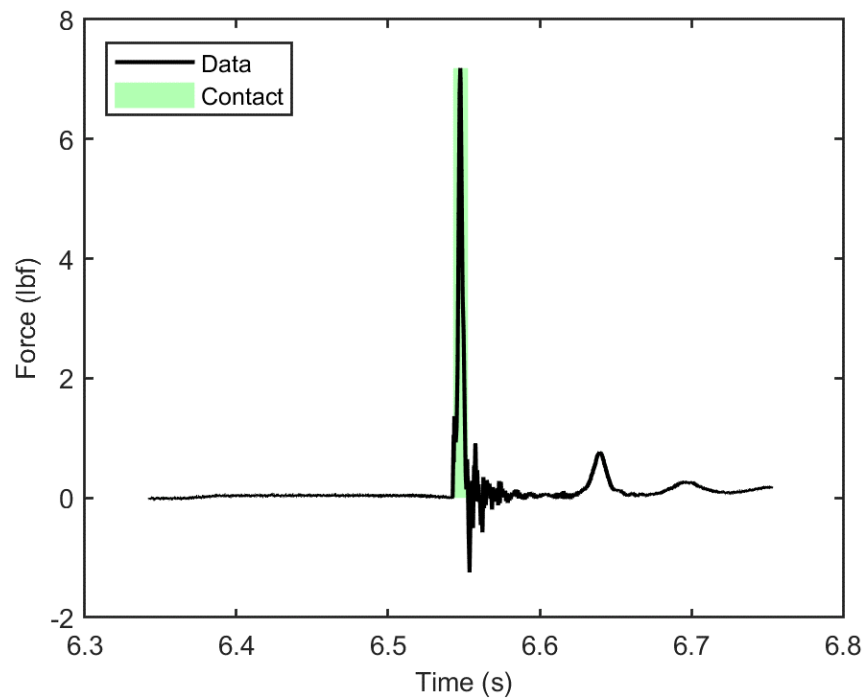


Figure 69. Force data for drop test MD1B, with contact time window marked.

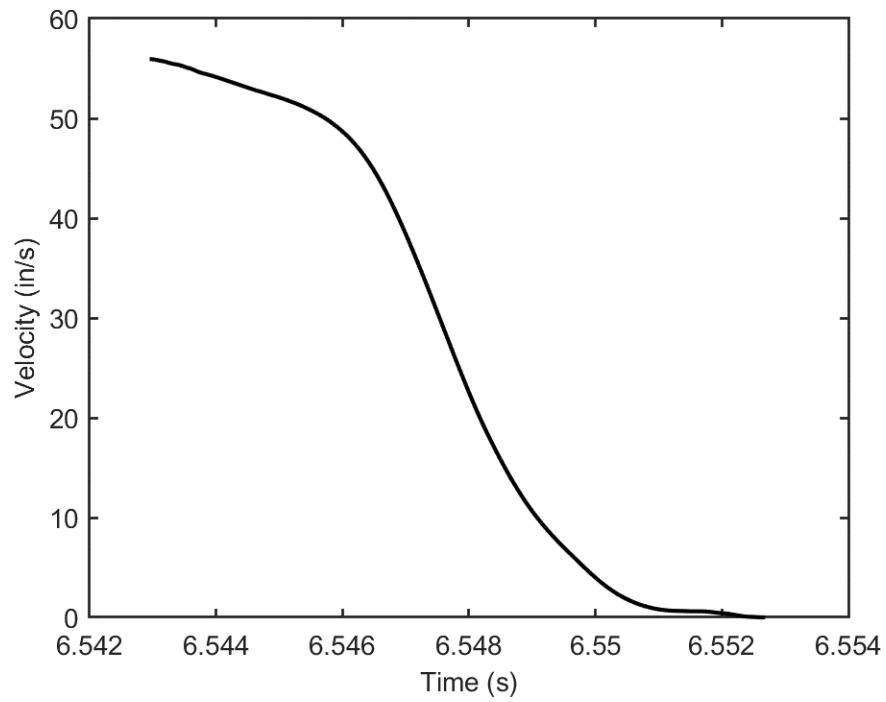


Figure 70. Velocity time history (from force data) for test MD1B during initial contact.

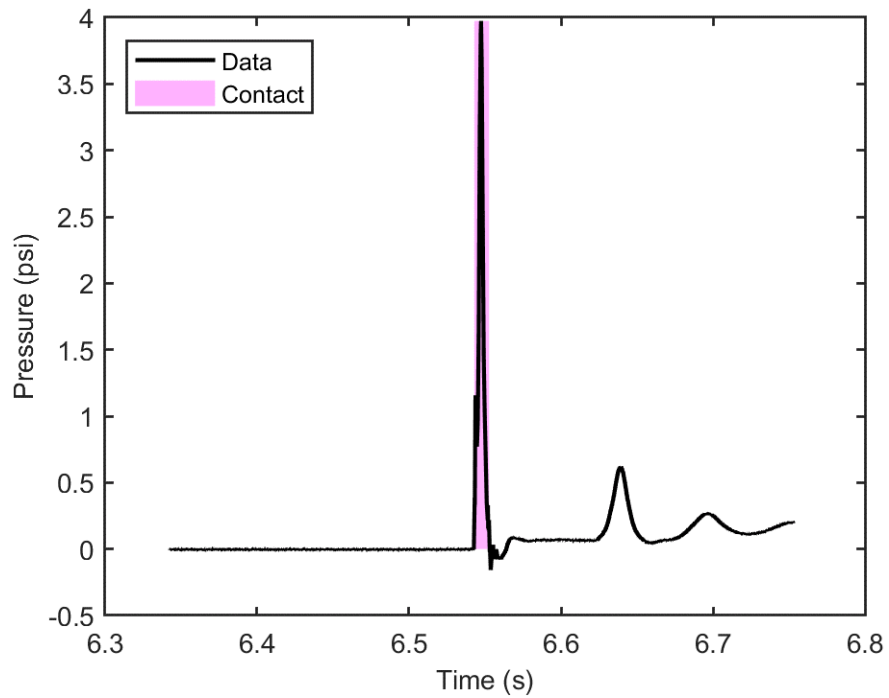


Figure 71. Pressure data for test MD1B, with contact time window marked.

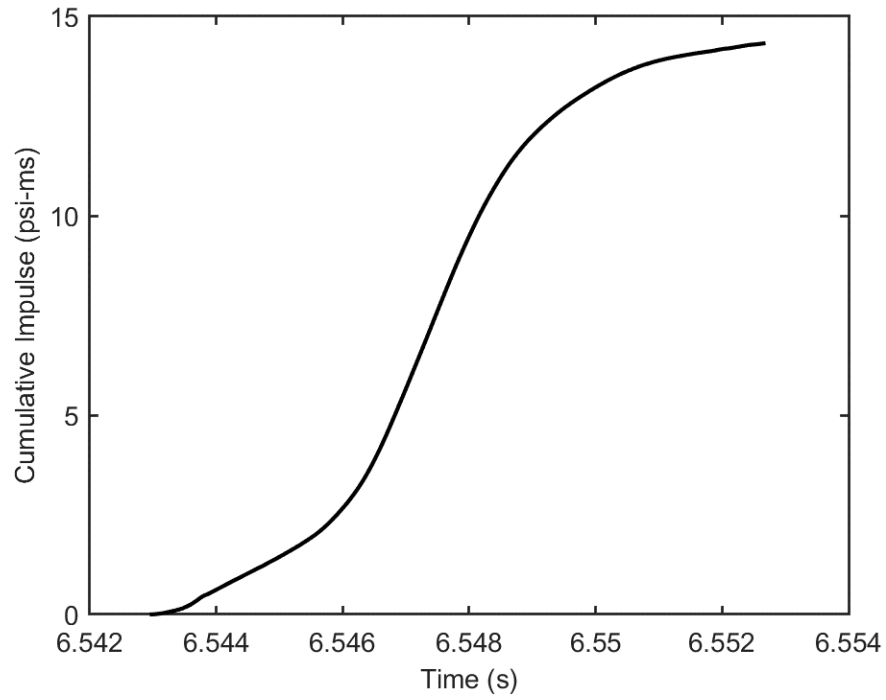


Figure 72. Impulse time history (from pressure data) for test MD1B during initial contact.

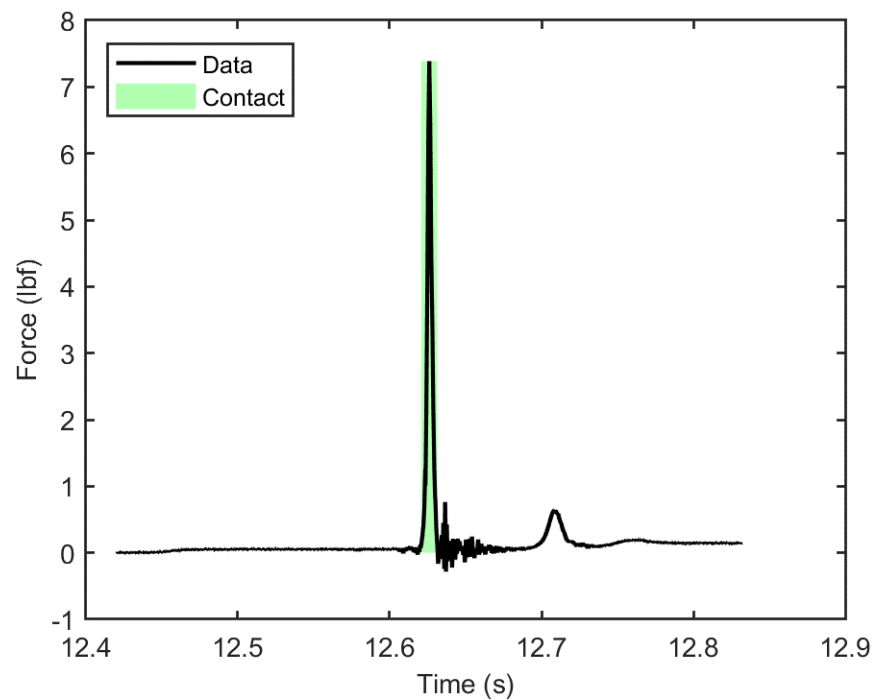


Figure 73. Force data for drop test MD2A, with contact time window marked.

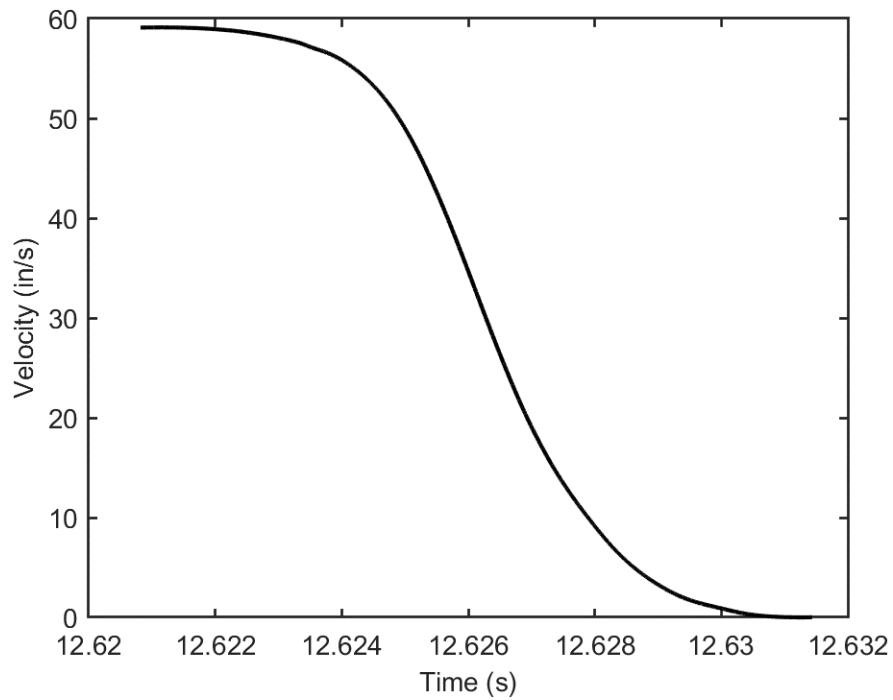


Figure 74. Velocity time history (from force data) for test MD2A during initial contact.

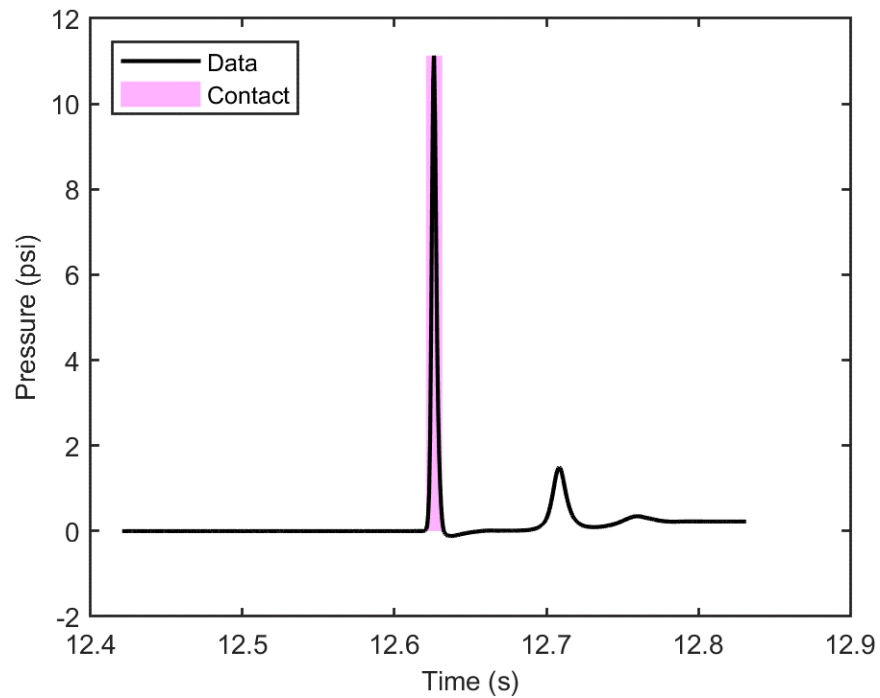


Figure 75. Pressure data for test MD2A, with contact time window marked.

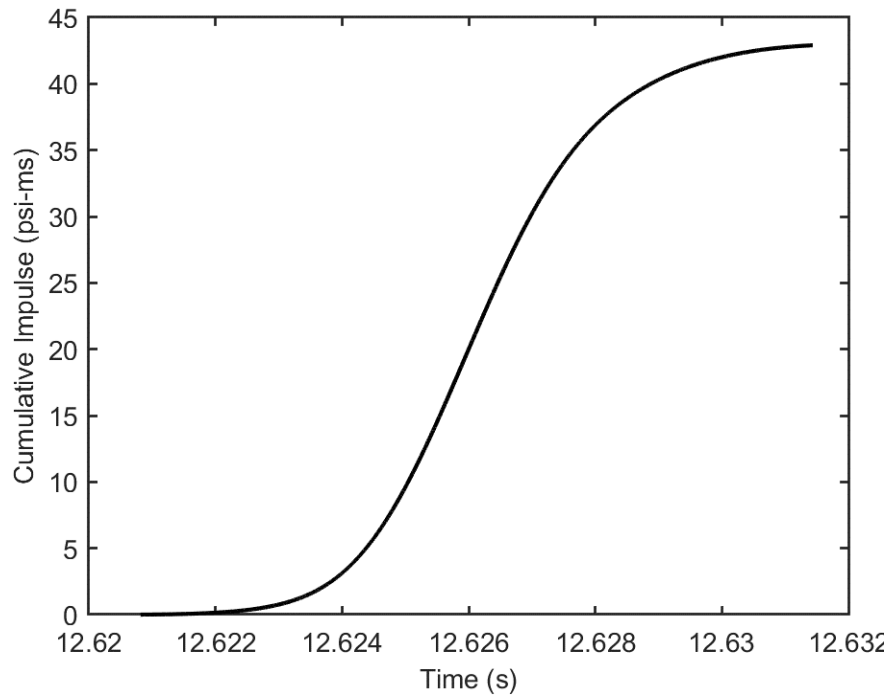


Figure 76. Impulse time history (from pressure data) for test MD2A during initial contact.

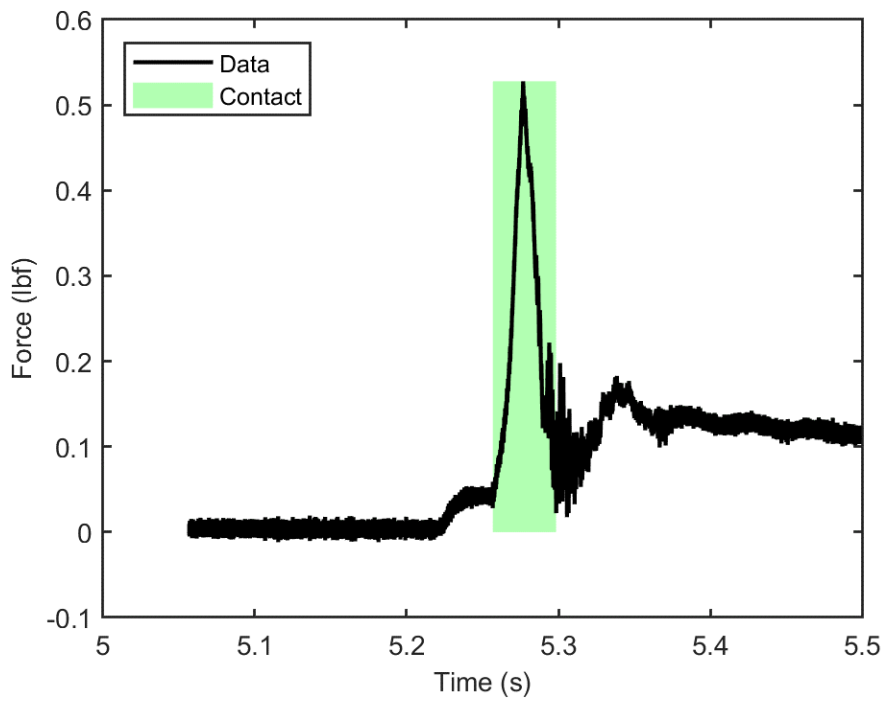


Figure 77. Force data for drop test MD3A, with contact time window marked.

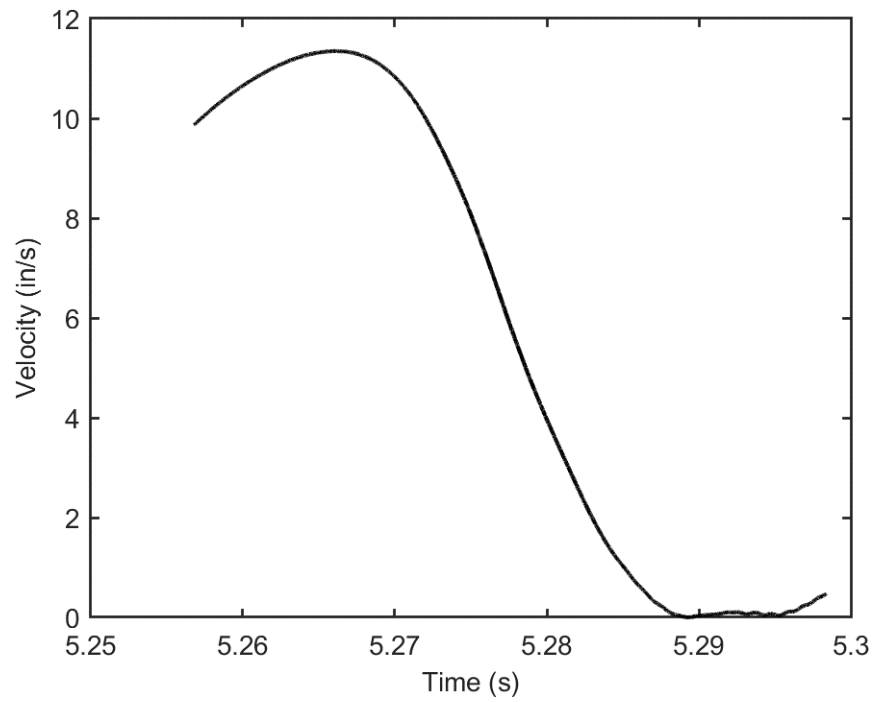


Figure 78. Velocity time history (from force data) for test MD3A during initial contact.

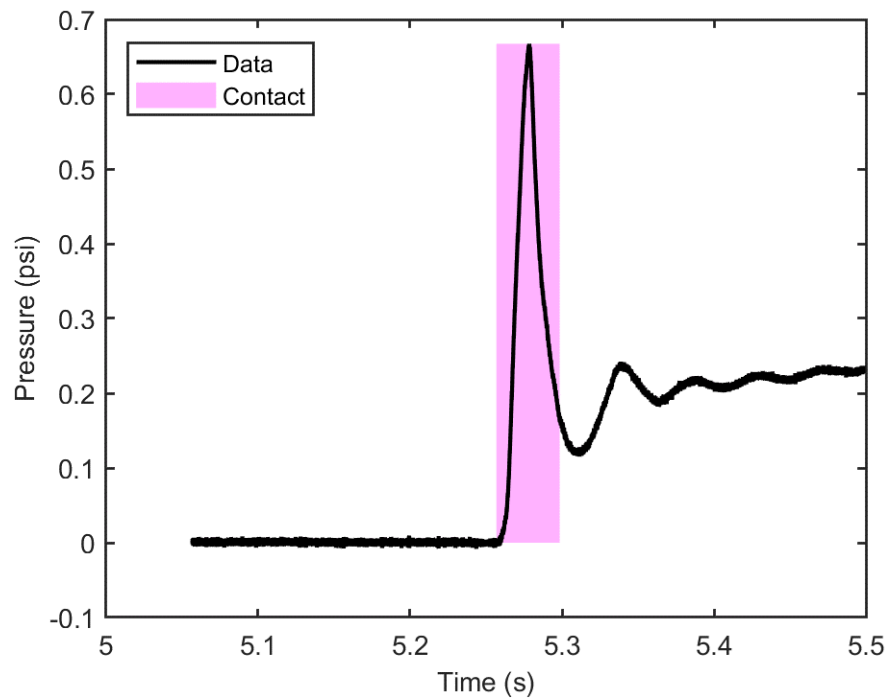


Figure 79. Pressure data for test MD3A, with contact time window marked.

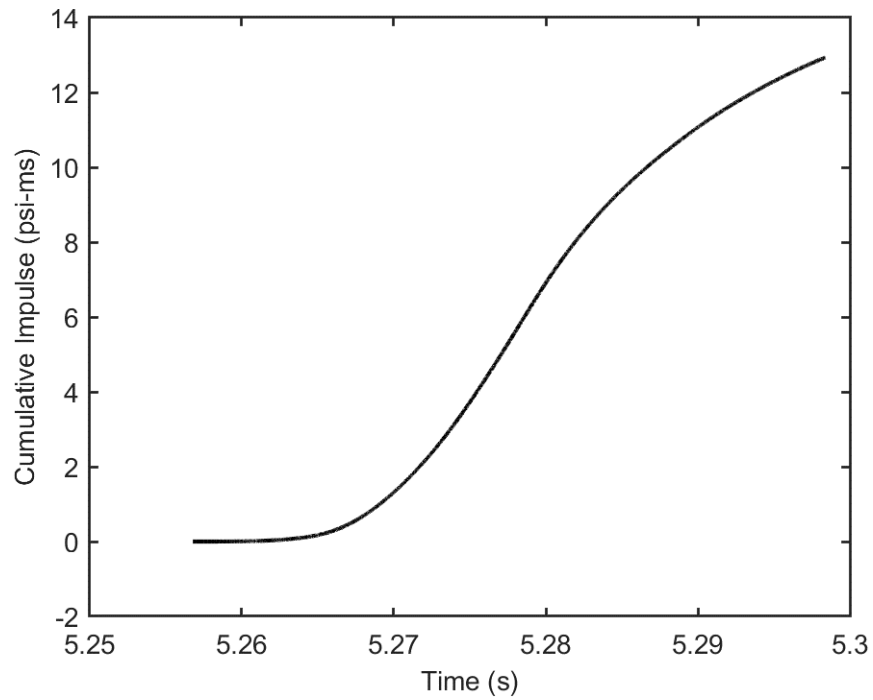


Figure 80. Impulse time history (from pressure data) for test MD3A during initial contact.

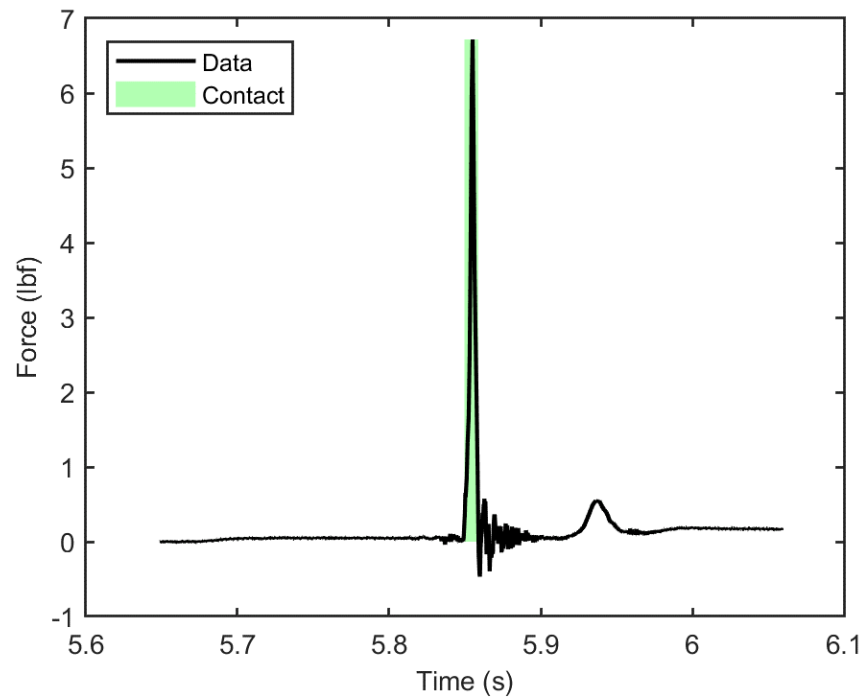


Figure 81. Force data for drop test MD3B, with contact time window marked.

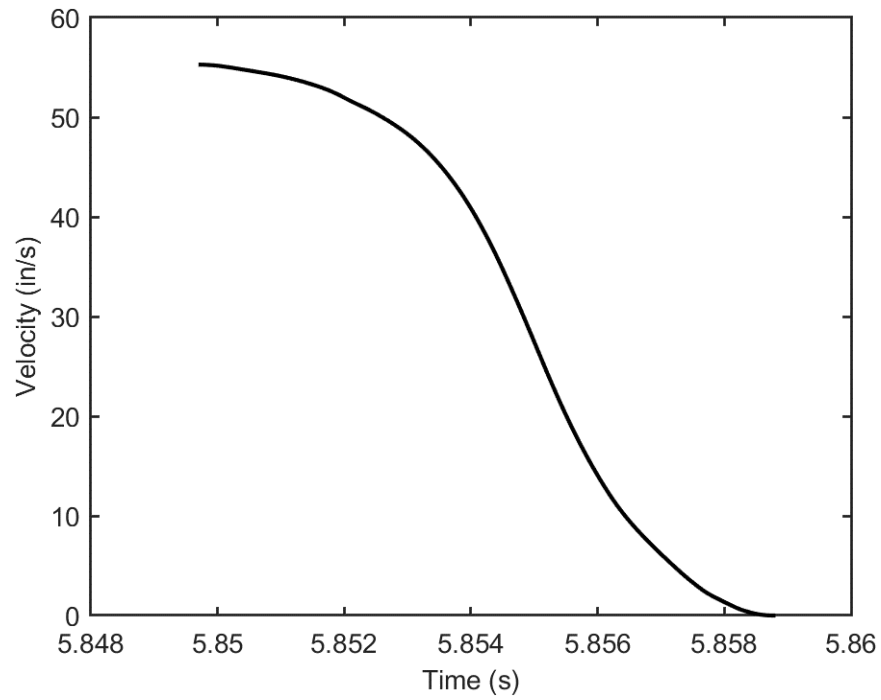


Figure 82. Velocity time history (from force data) for test MD3B during initial contact.

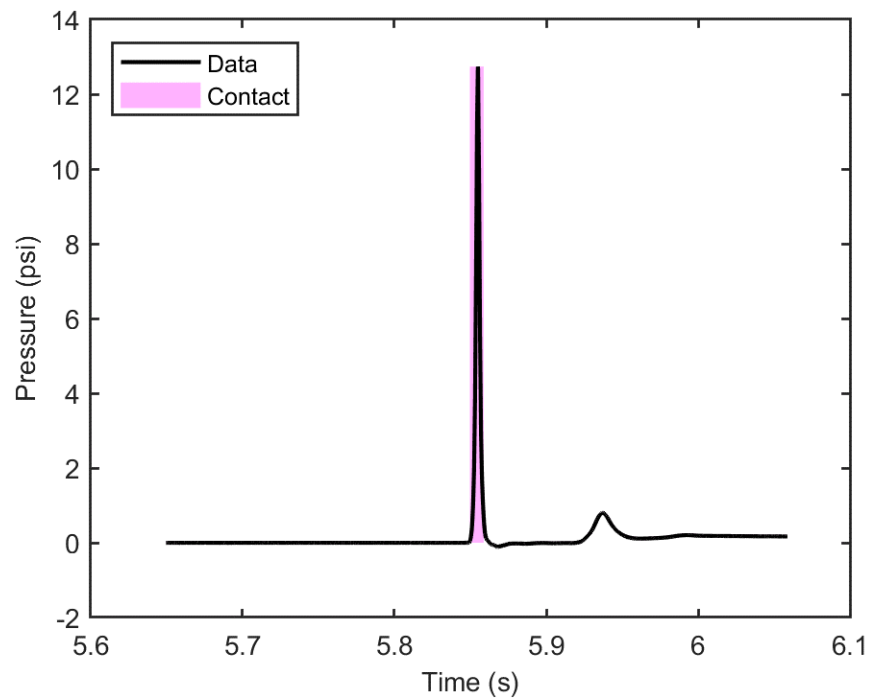


Figure 83. Pressure data for test MD3B, with contact time window marked.

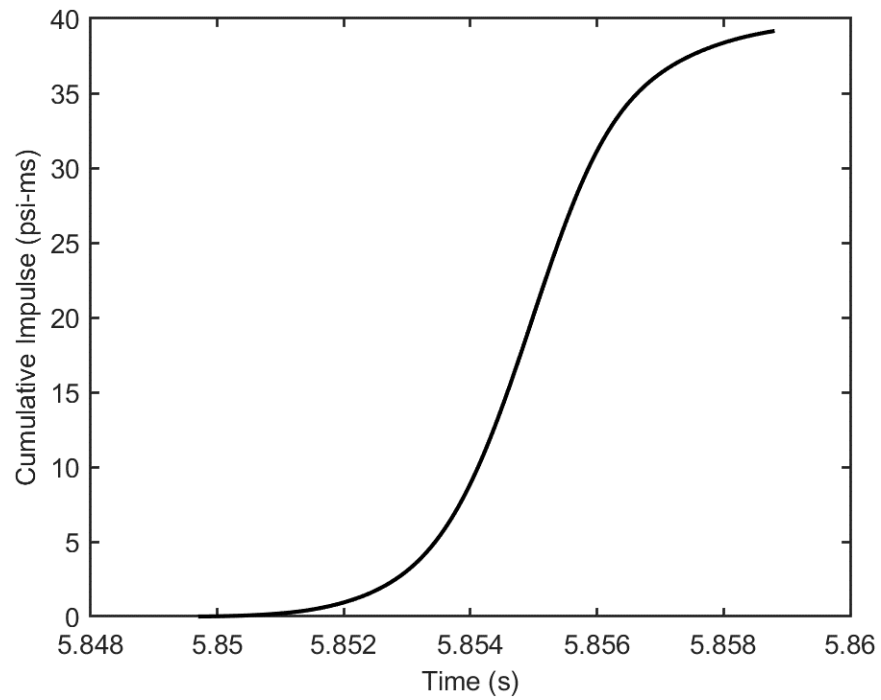


Figure 84. Impulse time history (from pressure data) for test MD3B during initial contact.

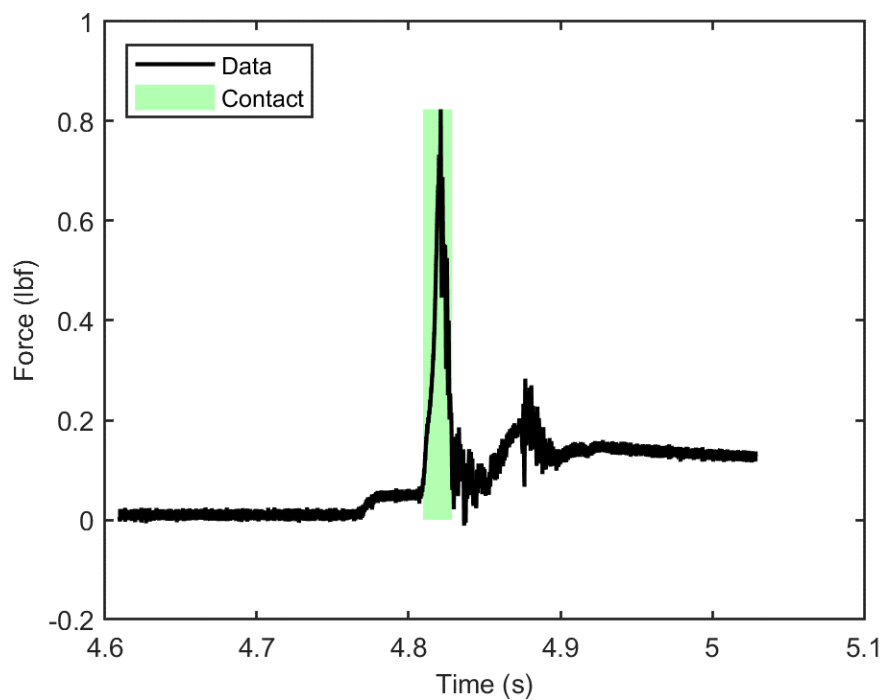


Figure 85. Force data for drop test MD4A, with contact time window marked.

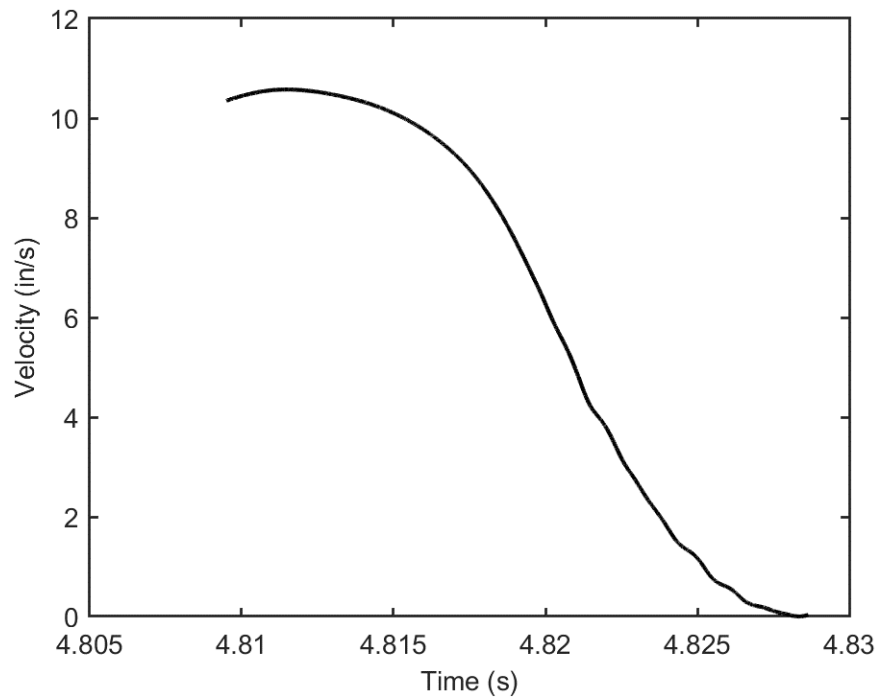


Figure 86. Velocity time history (from force data) for test MD4A during initial contact.

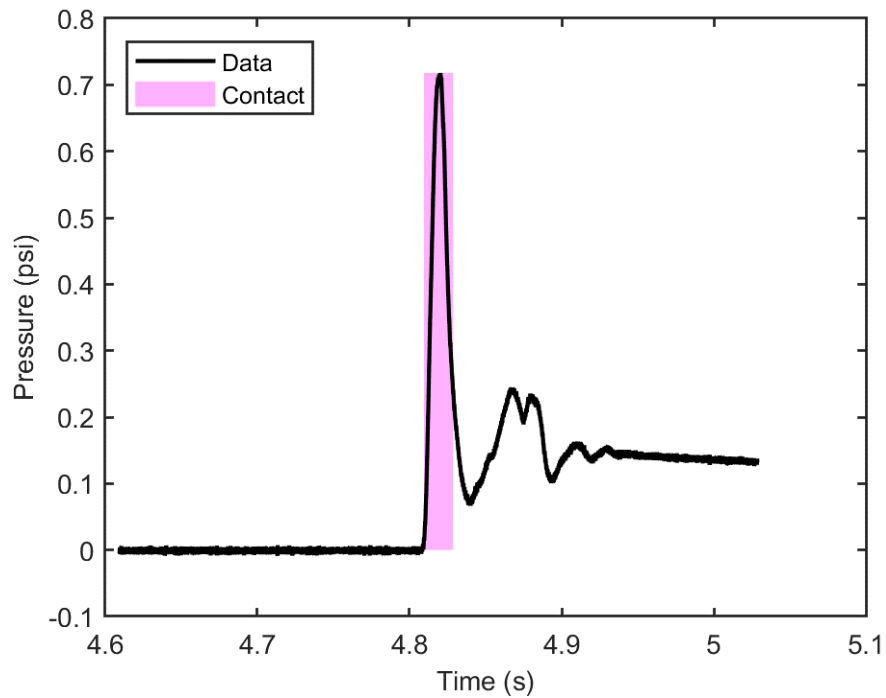


Figure 87. Pressure data for test MD4A, with contact time window marked.

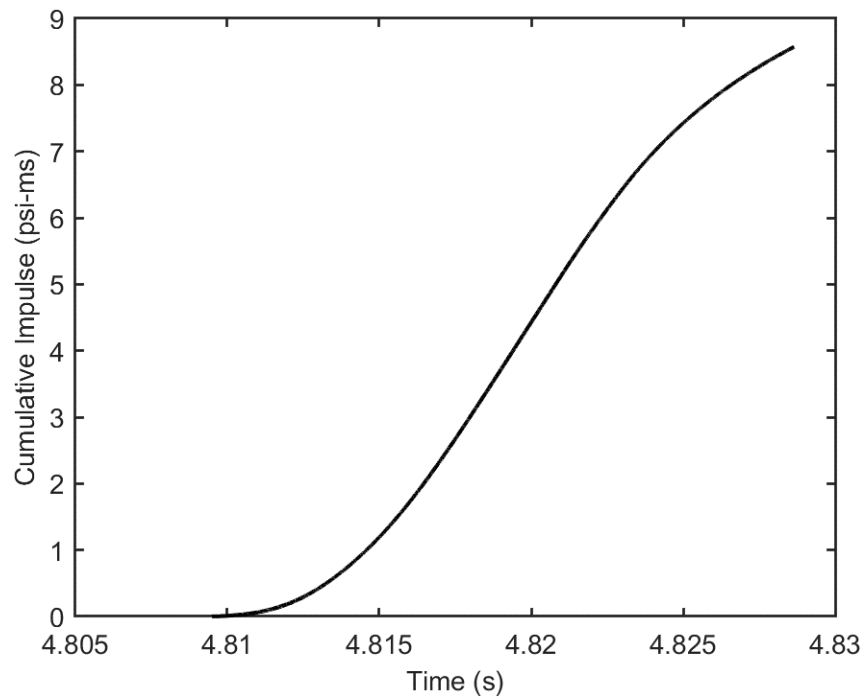


Figure 88. Impulse time history (from pressure data) for test MD4A during initial contact.

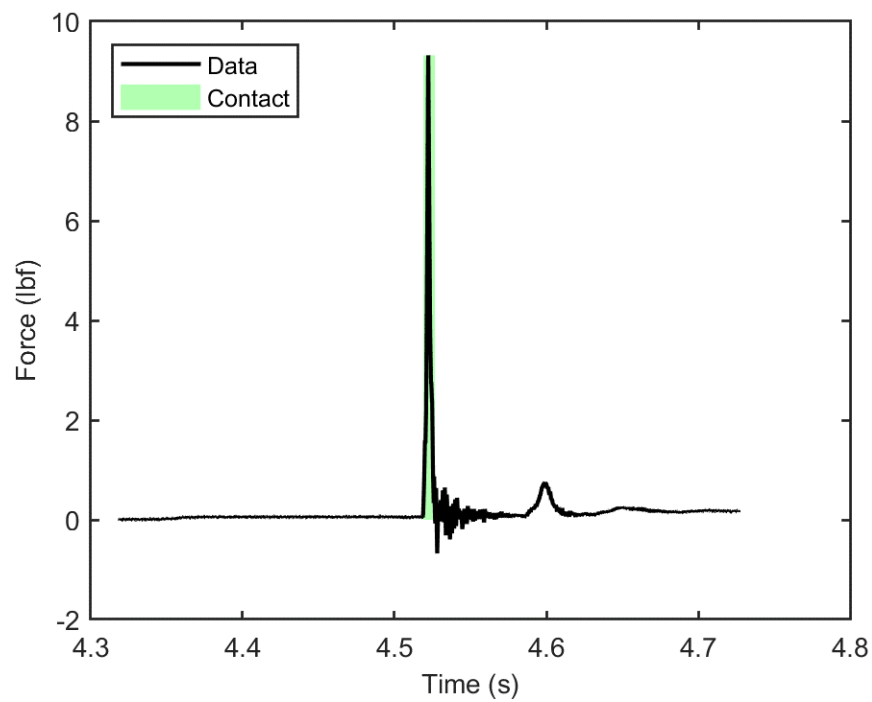


Figure 89. Force data for drop test MD4B, with contact time window marked.

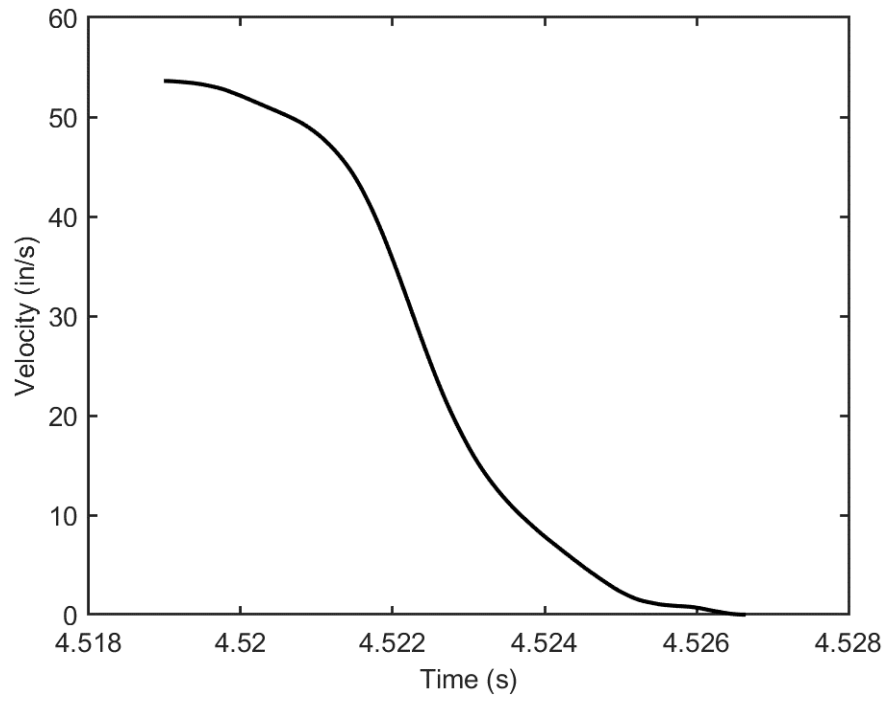


Figure 90. Velocity time history (from force data) for test MD4B during initial contact.

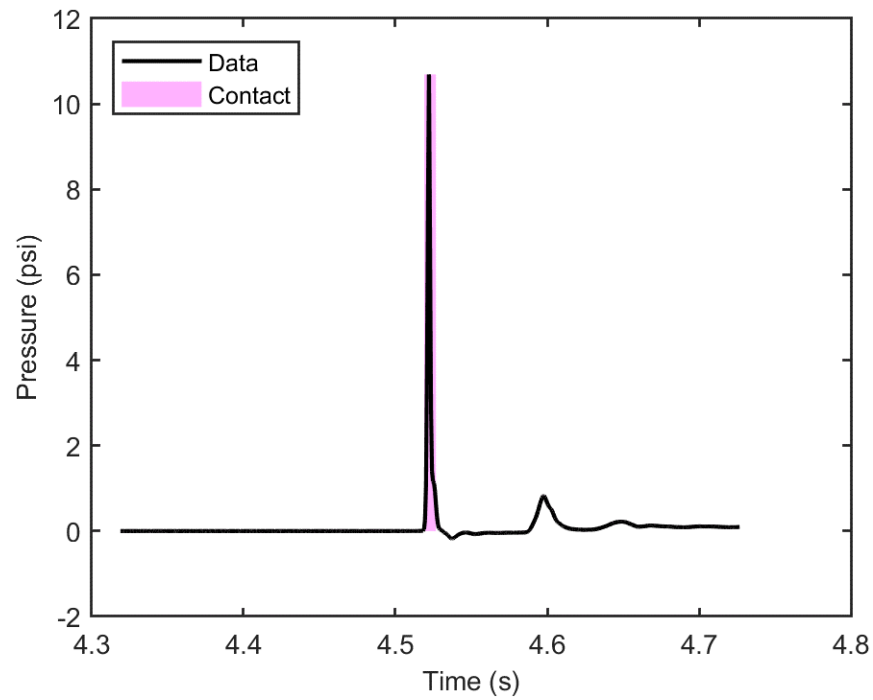


Figure 91. Pressure data for test MD4B, with contact time window marked.

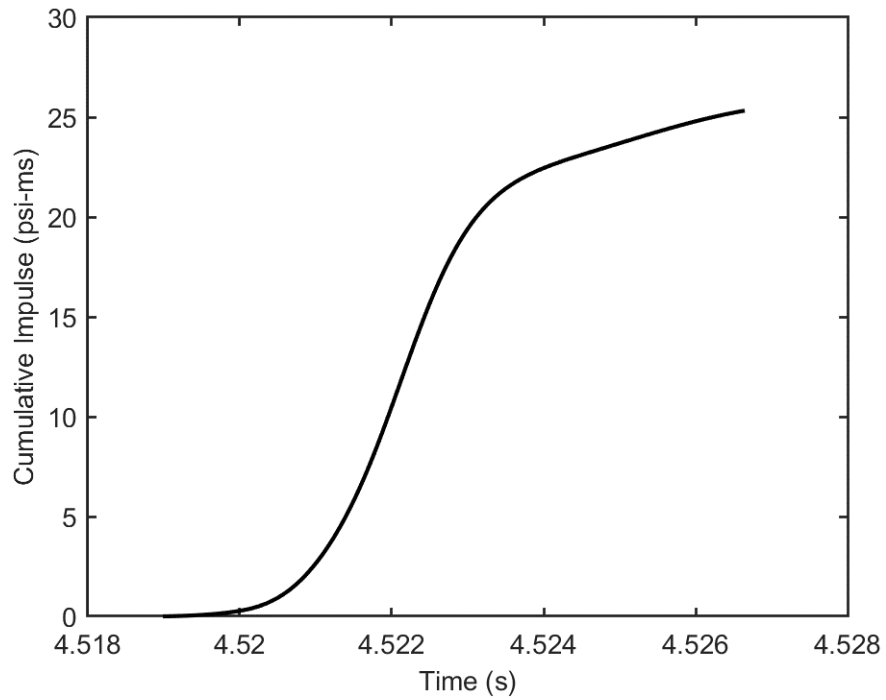


Figure 92. Impulse time history (from pressure data) for test MD4B during initial contact.

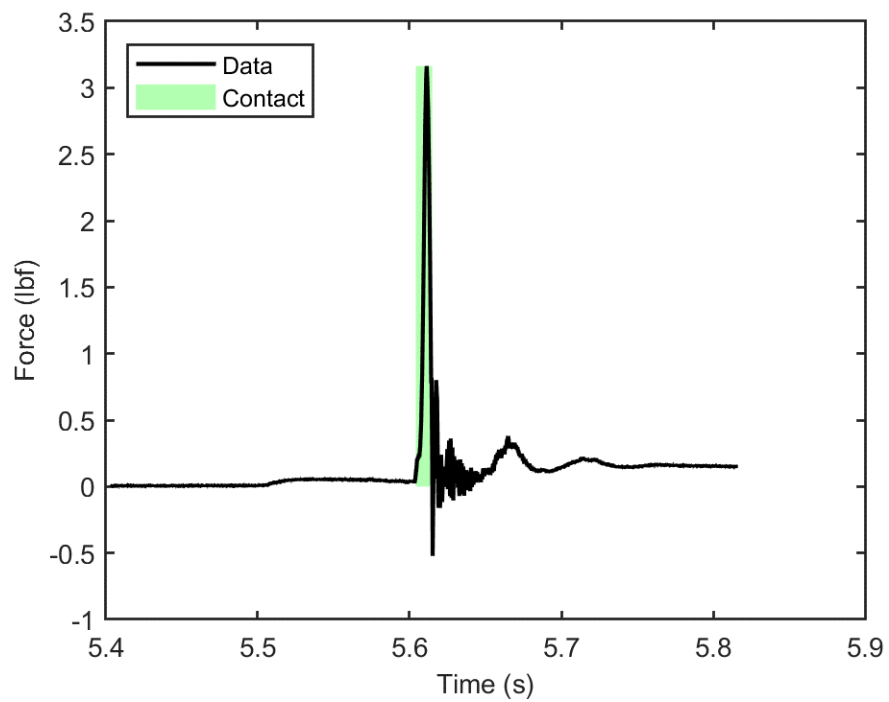


Figure 93. Force data for drop test MD5A, with contact time window marked.

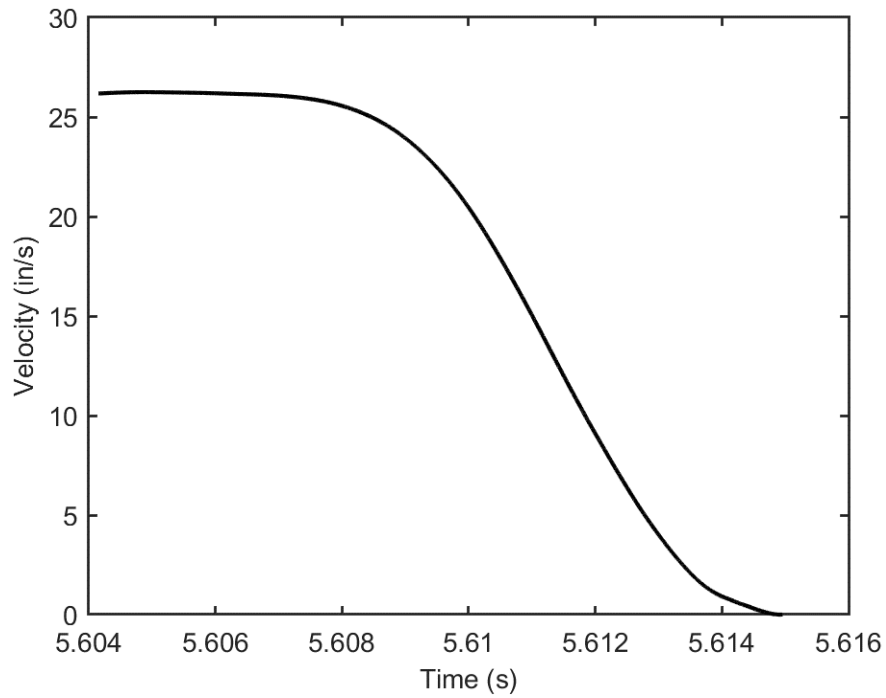


Figure 94. Velocity time history (from force data) for test MD5A during initial contact.

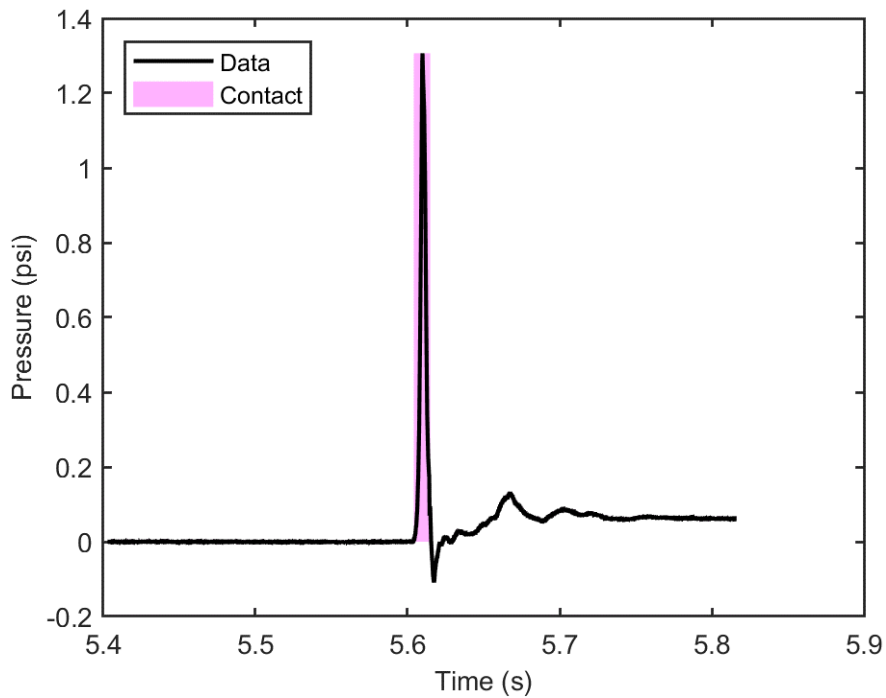


Figure 95. Pressure data for test MD5A, with contact time window marked.

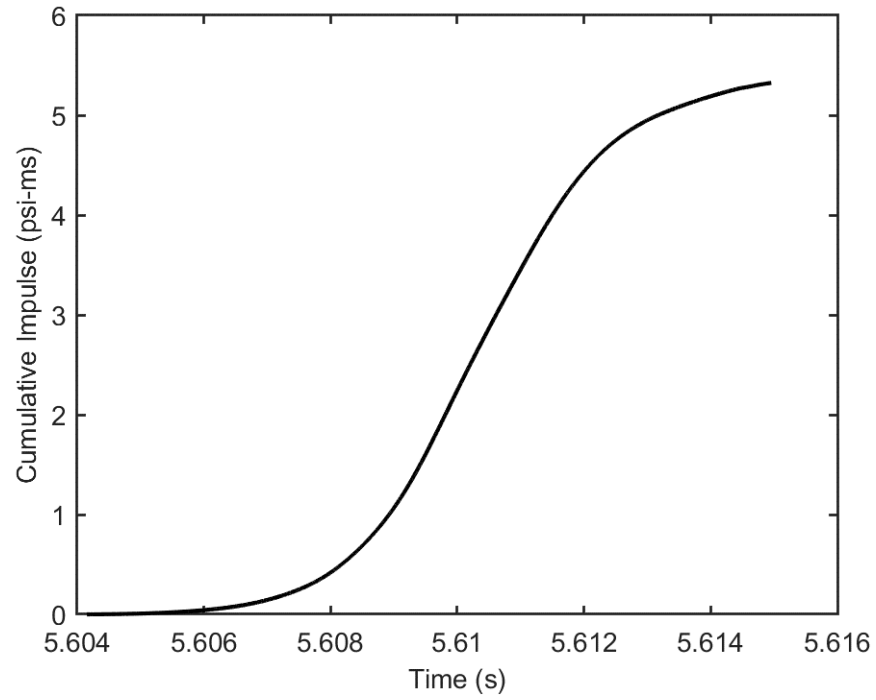


Figure 96. Impulse time history (from pressure data) for test MD5A during initial contact.

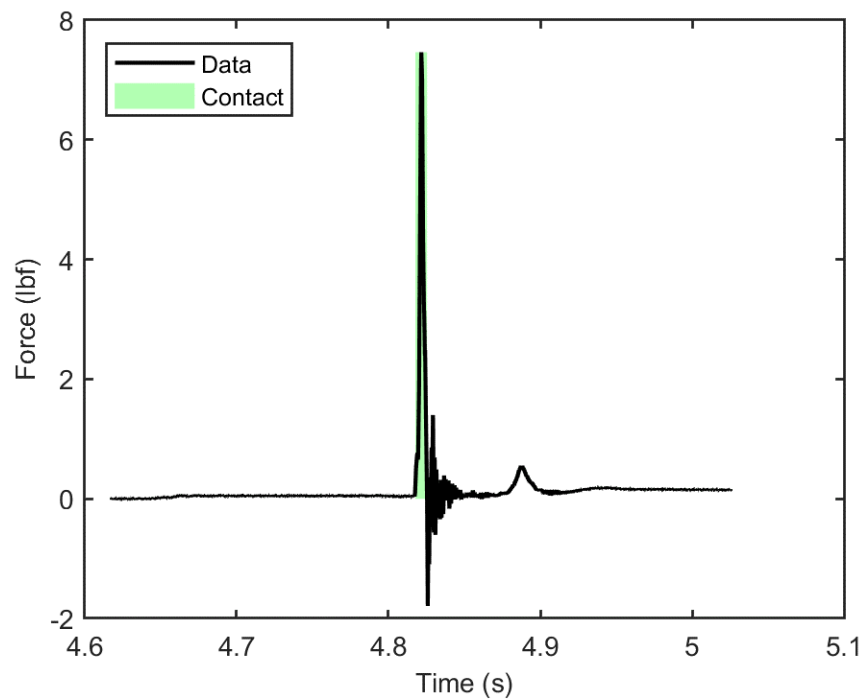


Figure 97. Force data for drop test MD5B, with contact time window marked.

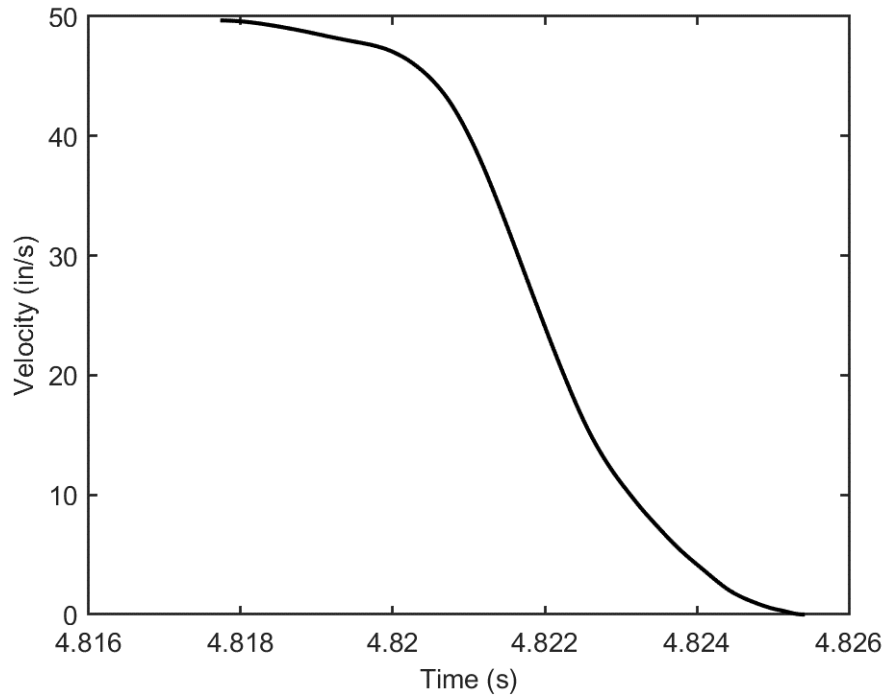


Figure 98. Velocity time history (from force data) for test MD5B during initial contact.

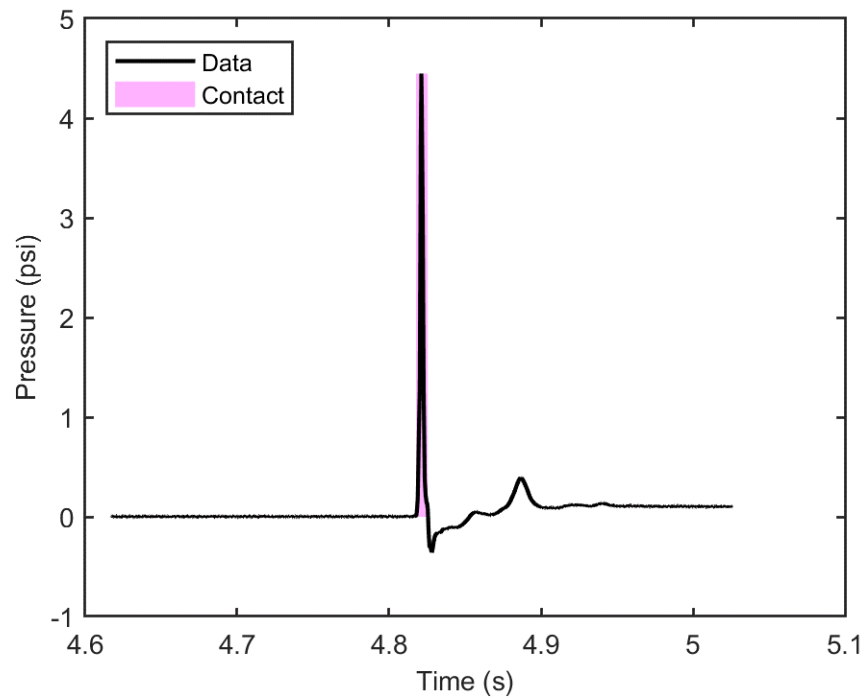


Figure 99. Pressure data for test MD5B, with contact time window marked.

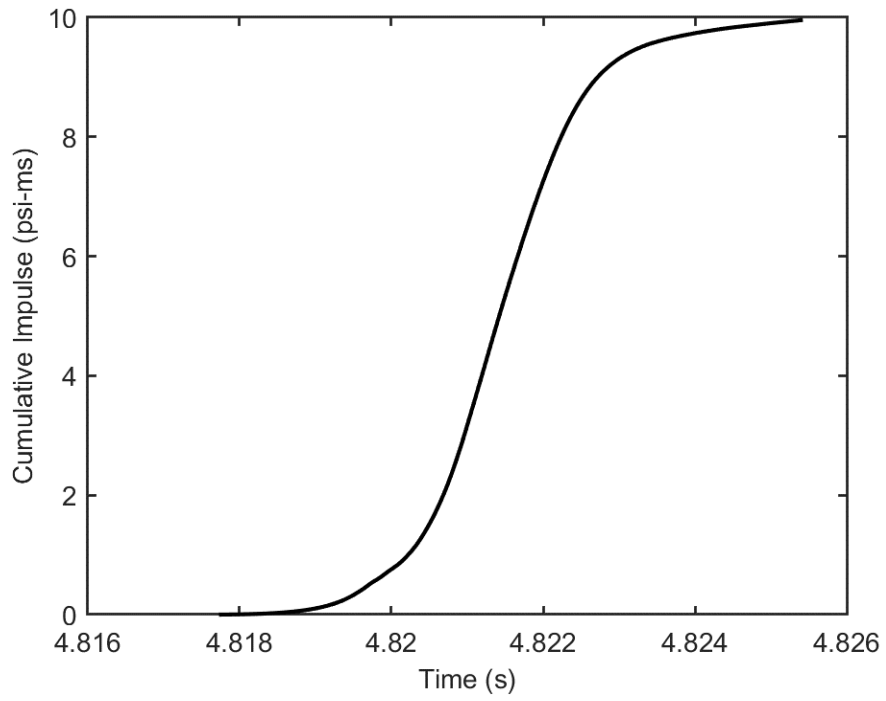


Figure 100. Impulse time history (from pressure data) for test MD5B during initial contact.

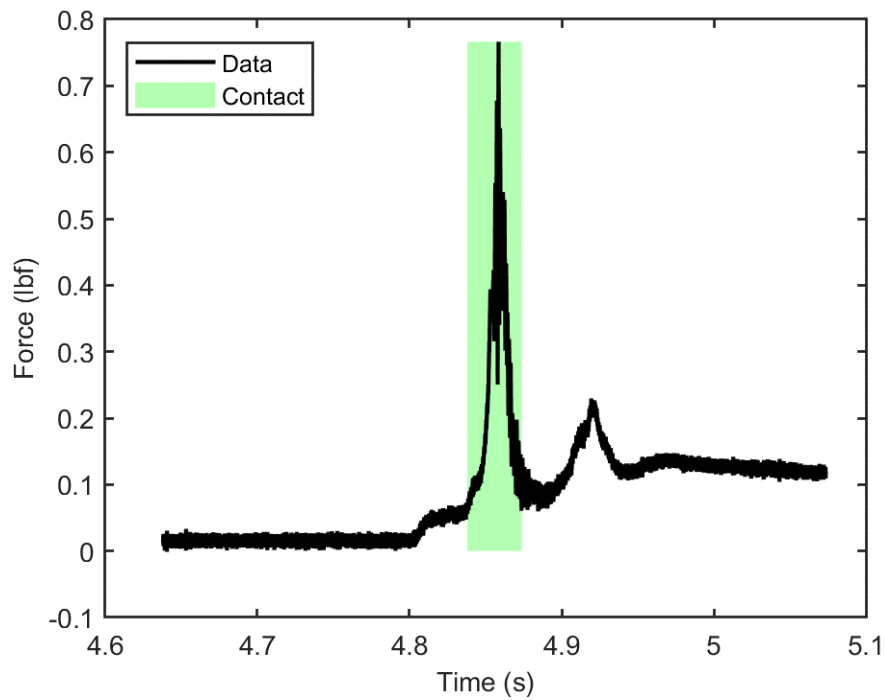


Figure 101. Force data for drop test MD6A, with contact time window marked.

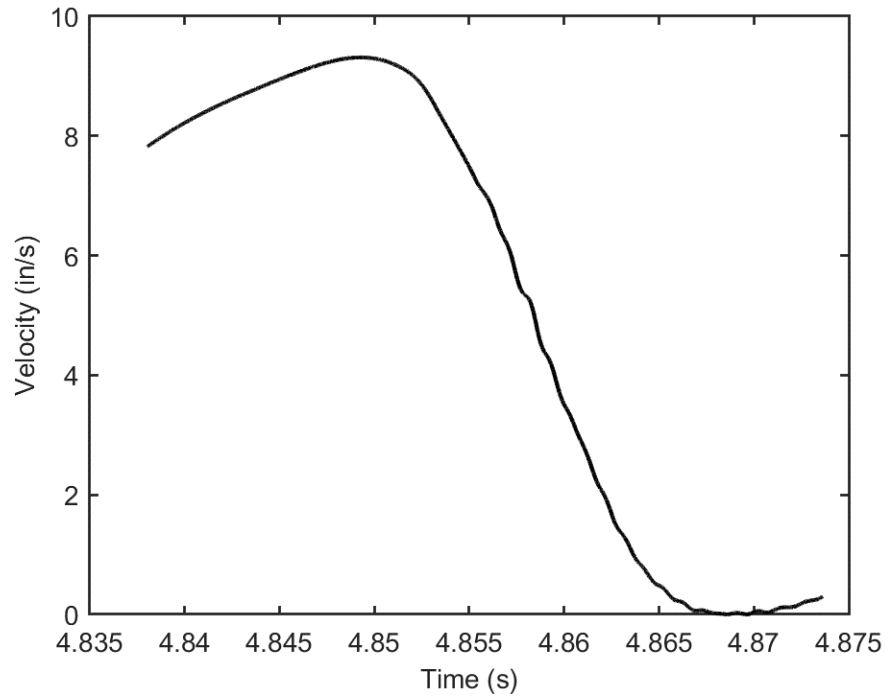


Figure 102. Velocity time history (from force data) for test MD6A during initial contact.

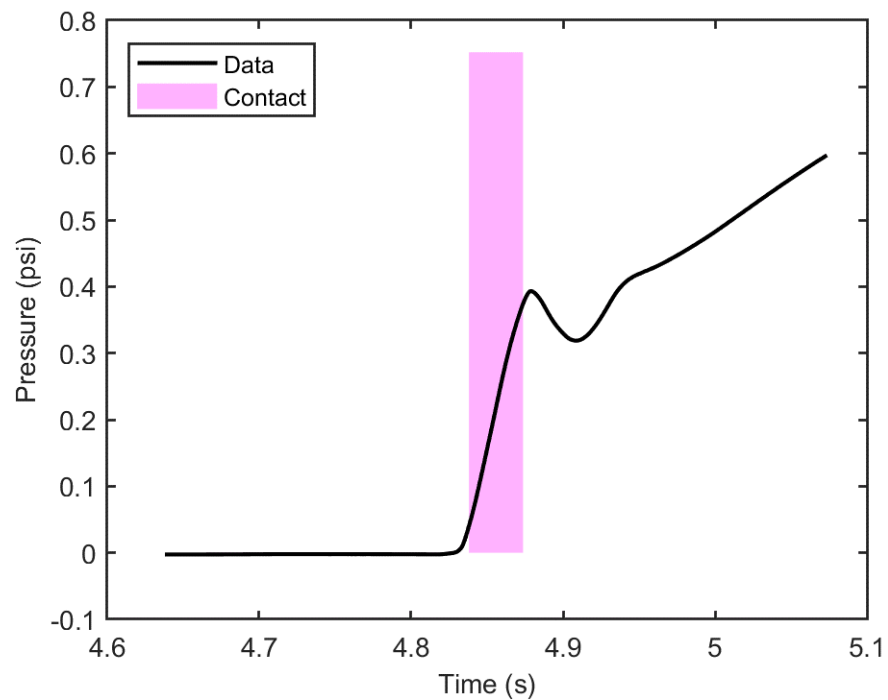


Figure 103. Pressure data for test MD6A, with contact time window marked.

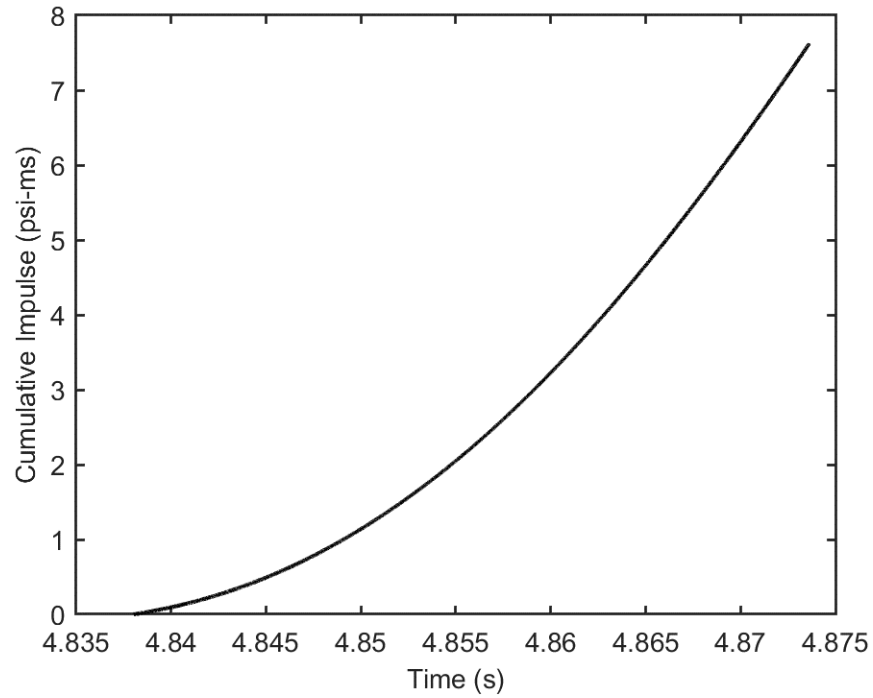


Figure 104. Impulse time history (from pressure data) for test MD6A during initial contact.

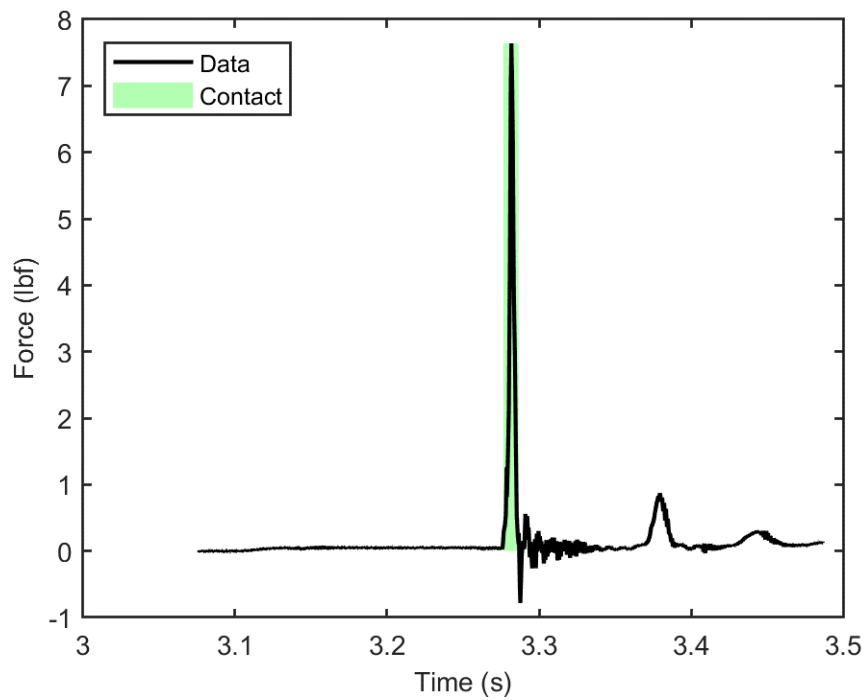


Figure 105. Force data for drop test MD6B, with contact time window marked.

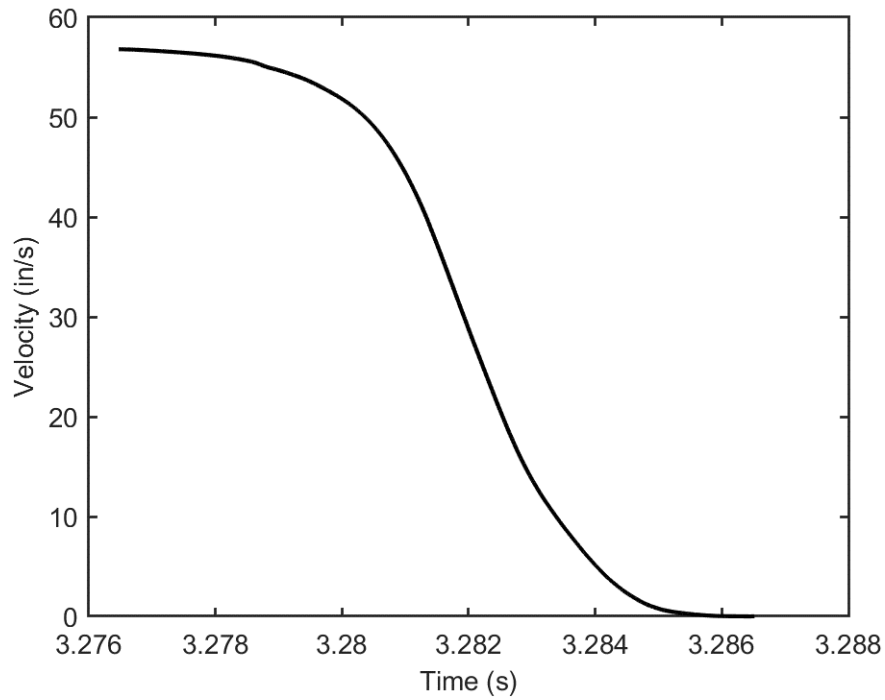


Figure 106. Velocity time history (from force data) for test MD6B during initial contact.

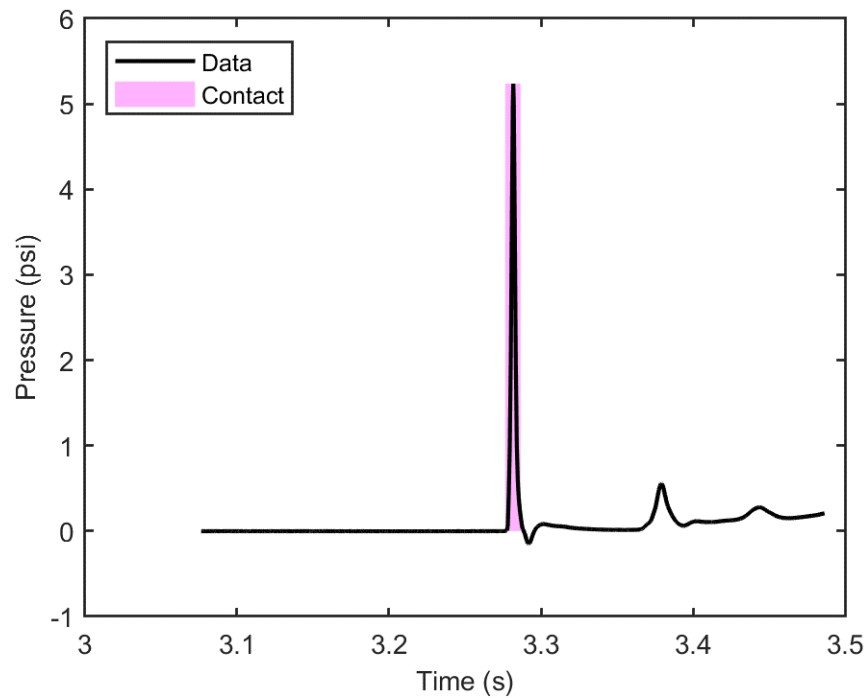


Figure 107. Pressure data for test MD6B, with contact time window marked.

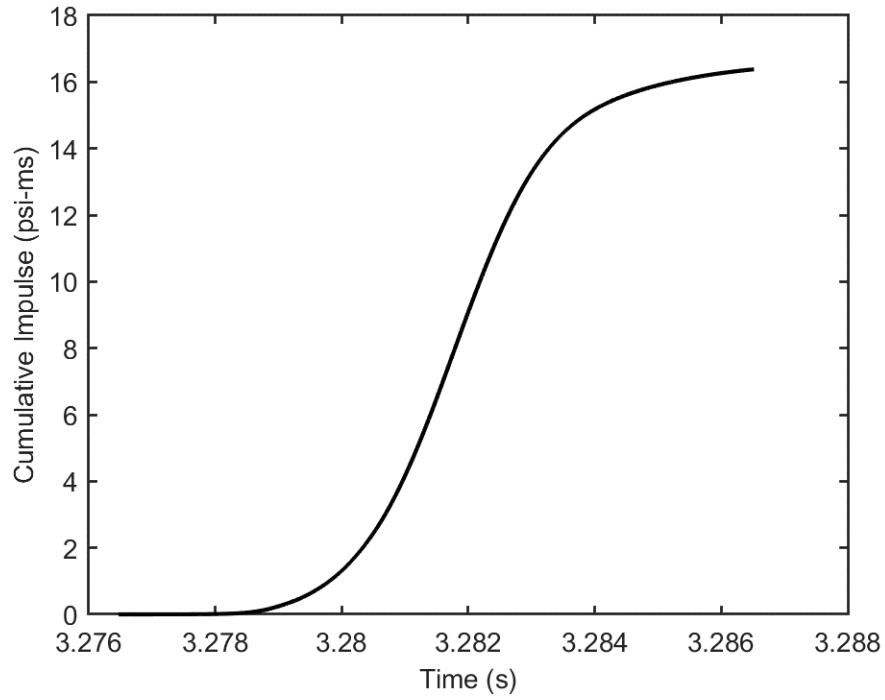


Figure 108. Impulse time history (from pressure data) for test MD6B during initial contact.

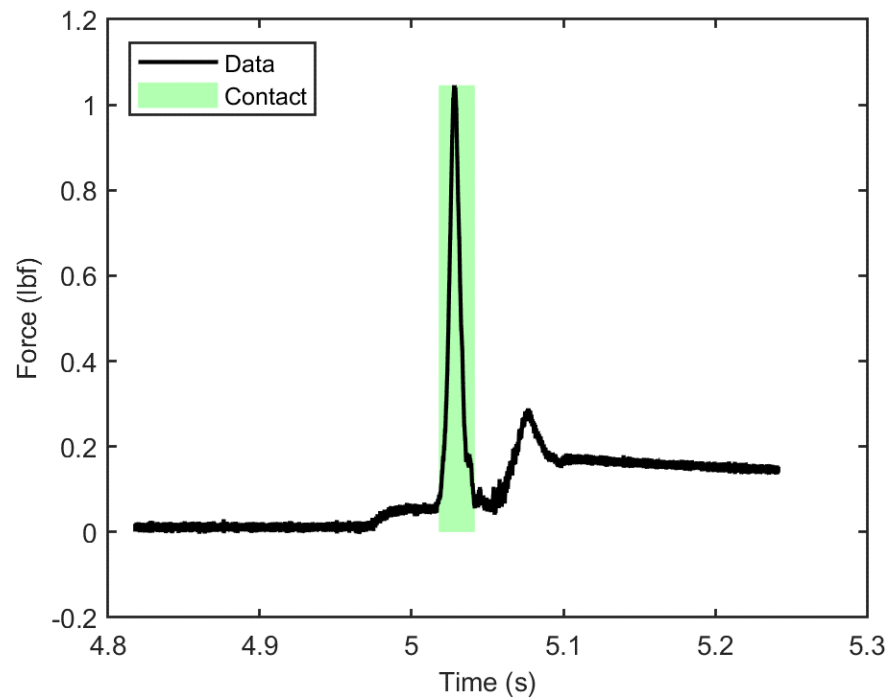


Figure 109. Force data for drop test MD7A, with contact time window marked.

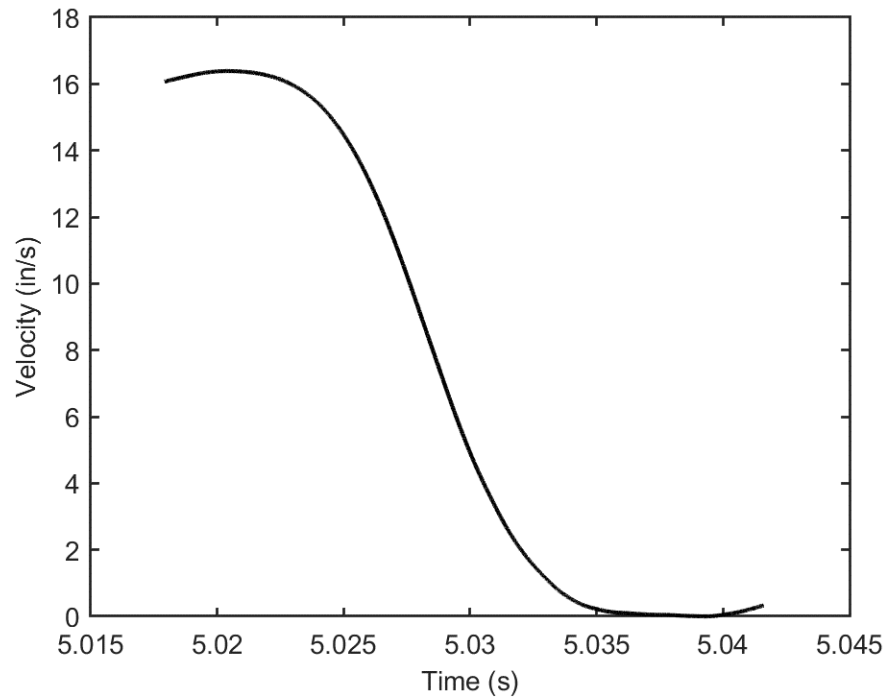


Figure 110. Velocity time history (from force data) for test MD7A during initial contact.

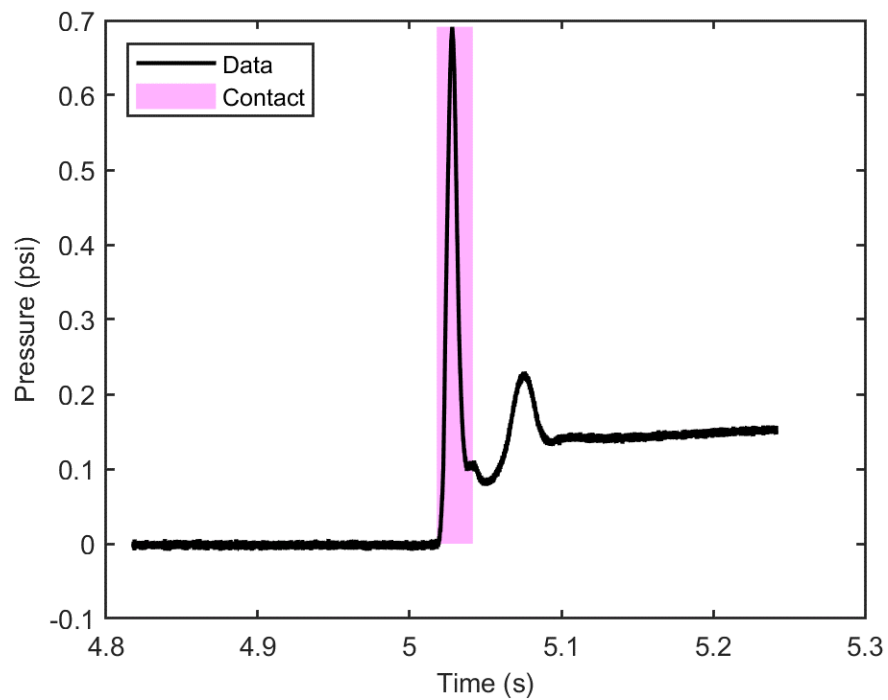


Figure 111. Pressure data for test MD7A, with contact time window marked.

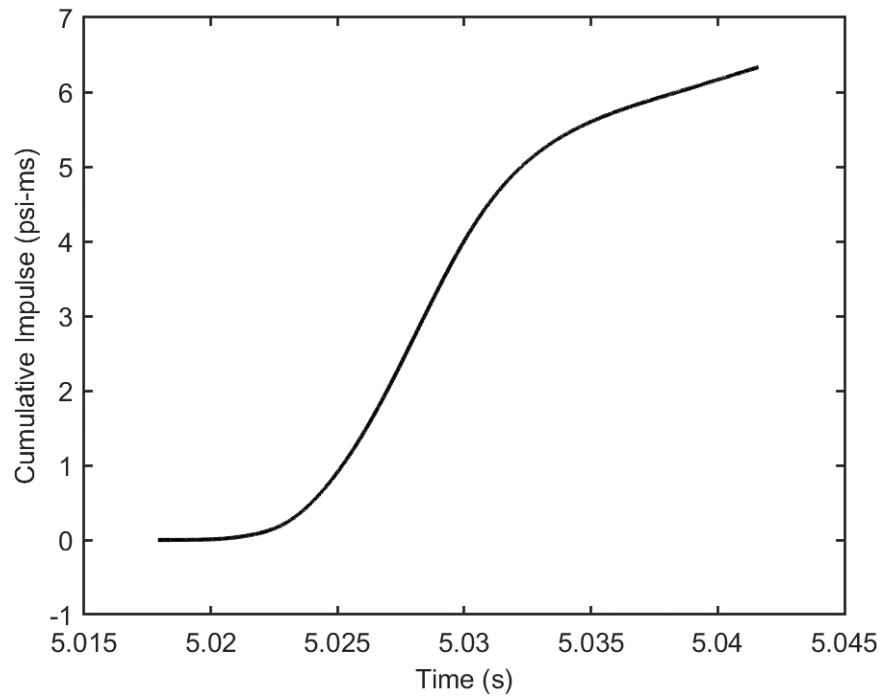


Figure 112. Impulse time history (from pressure data) for test MD7A during initial contact.

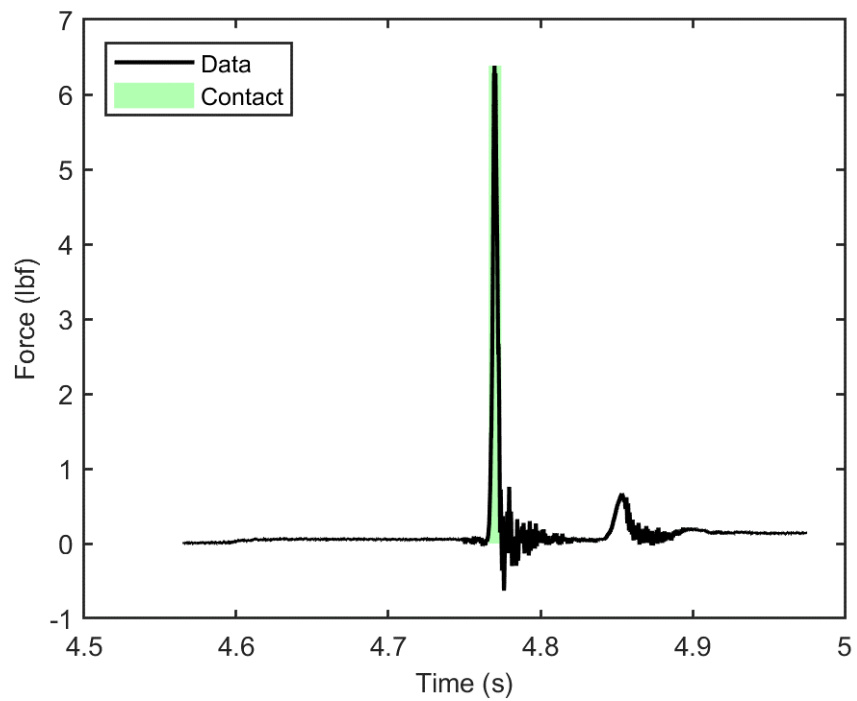


Figure 113. Force data for drop test MD7B, with contact time window marked.

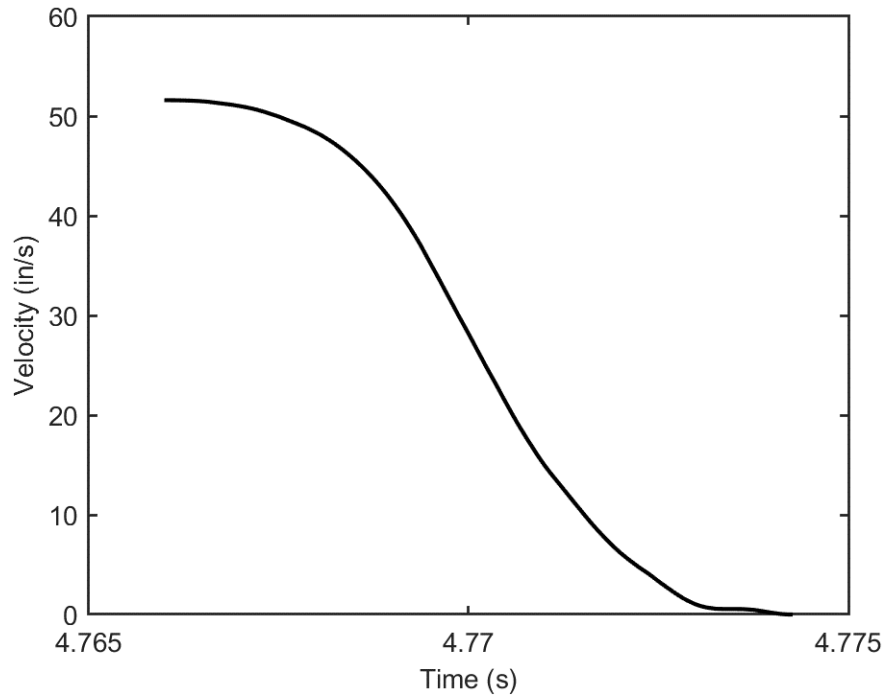


Figure 114. Velocity time history (from force data) for test MD7B during initial contact.

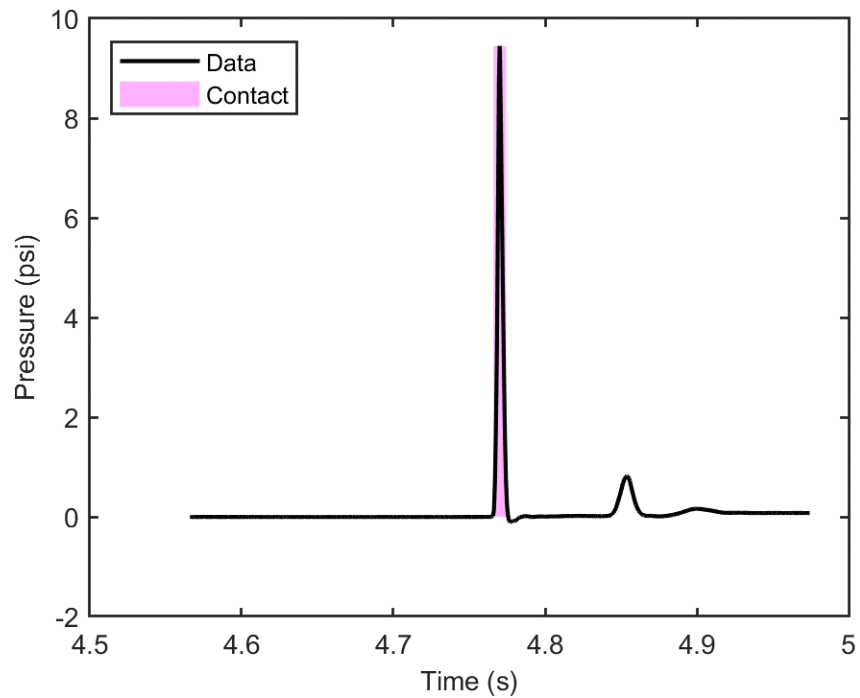


Figure 115. Pressure data for test MD7B, with contact time window marked.

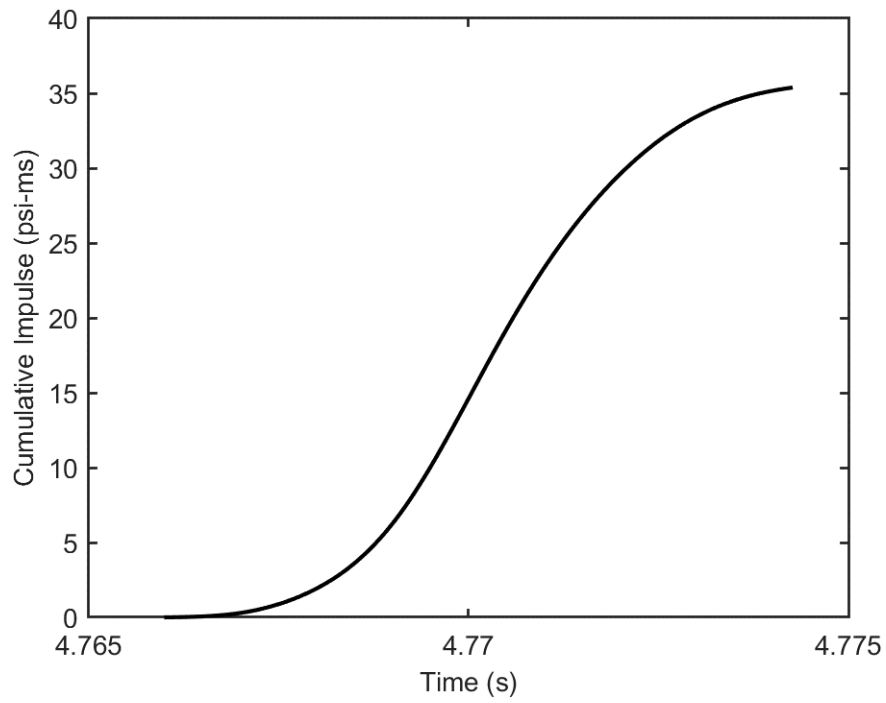


Figure 116. Impulse time history (from pressure data) for test MD7B during initial contact.

B.2.2 Melon, Harbor Porpoise (*Phocoena phocoena*)

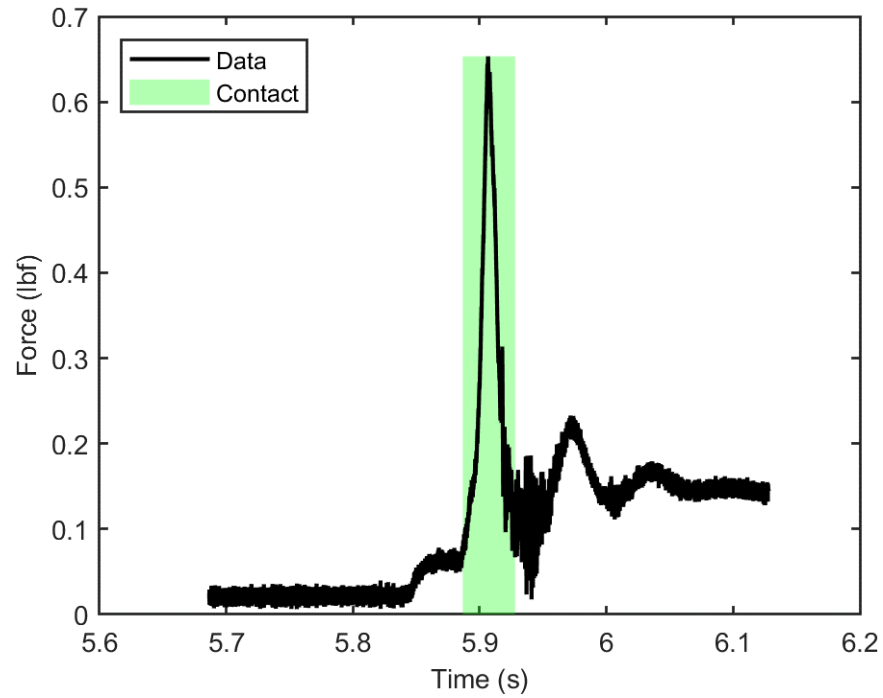


Figure 117. Force data for drop test MP1A, with contact time window marked.

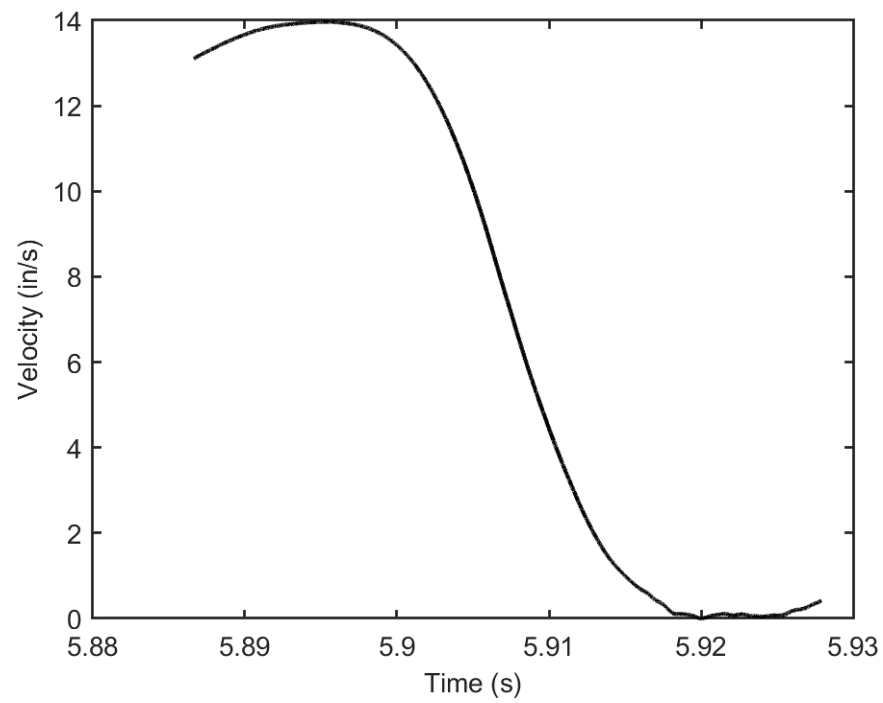


Figure 118. Velocity time history (from force data) for test MP1A during initial contact.

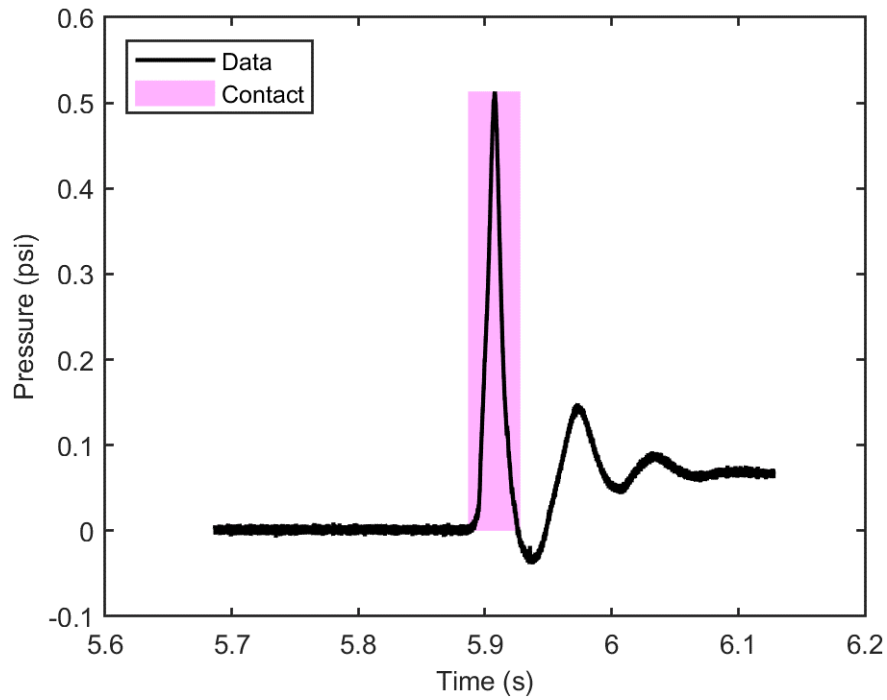


Figure 119. Pressure data for test MP1A, with contact time window marked.

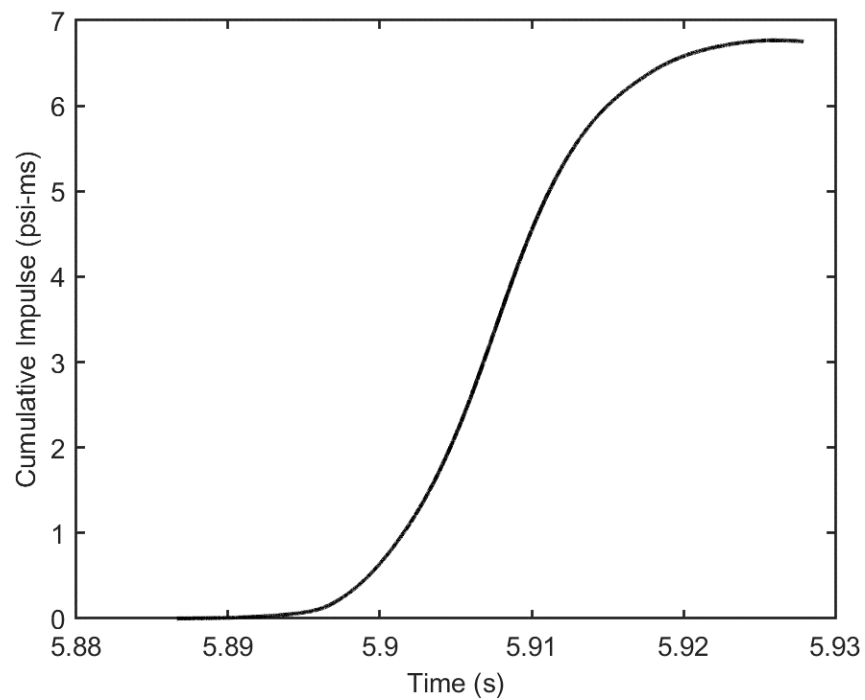


Figure 120. Impulse time history (from pressure data) for test MP1A during initial contact.

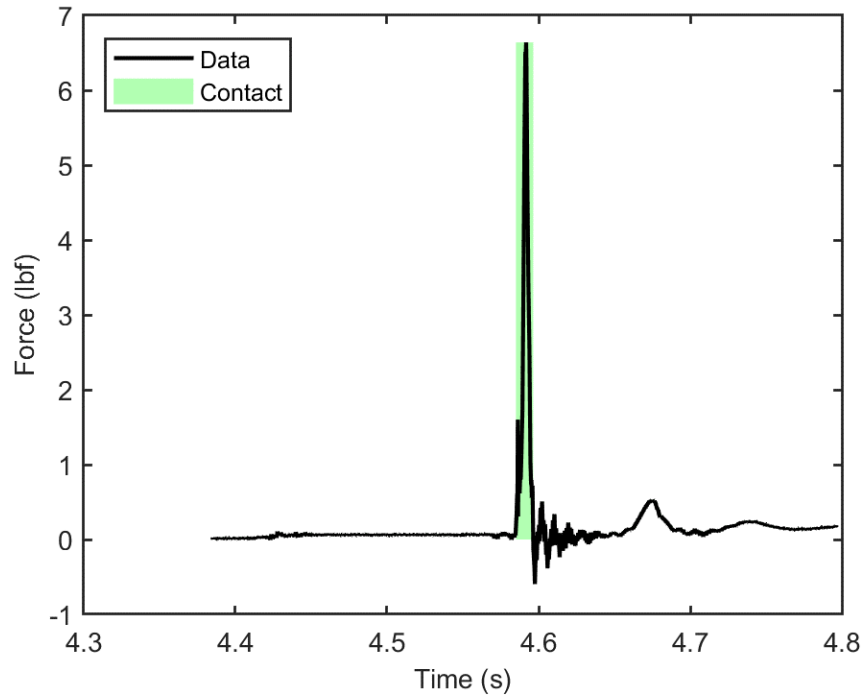


Figure 121. Force data for drop test MP1B, with contact time window marked.

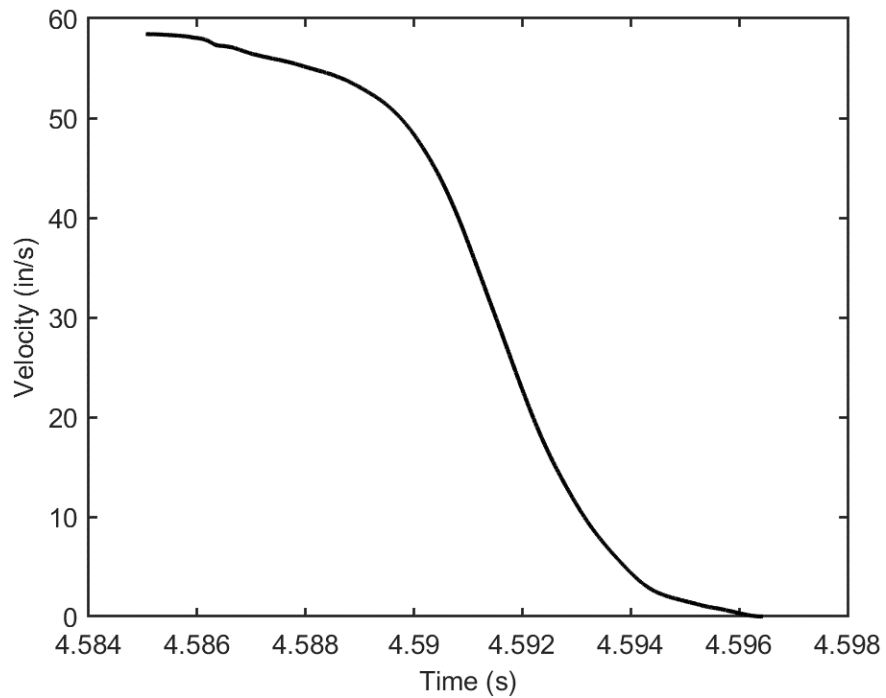


Figure 122. Velocity time history (from force data) for test MP1B during initial contact.

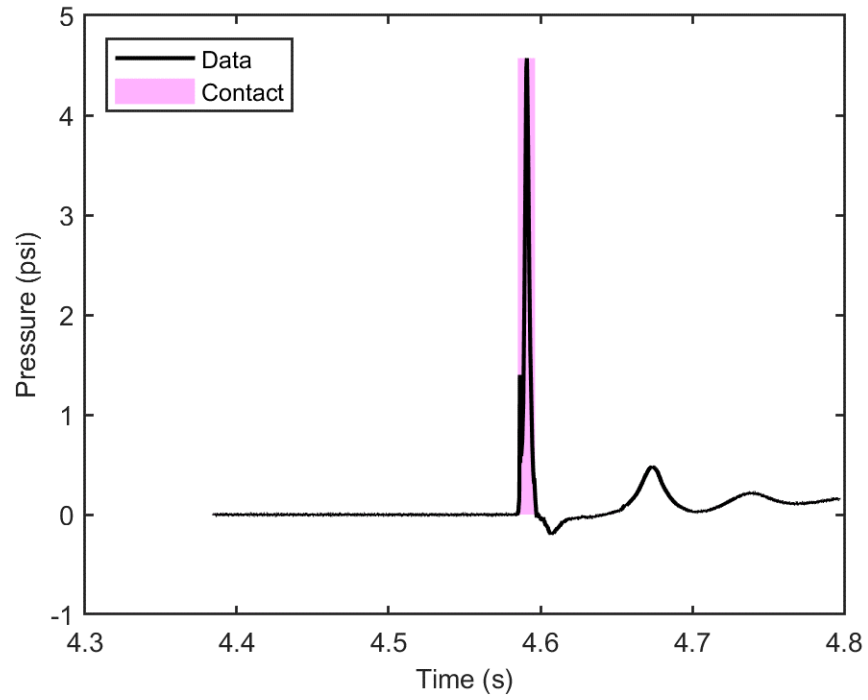


Figure 123. Pressure data for test MP1B, with contact time window marked.

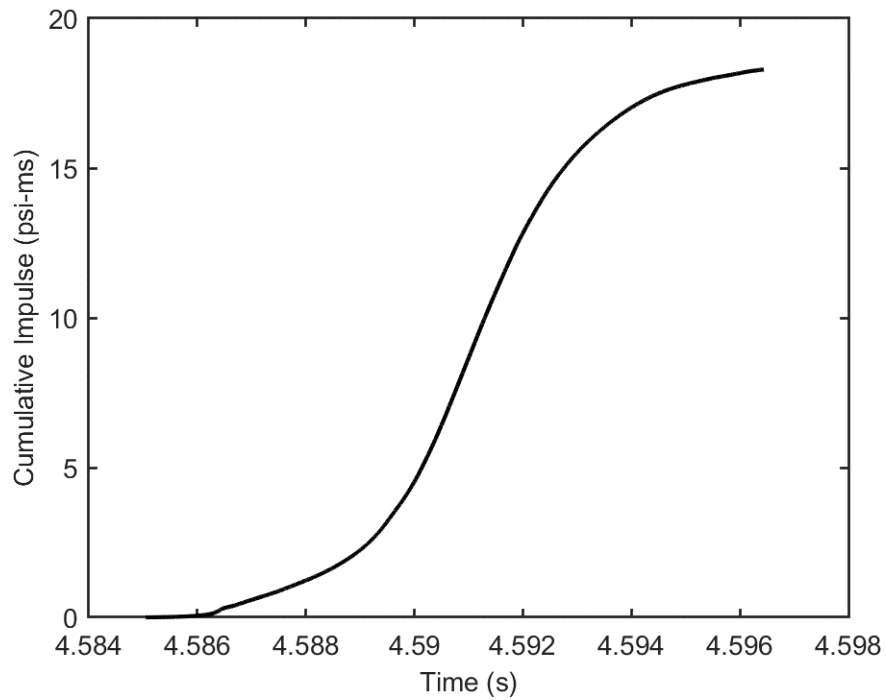


Figure 124. Impulse time history (from pressure data) for test MP1B during initial contact.

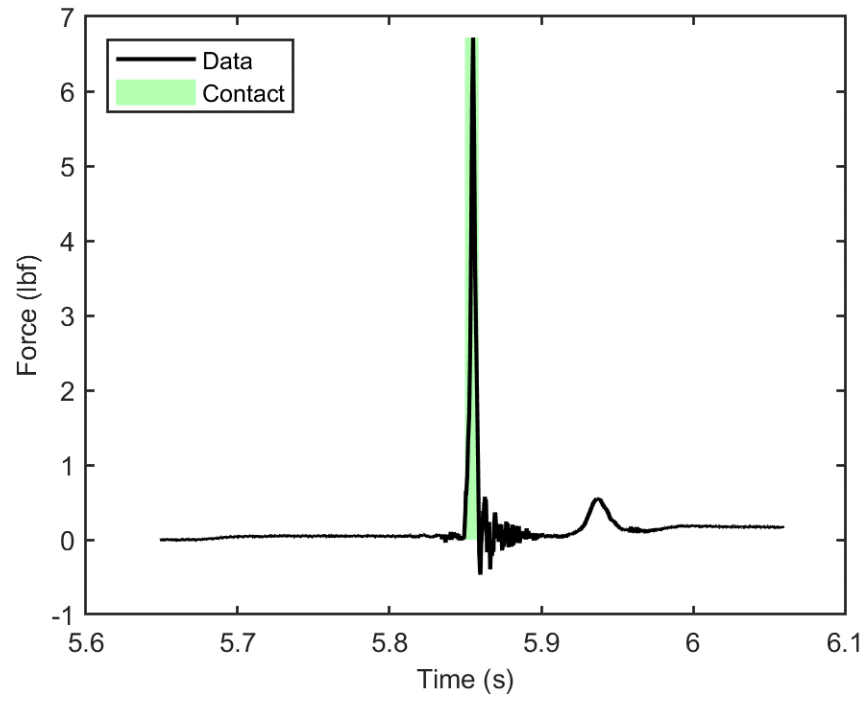


Figure 125. Force data for drop test MP2A, with contact time window marked.

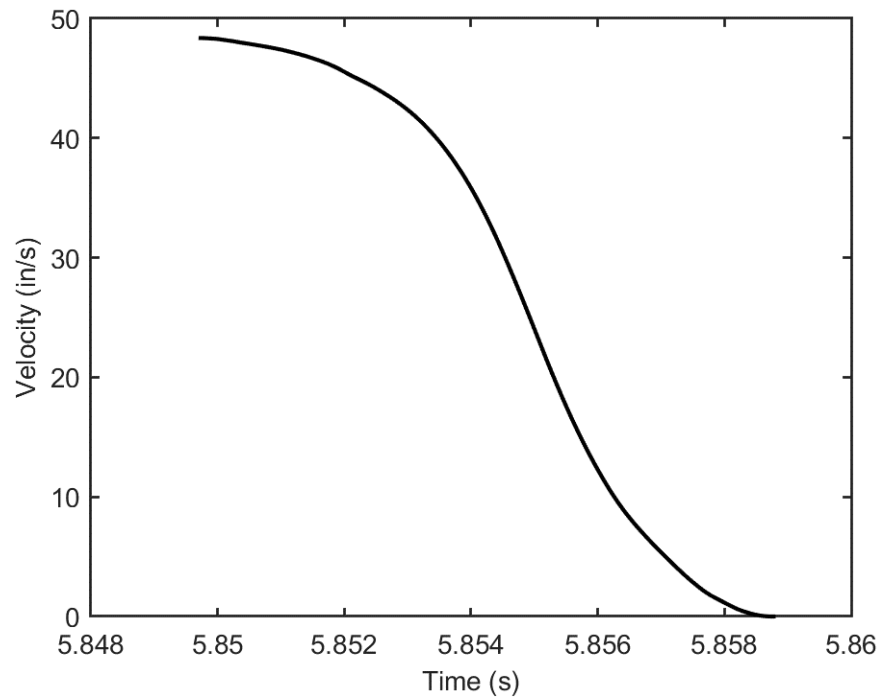


Figure 126. Velocity time history (from force data) for test MP2A during initial contact.

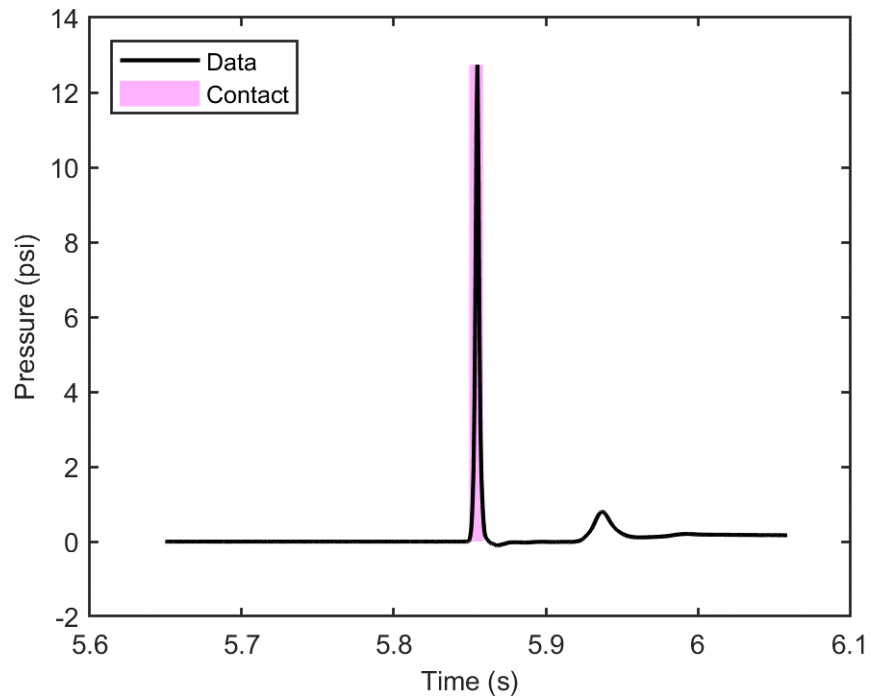


Figure 127. Pressure data for test MP2A, with contact time window marked.

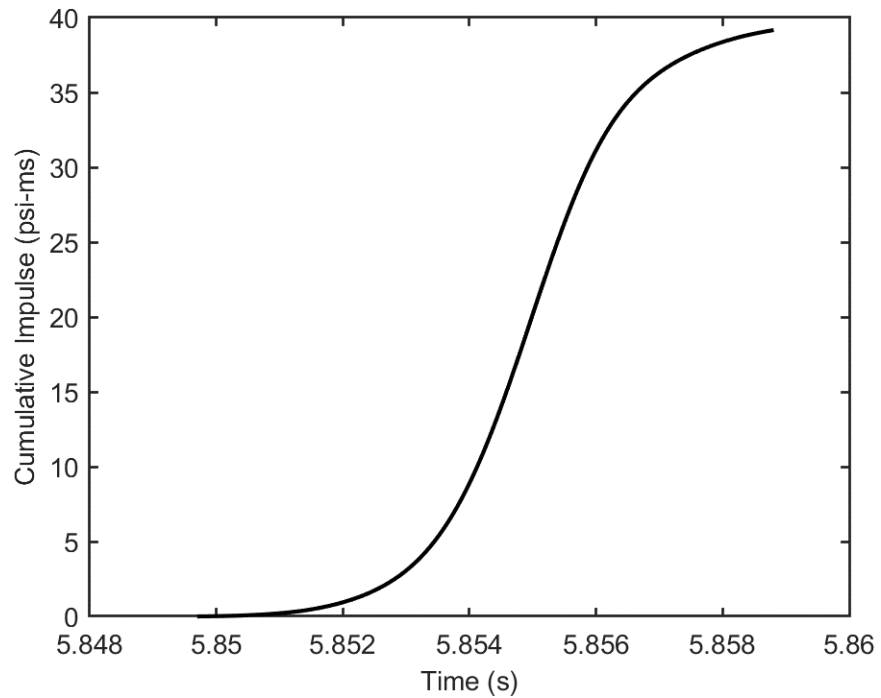


Figure 128. Impulse time history (from pressure data) for test MP2A during initial contact.

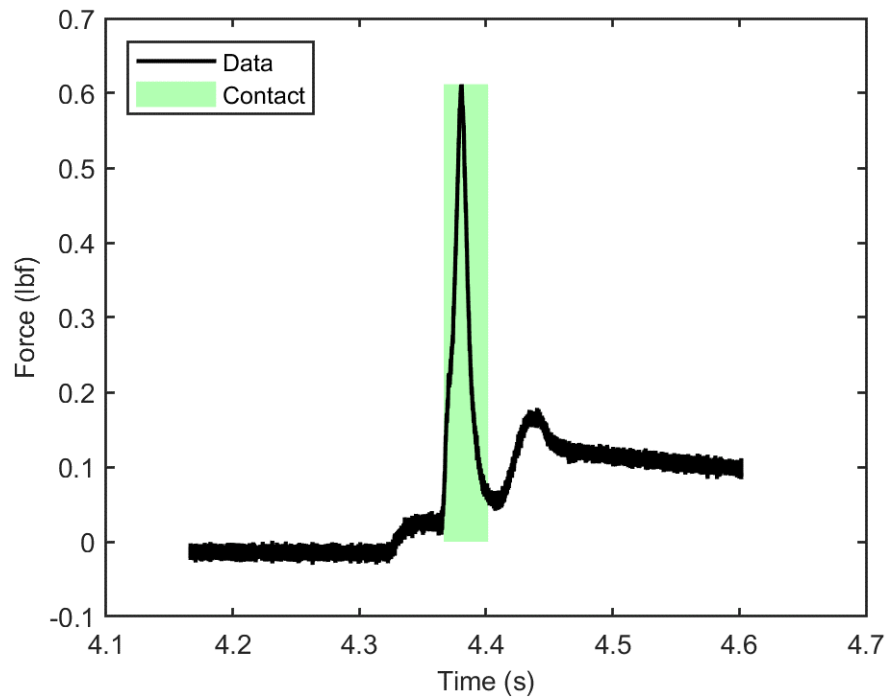


Figure 129. Force data for drop test MP3A, with contact time window marked.

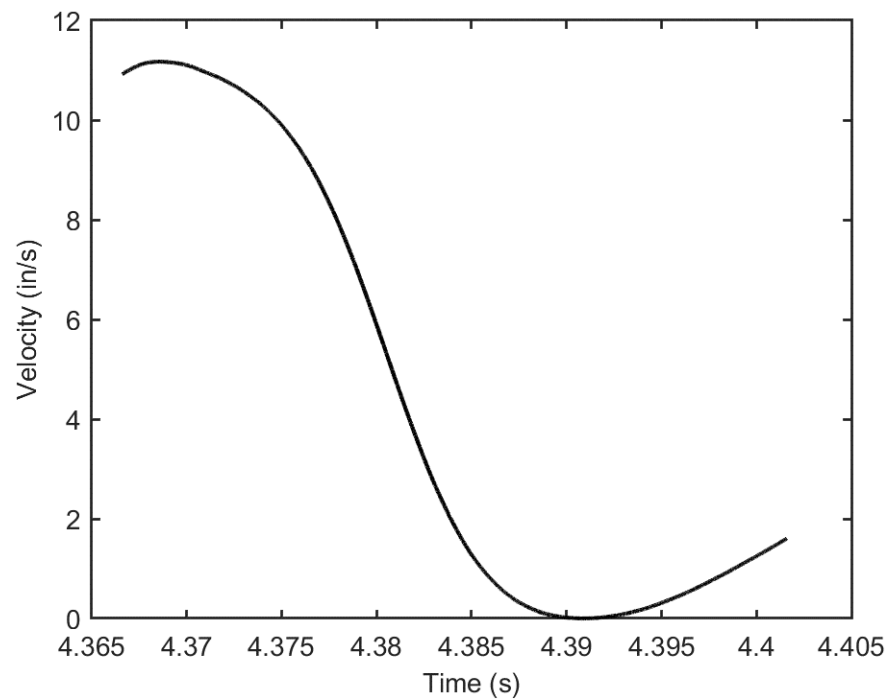


Figure 130. Velocity time history (from force data) for test MP3A during initial contact.

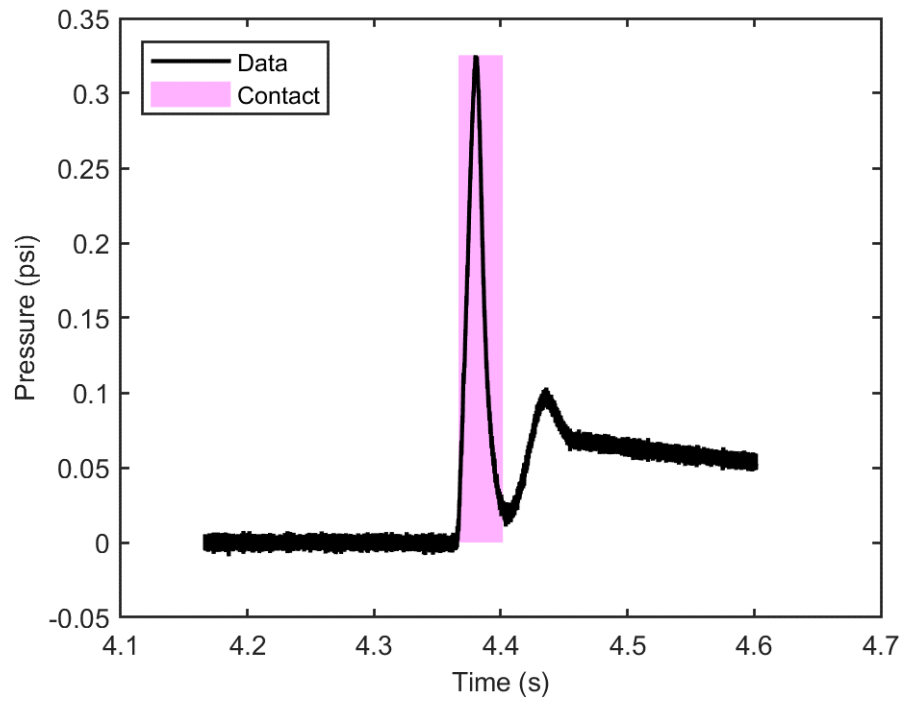


Figure 131. Pressure data for test MP3A, with contact time window marked.

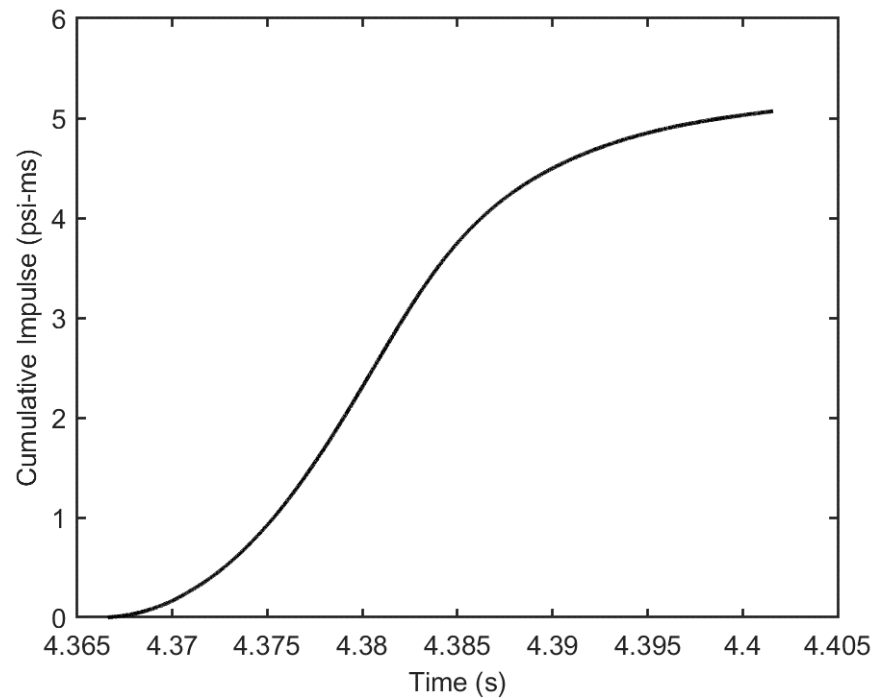


Figure 132. Impulse time history (from pressure data) for test MP3A during initial contact.

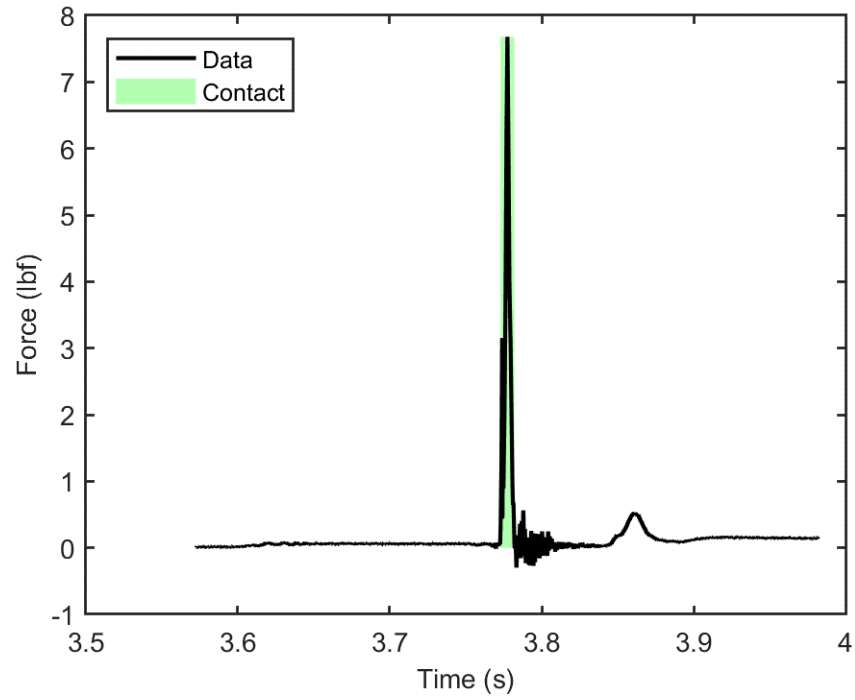


Figure 133. Force data for drop test MP3B, with contact time window marked.

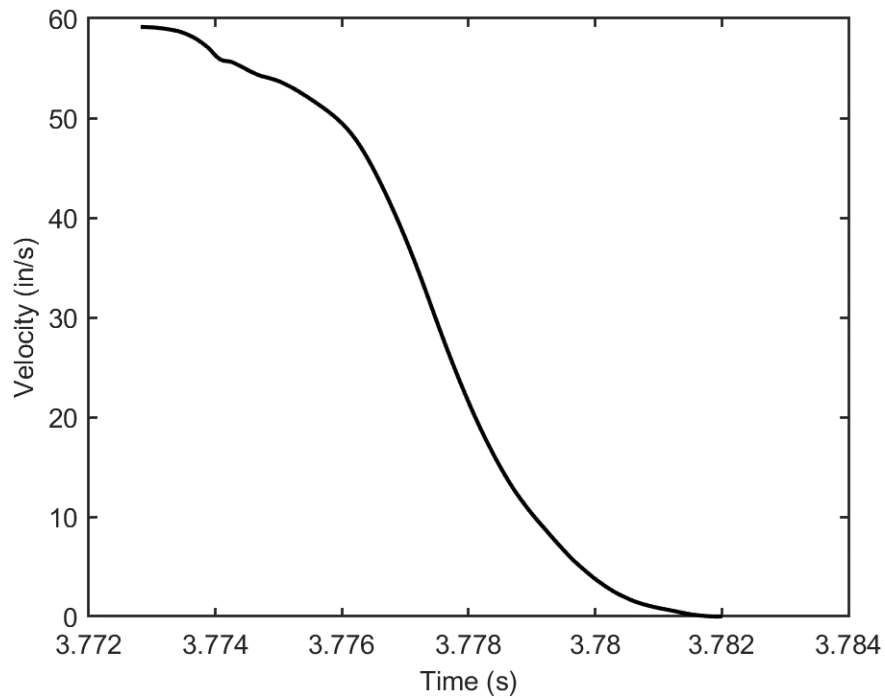


Figure 134. Velocity time history (from force data) for test MP3B during initial contact.

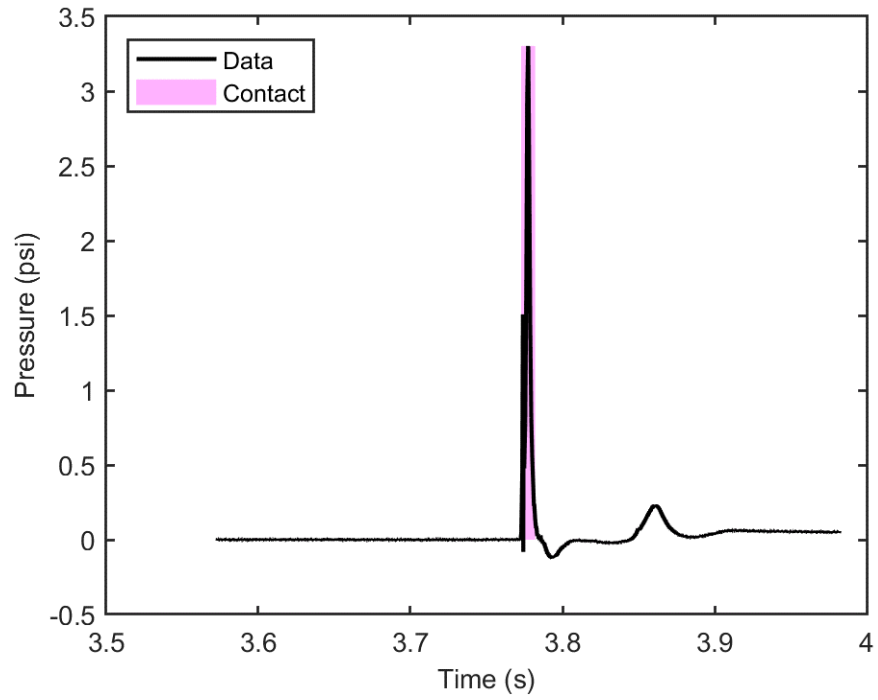


Figure 135. Pressure data for test MP3B, with contact time window marked.

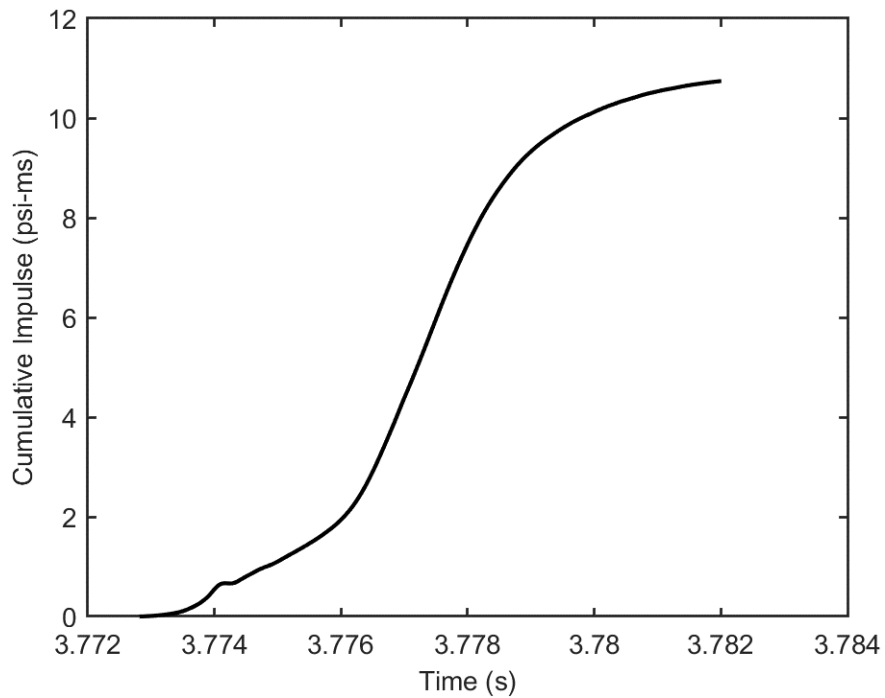


Figure 136. Impulse time history (from pressure data) for test MP3B during initial contact.

B.2.3 Ecoflex, Solid

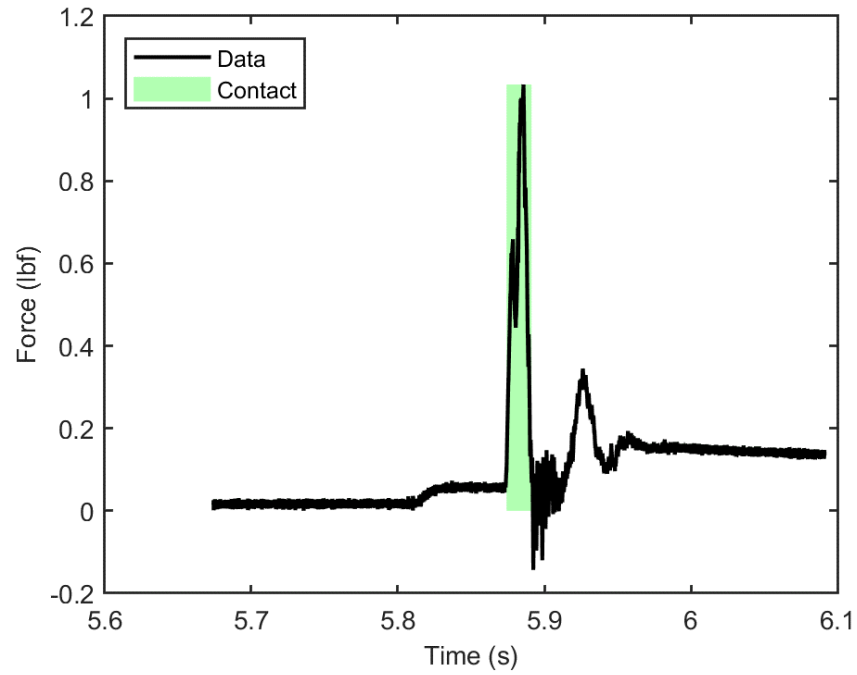


Figure 137. Force time history for drop test E1A, with contact time window marked.

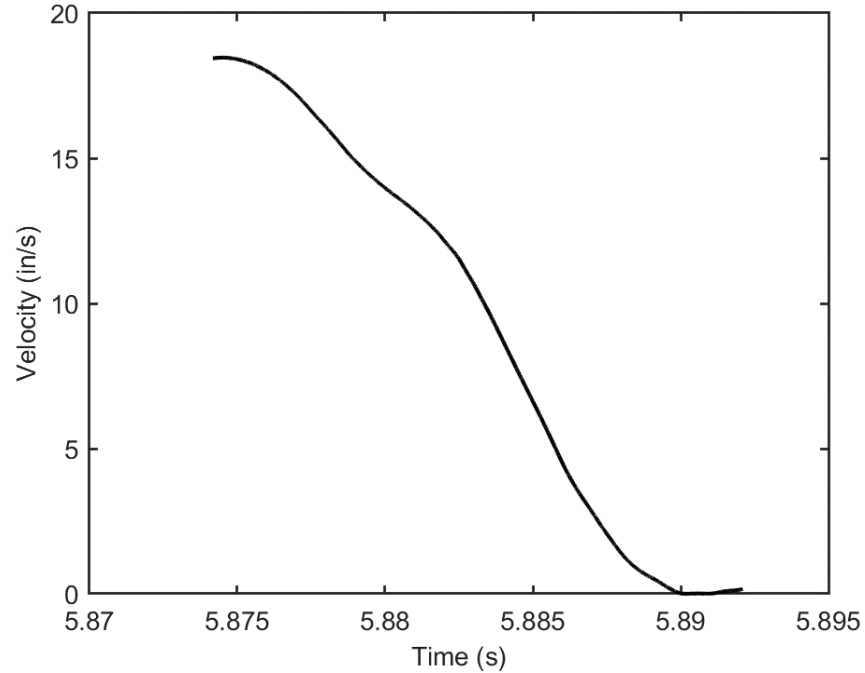


Figure 138. Velocity time history (from force data) for test E1A during initial contact.

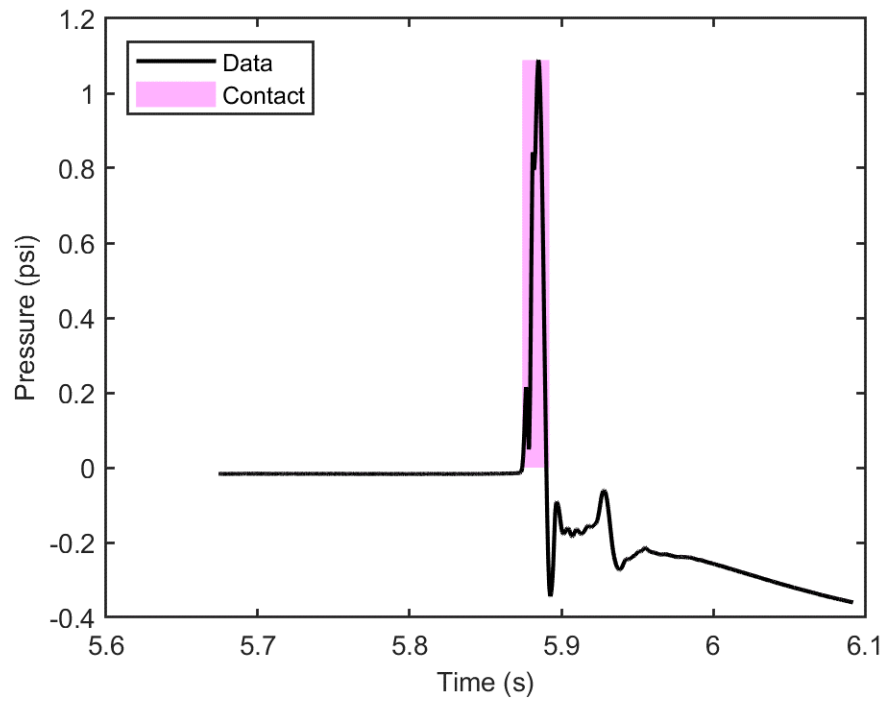


Figure 139. Pressure data for test E1A, with contact time window marked.

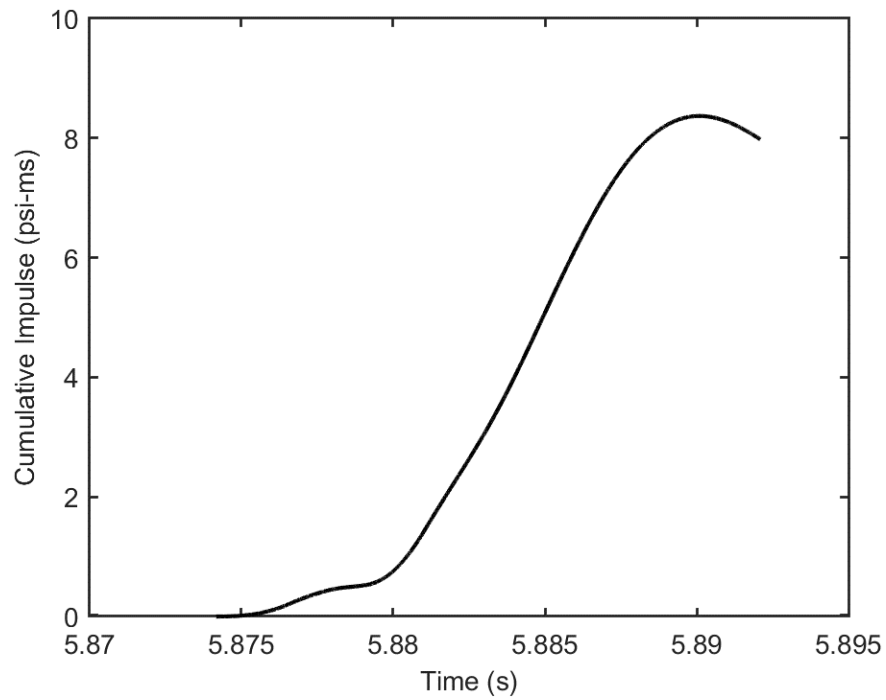


Figure 140. Impulse time history (from pressure data) for test E1A during initial contact.

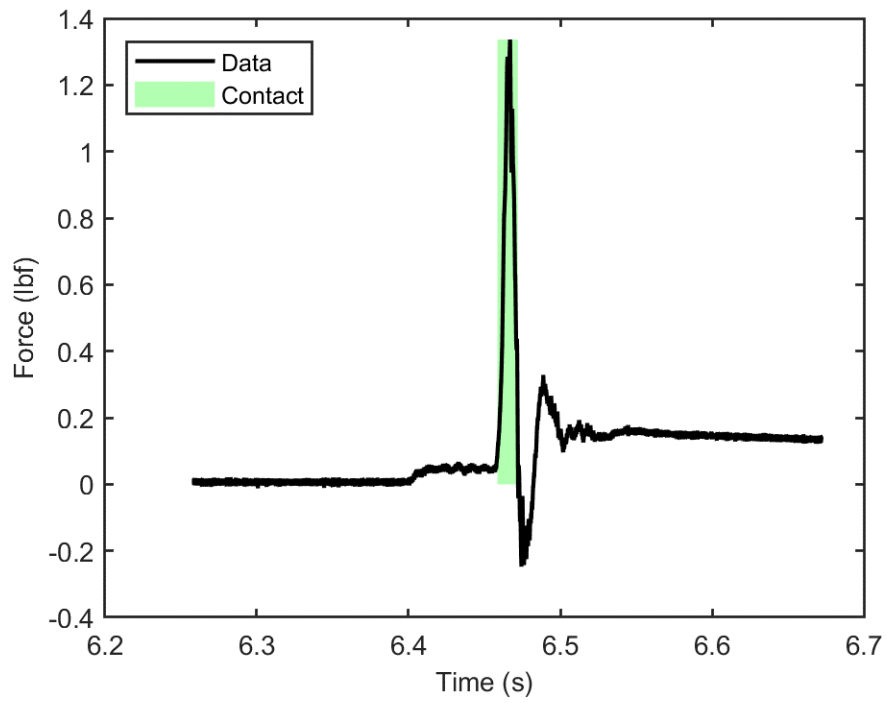


Figure 141. Force data for drop test E1A2, with contact time window marked.

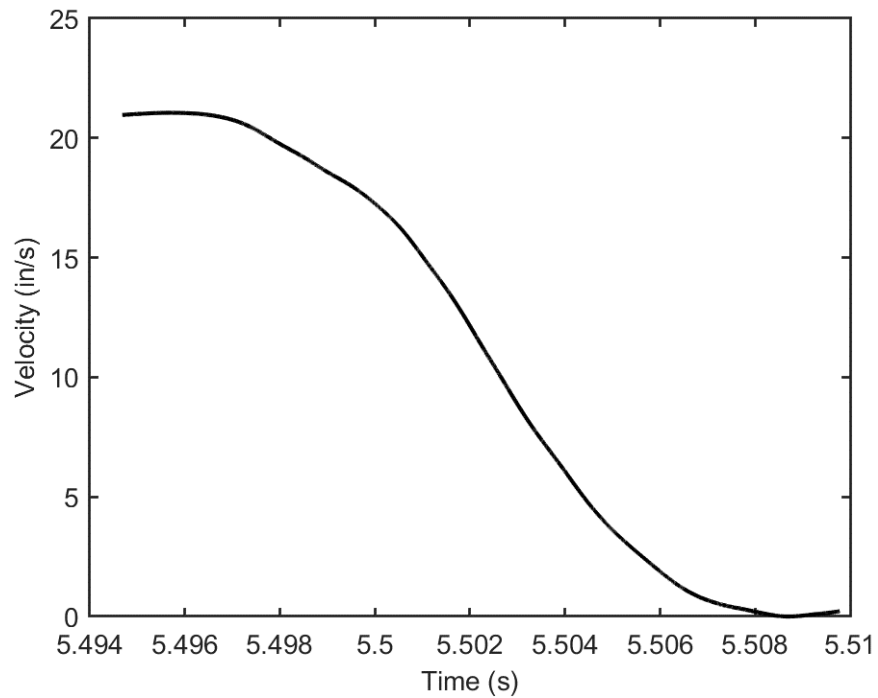


Figure 142. Velocity time history (from force data) for test E1A2 during initial contact.

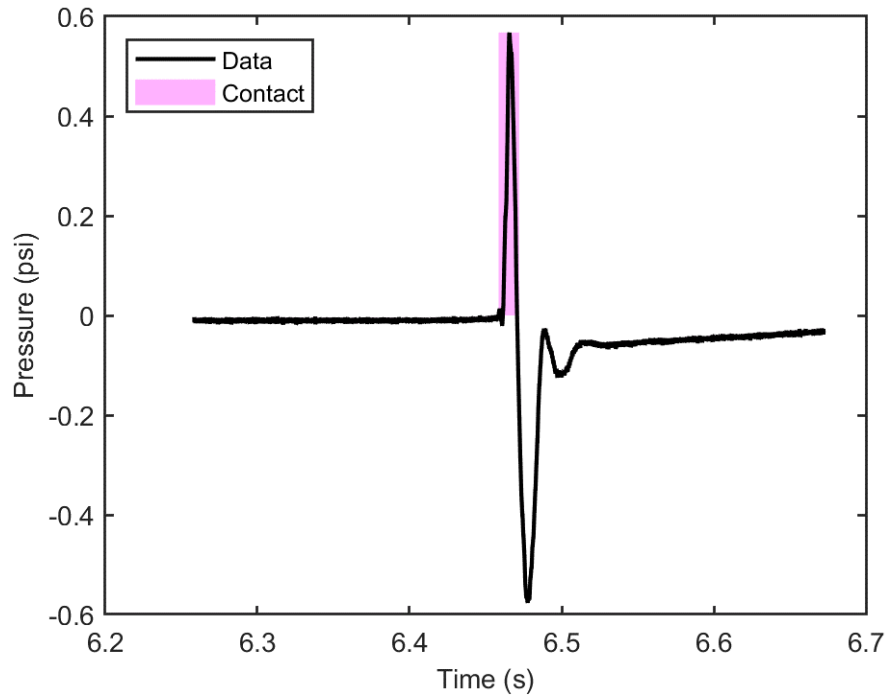


Figure 143. Pressure data for test E1A2, with contact time window marked.

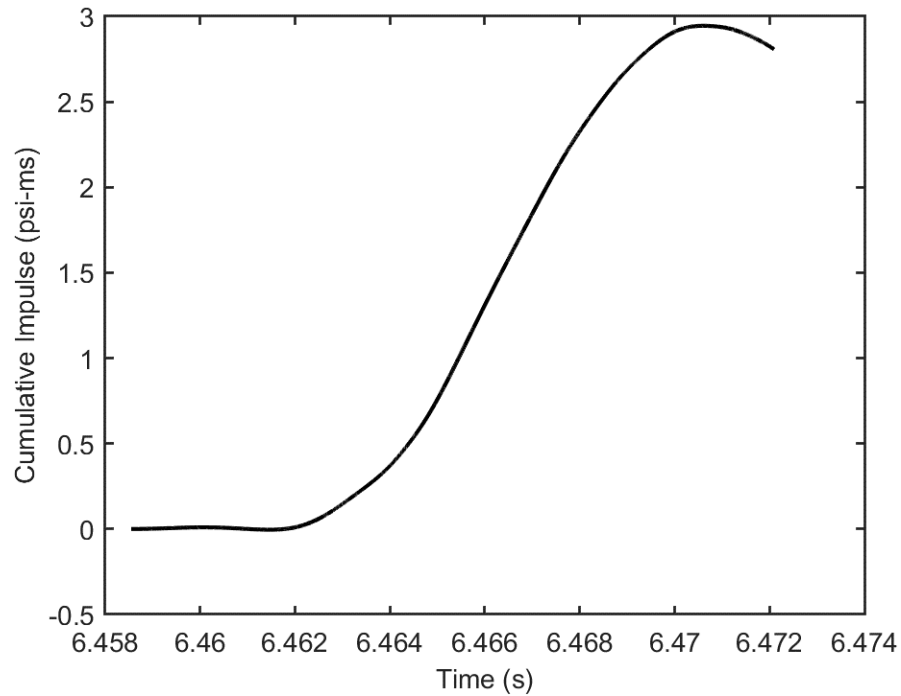


Figure 144. Impulse time history (from pressure data) for test E1A2 during initial contact.

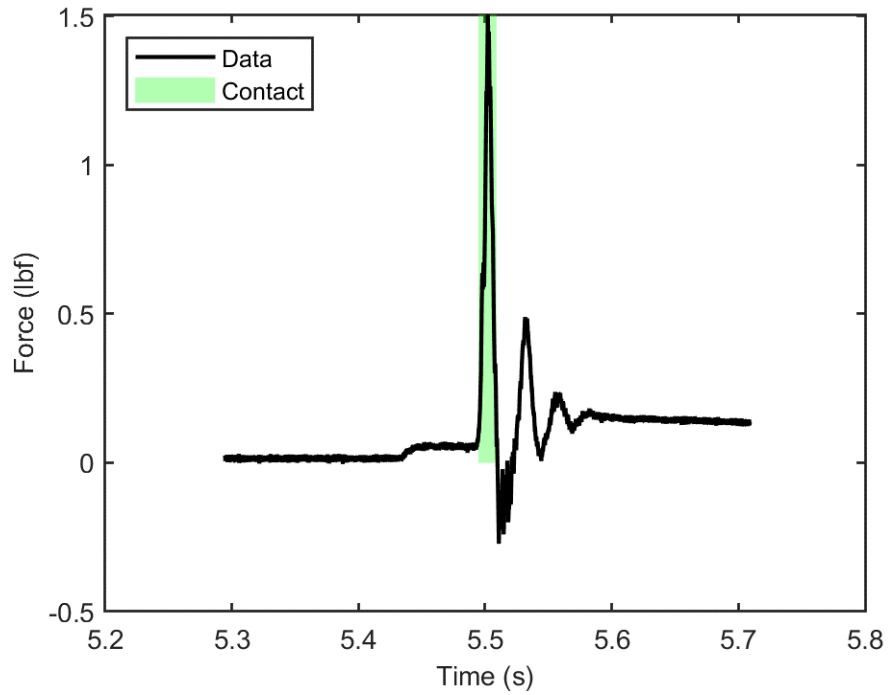


Figure 145. Force data for drop test E2A, with contact time window marked.

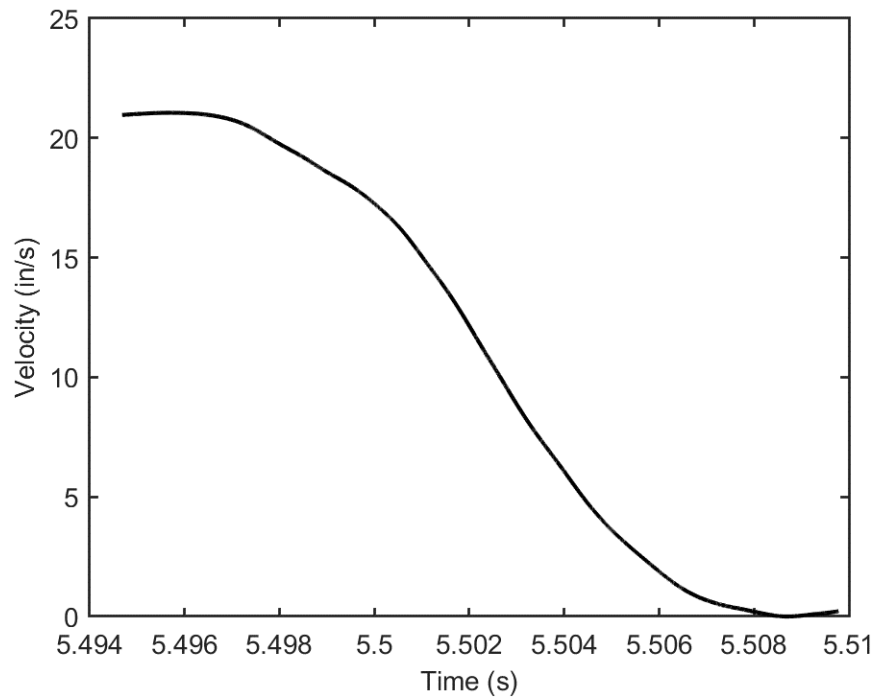


Figure 146. Velocity time history (from force data) for test E2A during initial contact.

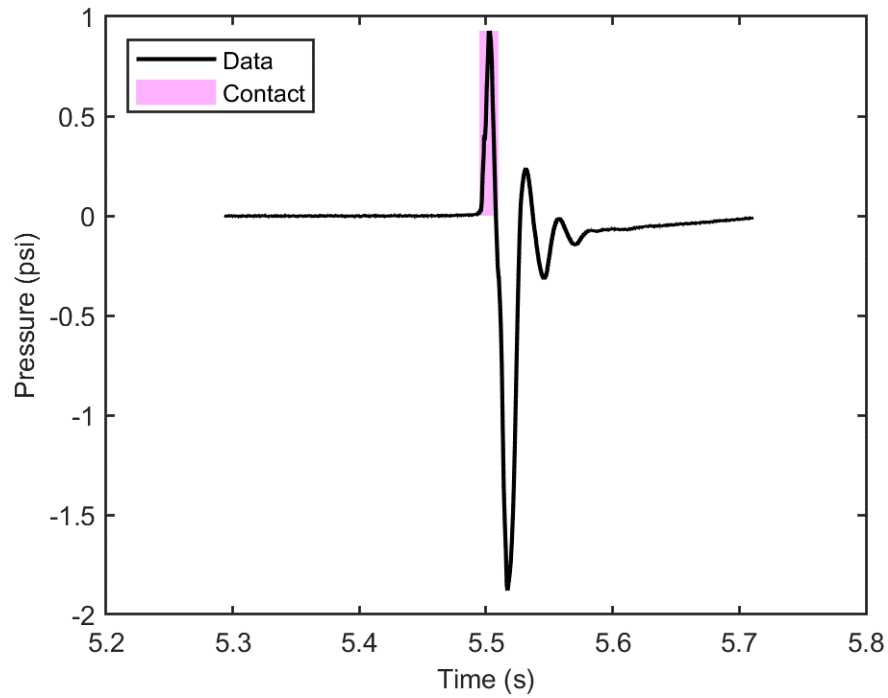


Figure 147. Pressure data for test E2A, with contact time window marked.

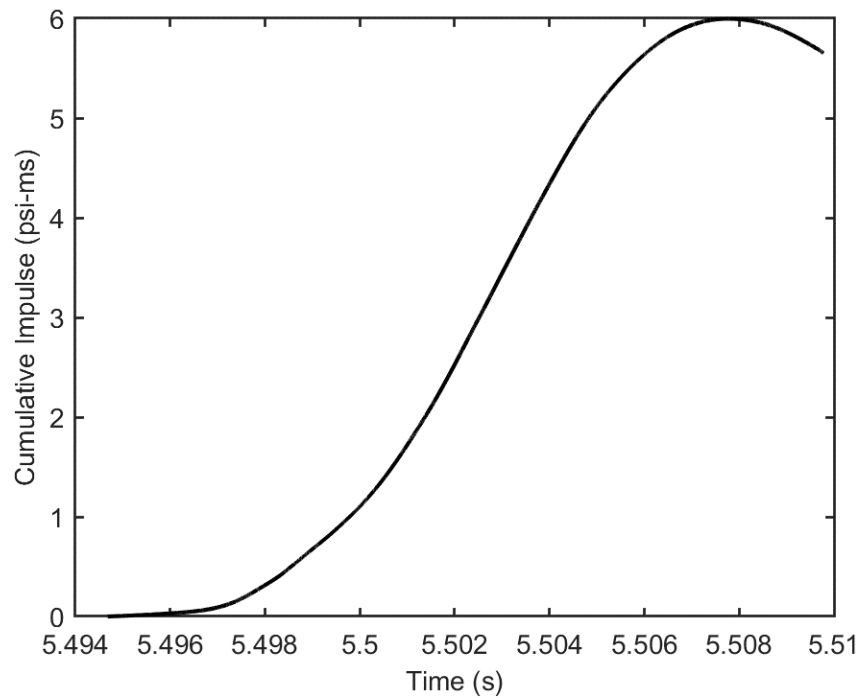


Figure 148. Impulse time history (from pressure data) for test E2A during initial contact.

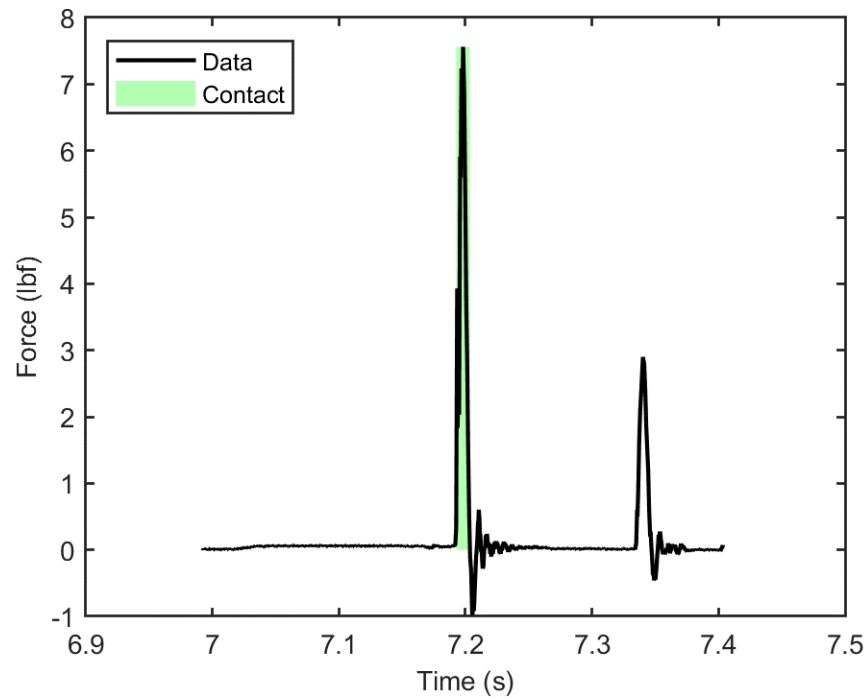


Figure 149. Force data for drop test E2B, with contact time window marked.

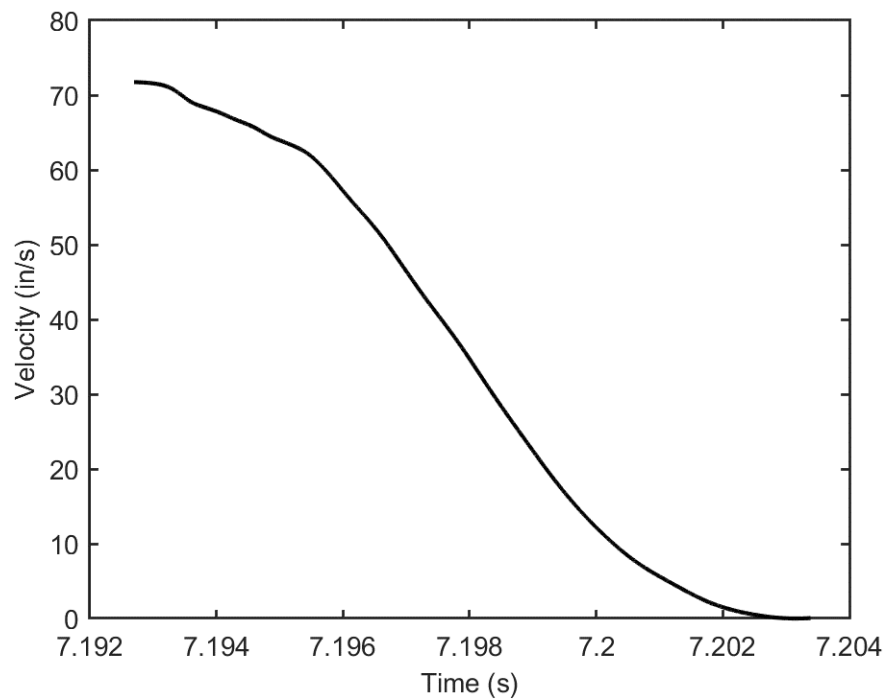


Figure 150. Velocity time history (from force data) for test E2B during initial contact.

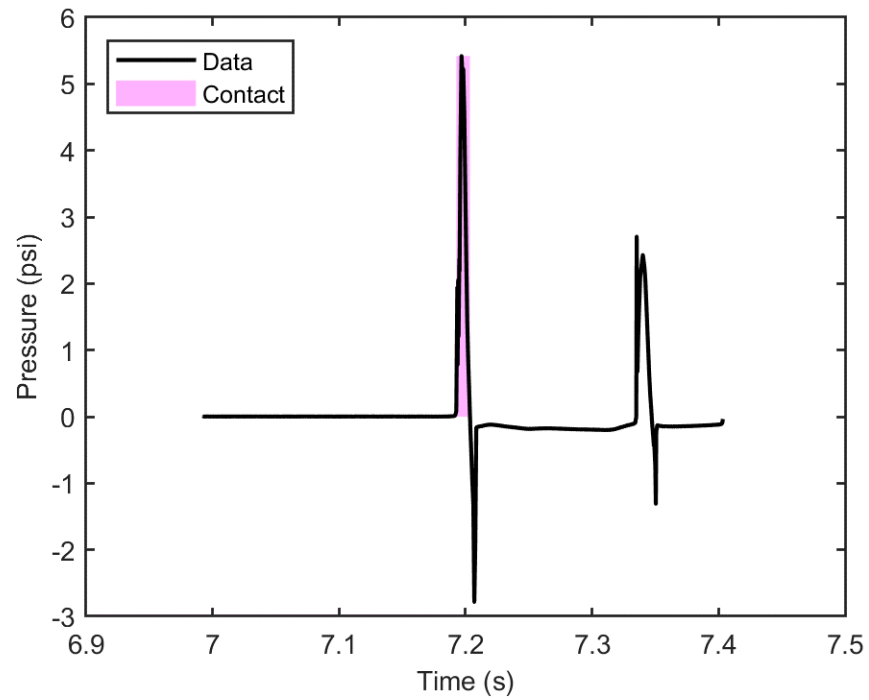


Figure 151. Pressure data for test E2B, with contact time window marked.

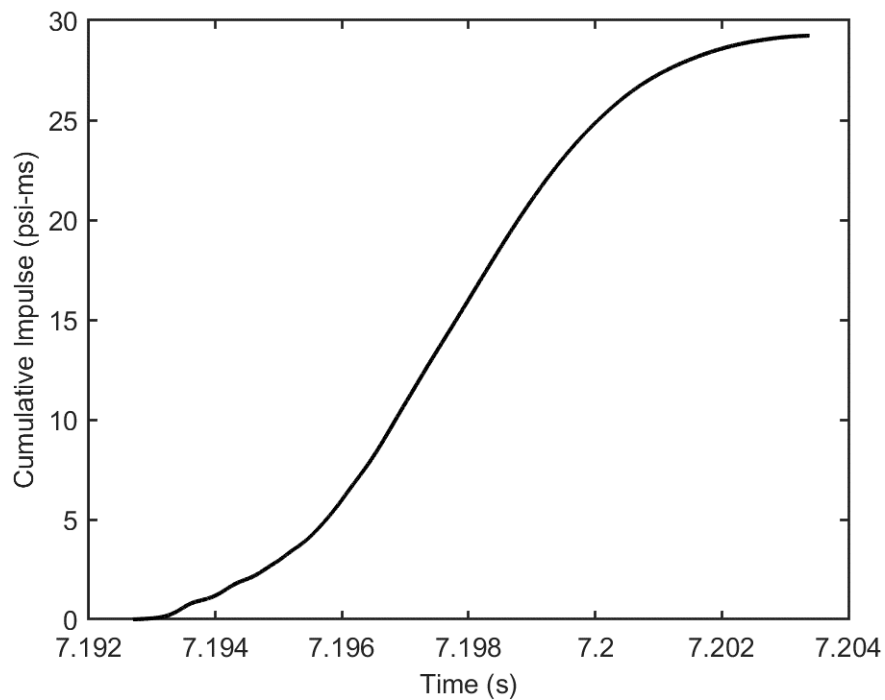


Figure 152. Impulse time history (from pressure data) for test E2B during initial contact.

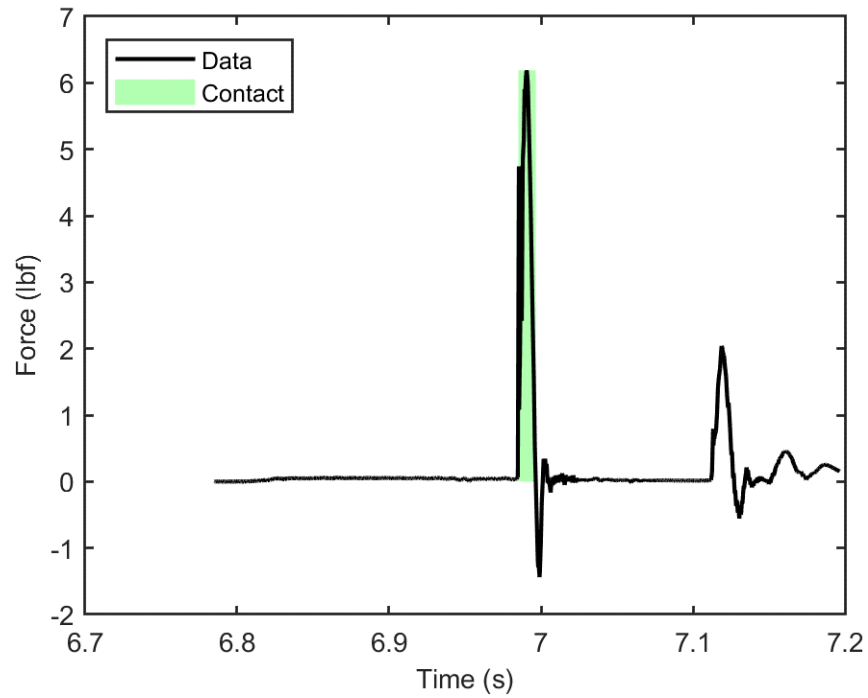


Figure 153. Force data for drop test E3A, with contact time window marked.

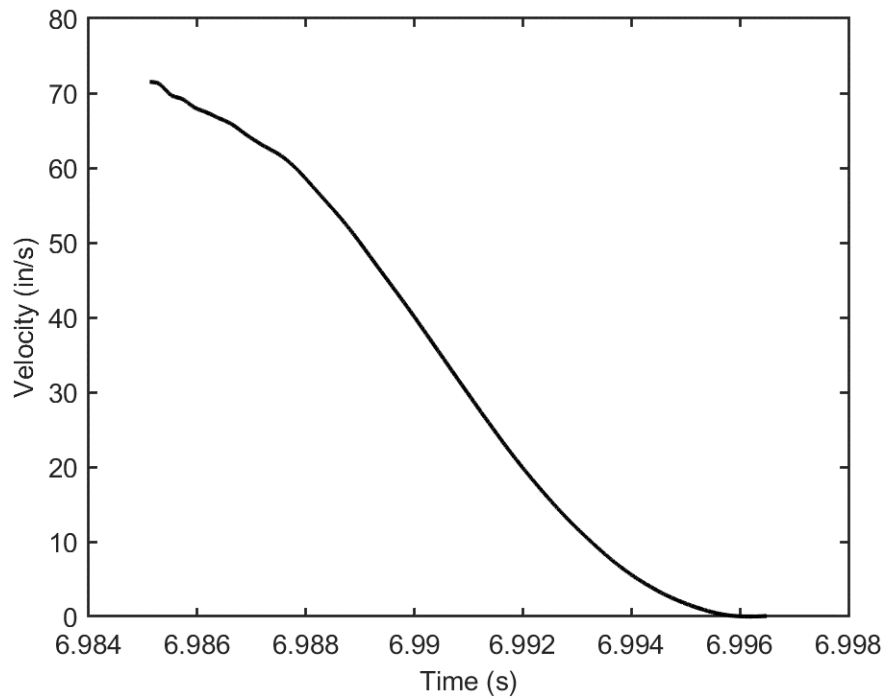


Figure 154. Velocity time history (from force data) for test E3A during initial contact.

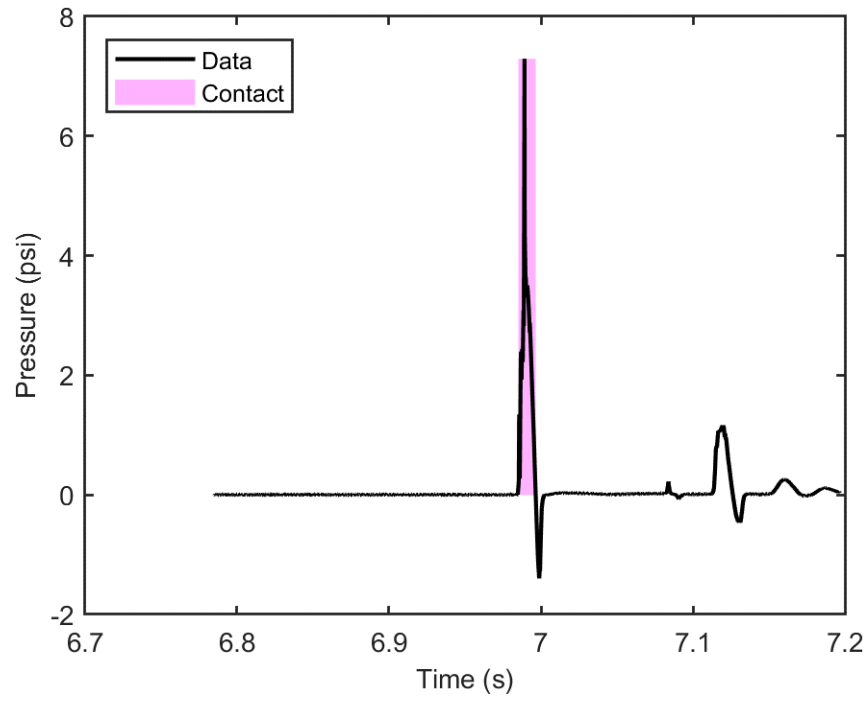


Figure 155. Pressure data for test E3A, with contact time window marked.

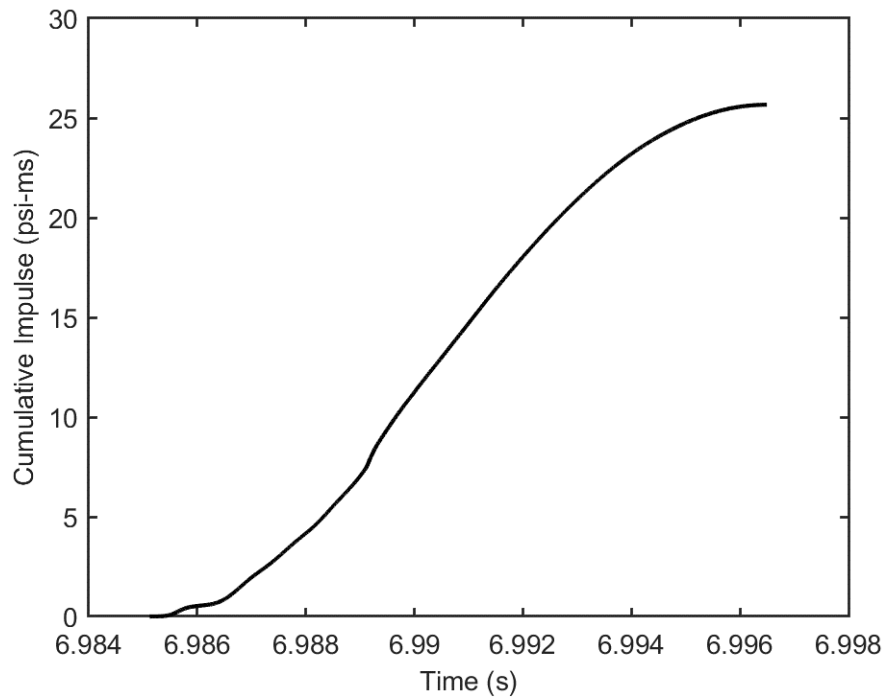


Figure 156. Impulse time history (from pressure data) for test E3A during initial contact.

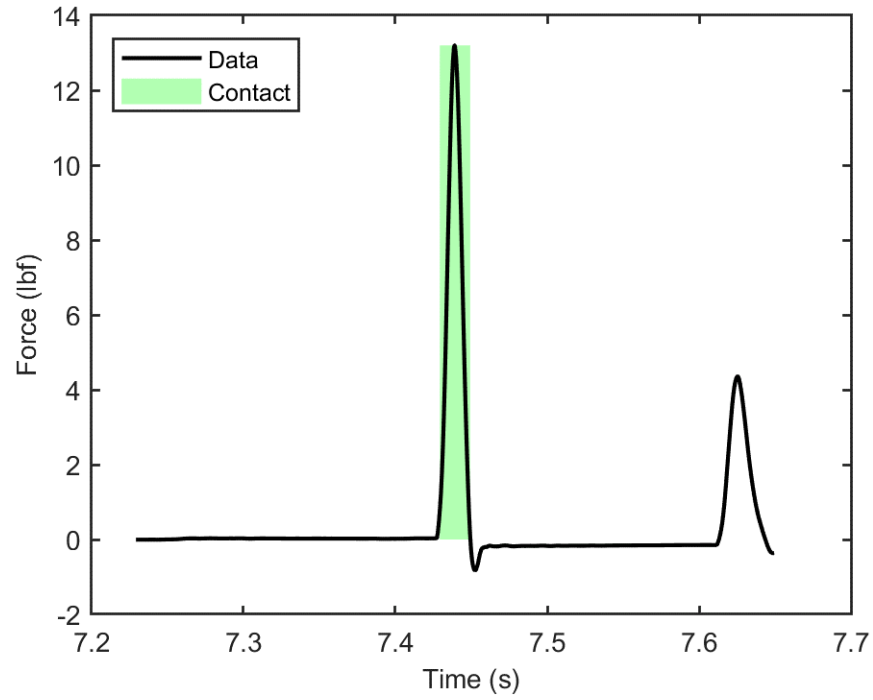


Figure 157. Force data for drop test E3B, with contact time window marked.

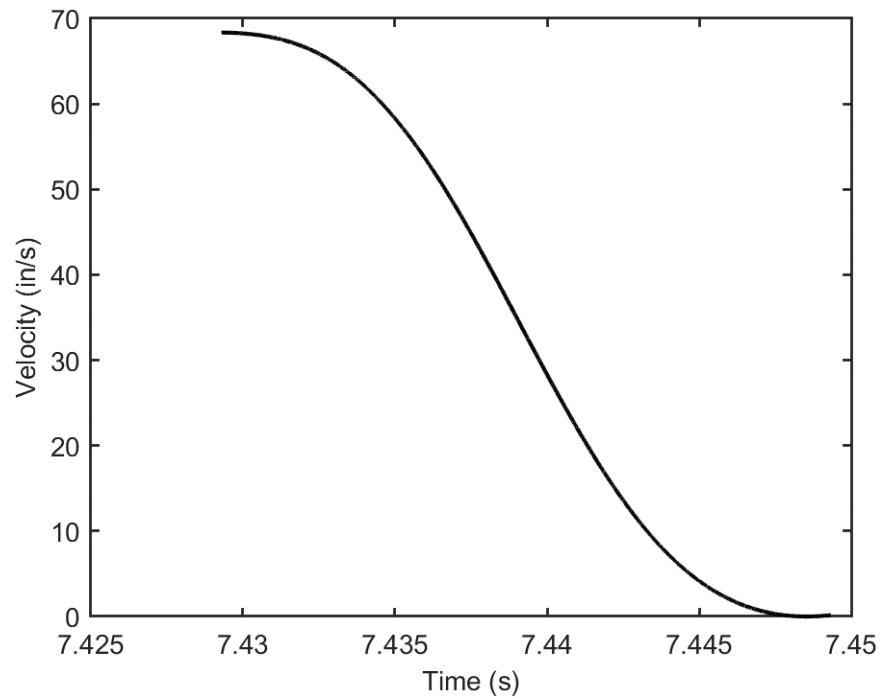


Figure 158. Velocity time history (from force data) for test E3B during initial contact.

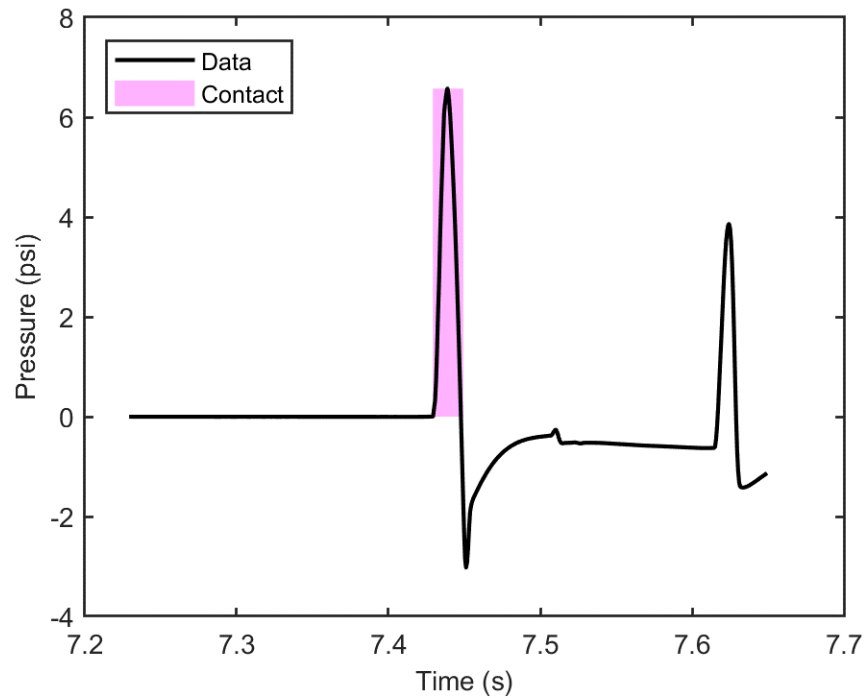


Figure 159. Pressure data for test E3B, with contact time window marked.

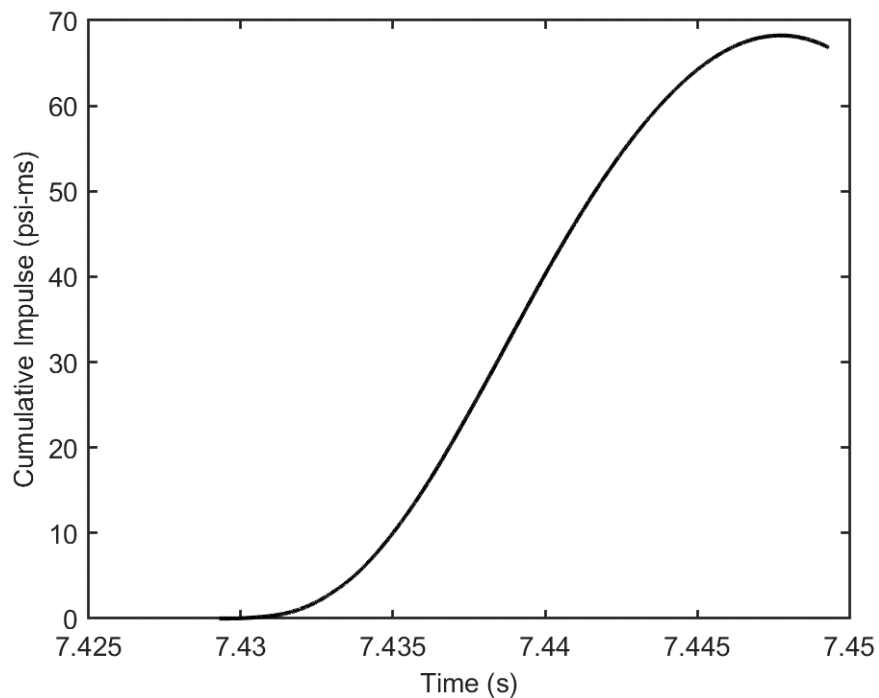


Figure 160. Impulse time history (from pressure data) for test E3B during initial contact.

B.2.4 Ecoflex, Vascularized

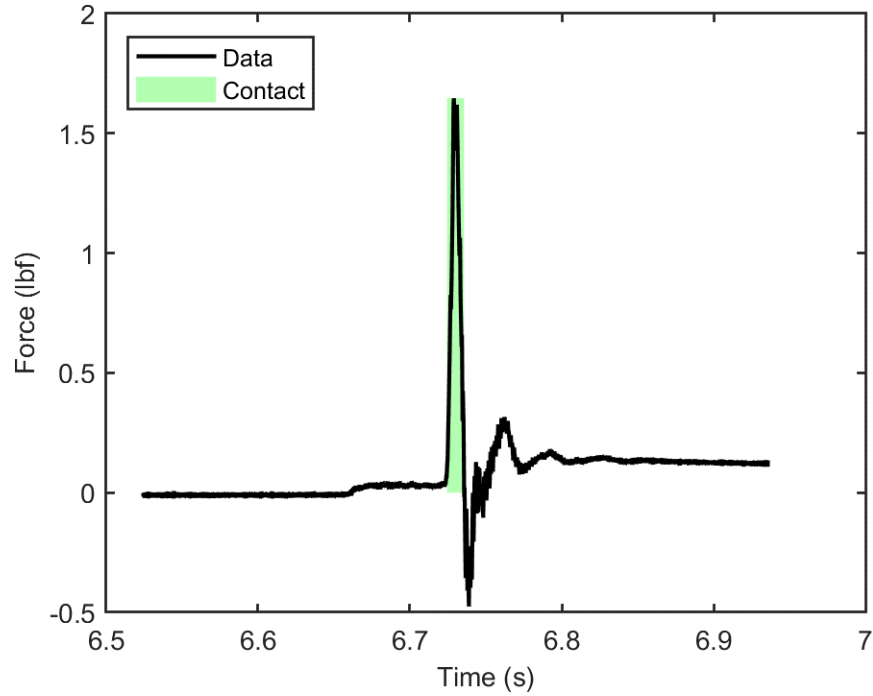


Figure 161. Force time history for drop test EV1A, with contact time window marked.

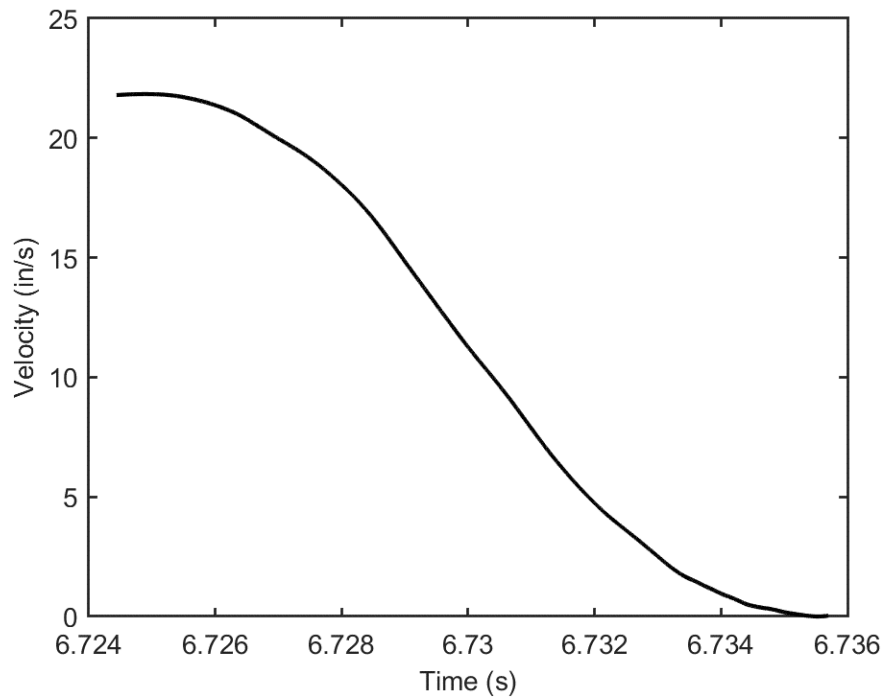


Figure 162. Velocity time history (from force data) for test EV1A during initial contact.

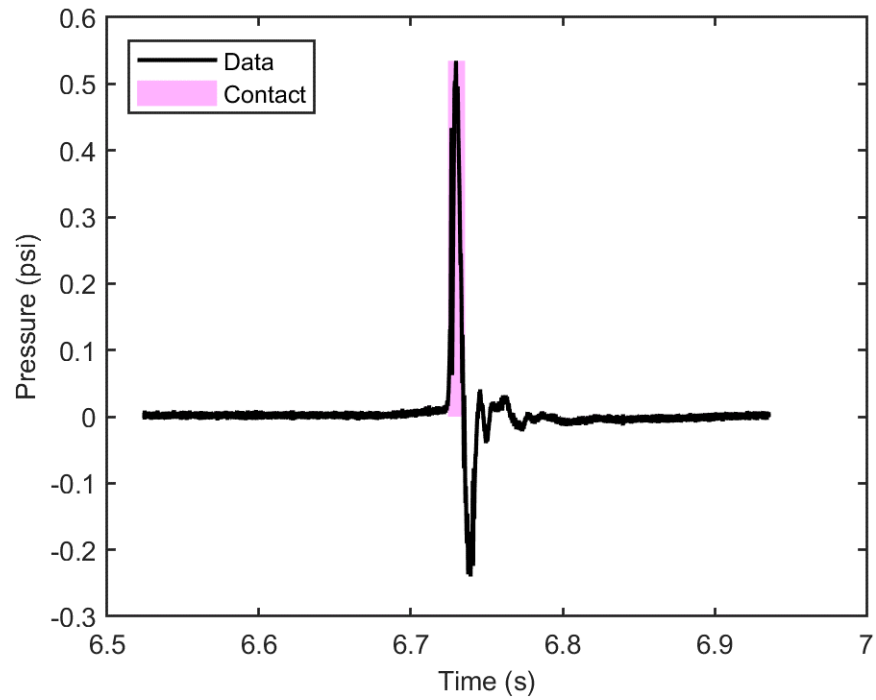


Figure 163. Pressure data for test EV1A, with contact time window marked.

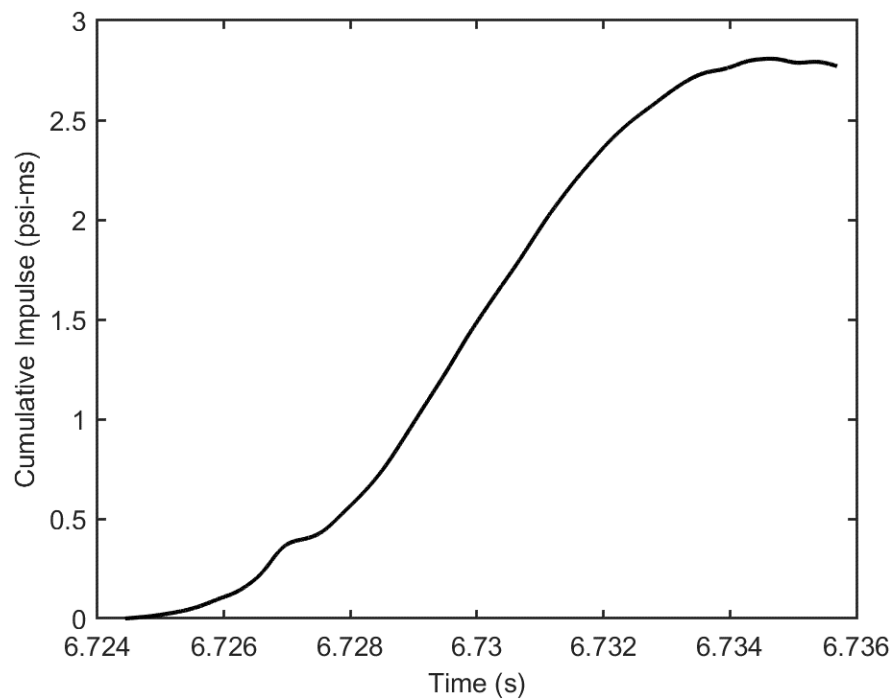


Figure 164. Impulse time history (from pressure data) for test EV1A during initial contact.

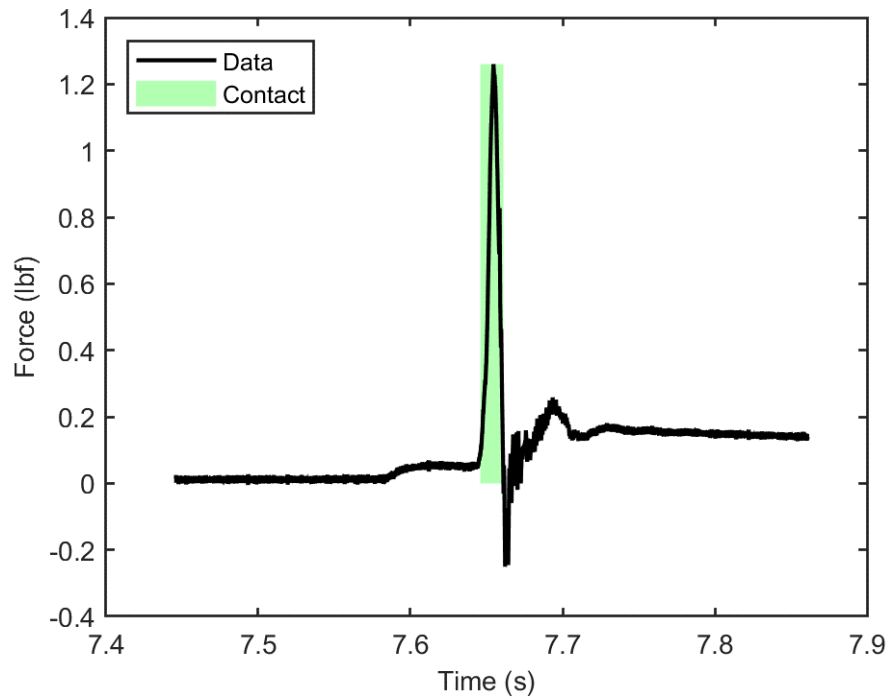


Figure 165. Force data for drop test EV2A, with contact time window marked.

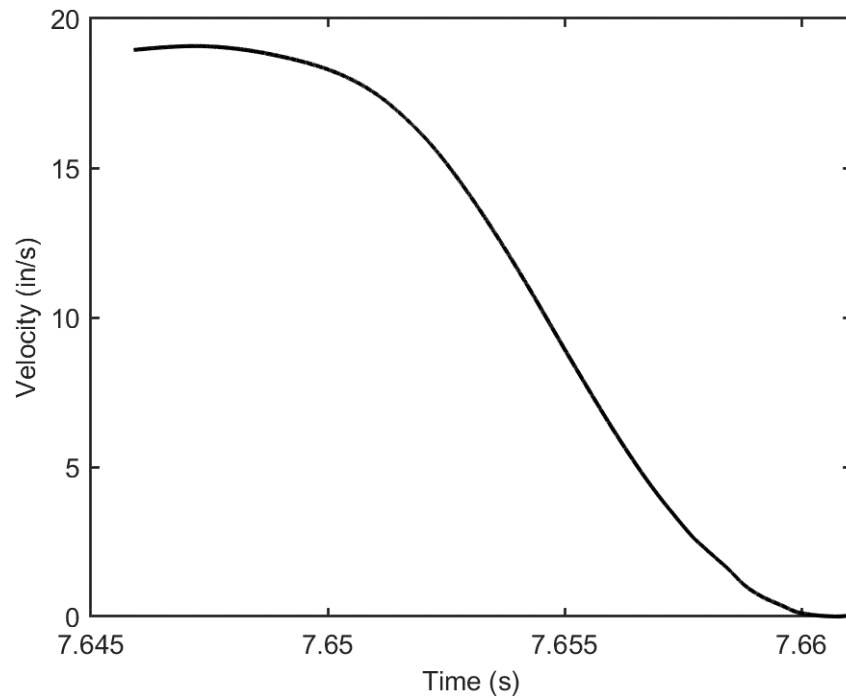


Figure 166. Velocity time history (from force data) for test EV2A during initial contact.

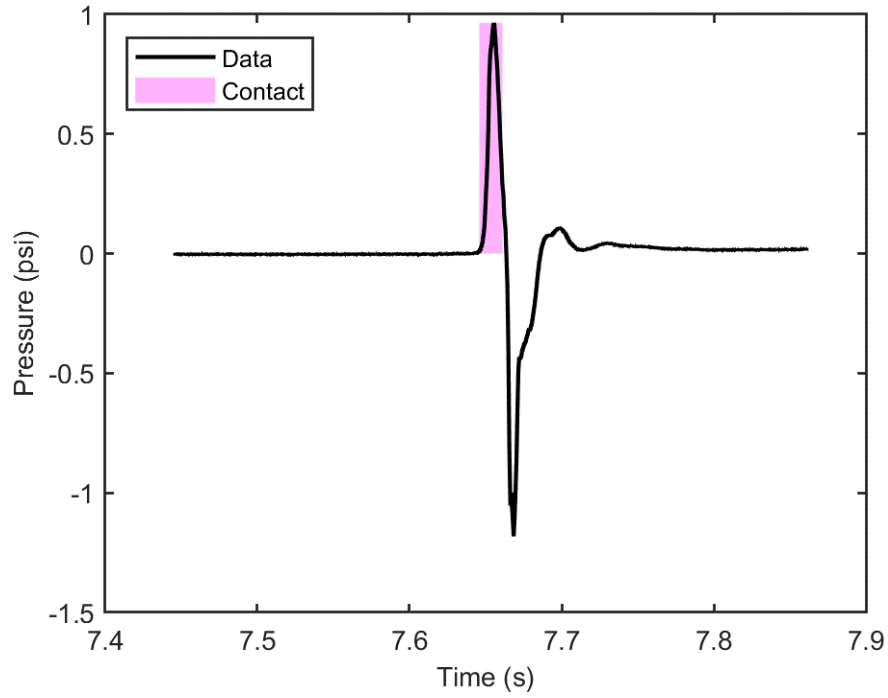


Figure 167. Pressure data for test EV2A, with contact time window marked.

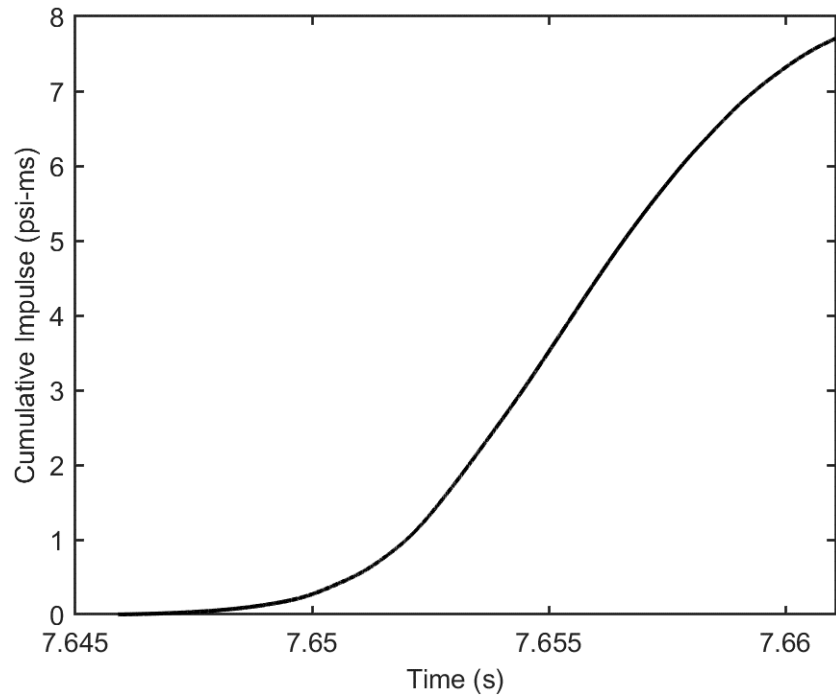


Figure 168. Impulse time history (from pressure data) for test EV2A during initial contact.

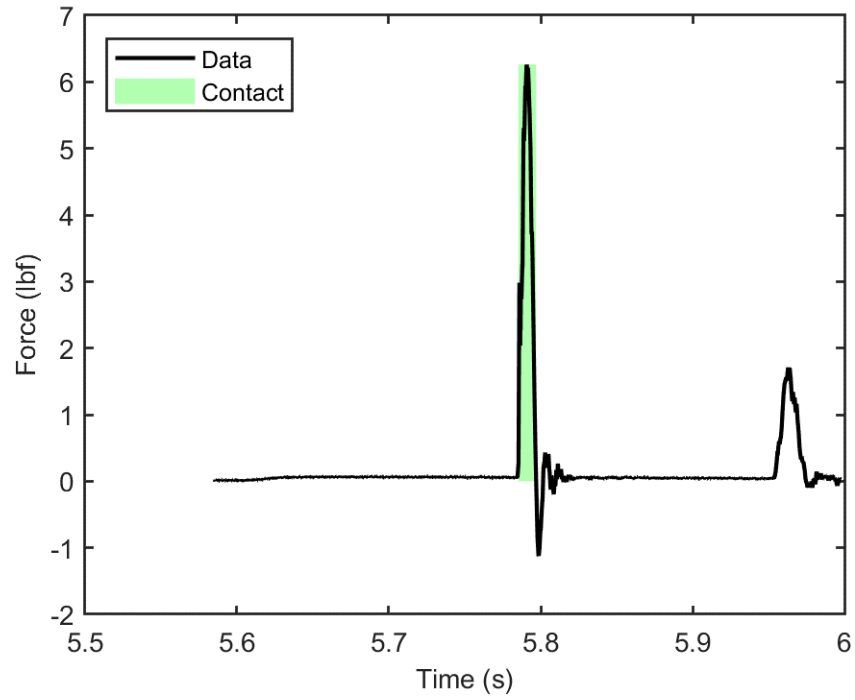


Figure 169. Force data for drop test EV2B, with contact time window marked.

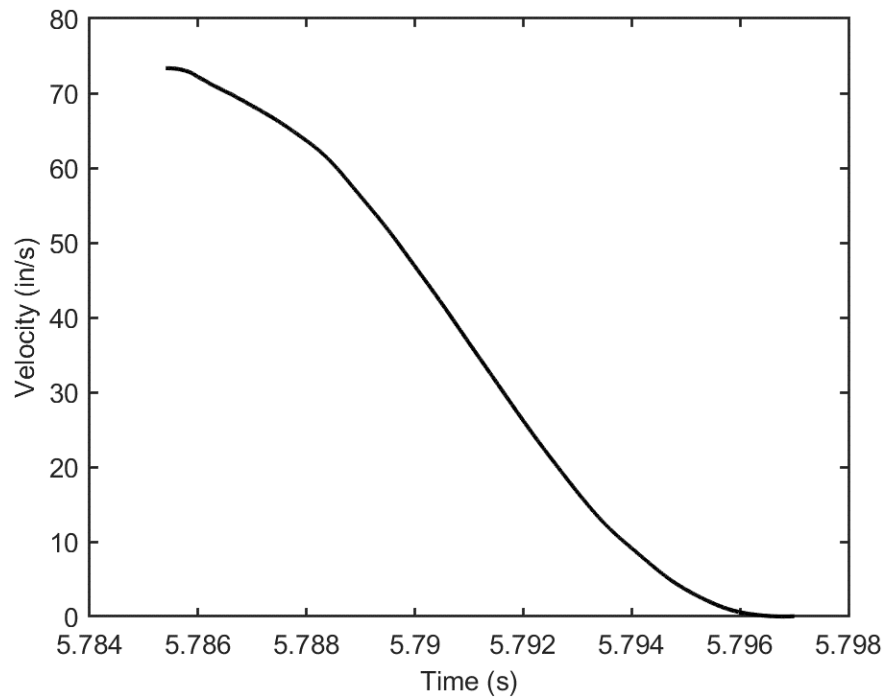


Figure 170. Velocity time history (from force data) for test EV2B during initial contact.

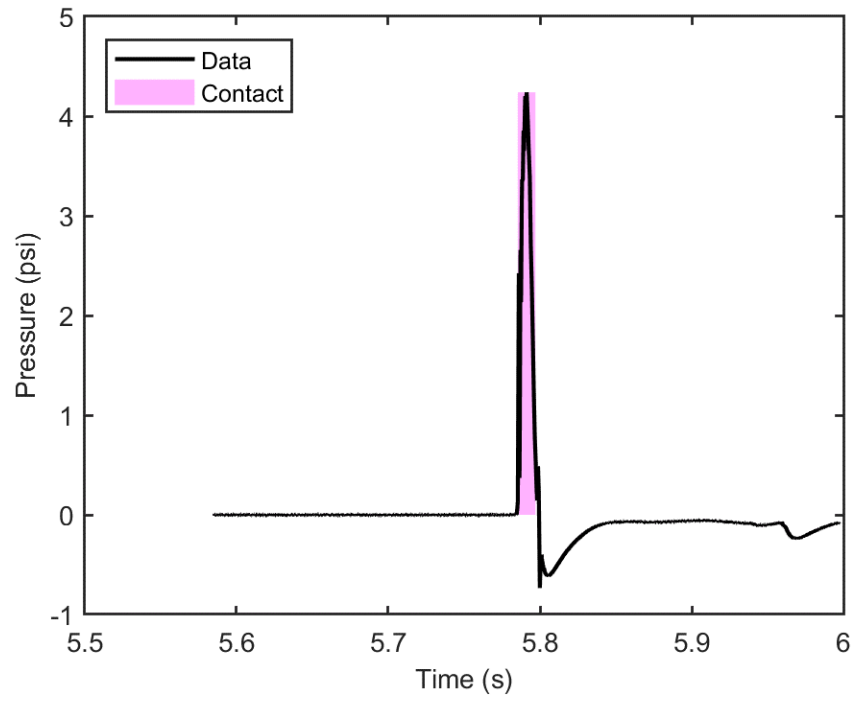


Figure 171. Pressure data for test EV2B, with contact time window marked.

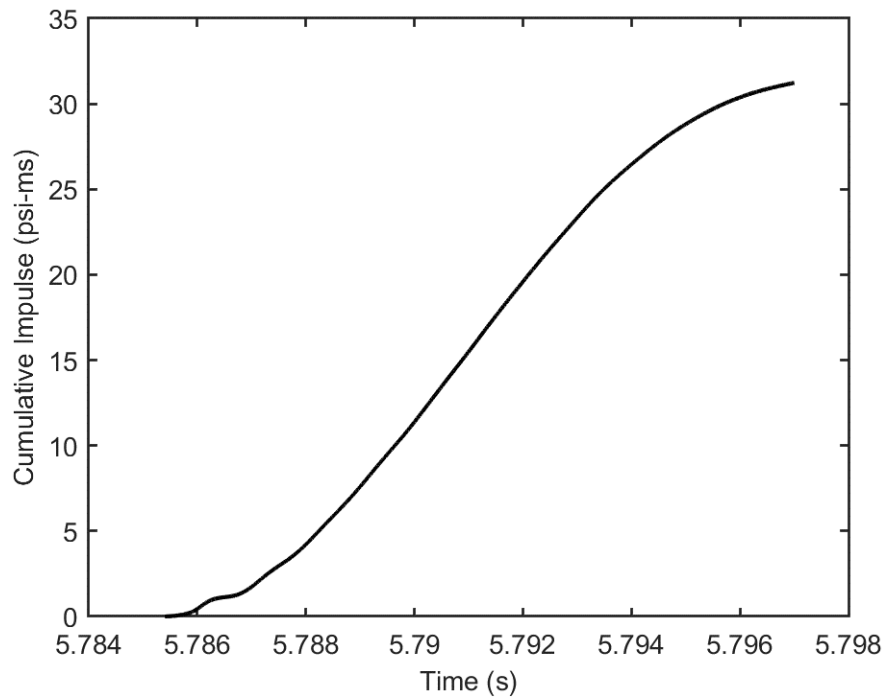


Figure 172. Impulse time history (from pressure data) for test EV2B during initial contact.

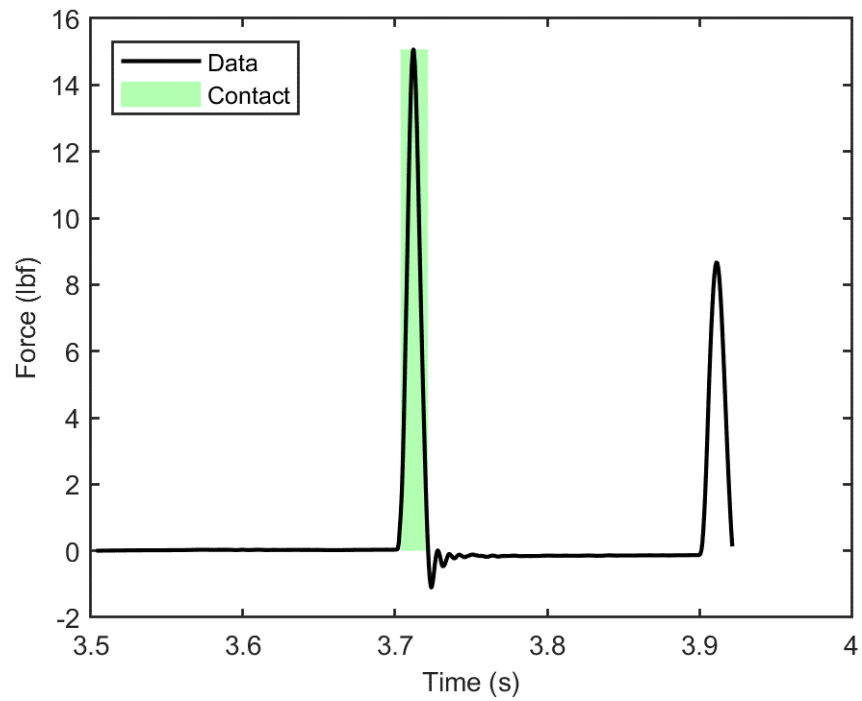


Figure 173. Force data for drop test EV3A, with contact time window marked.

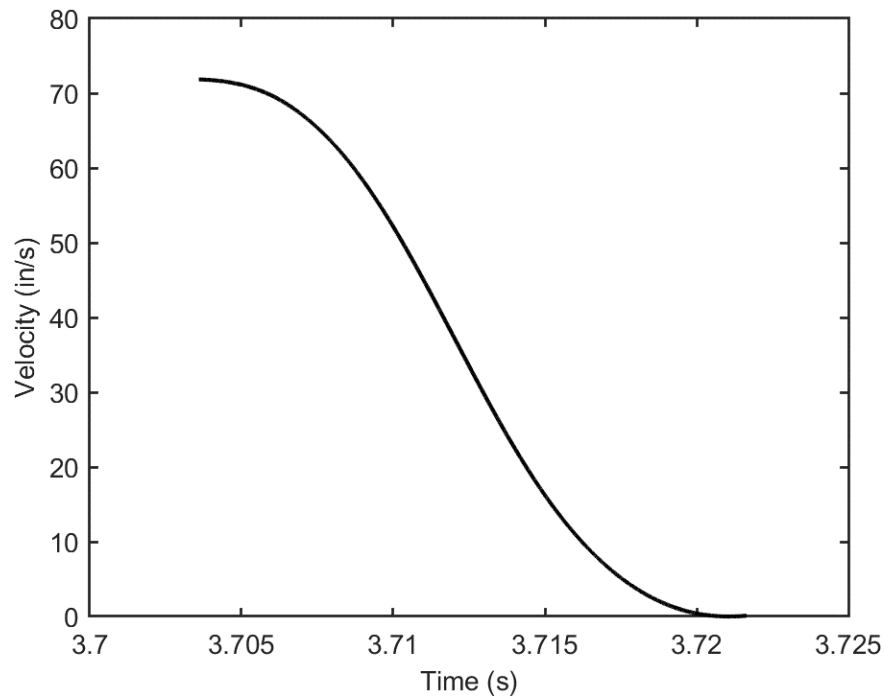


Figure 174. Velocity time history (from force data) for test EV3A during initial contact.

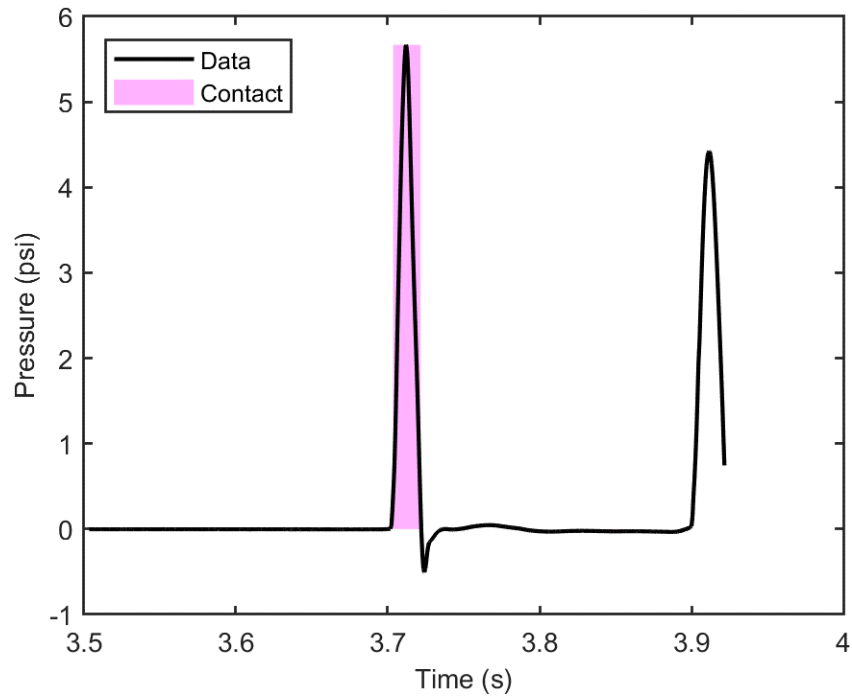


Figure 175. Pressure data for test EV3A, with contact time window marked.

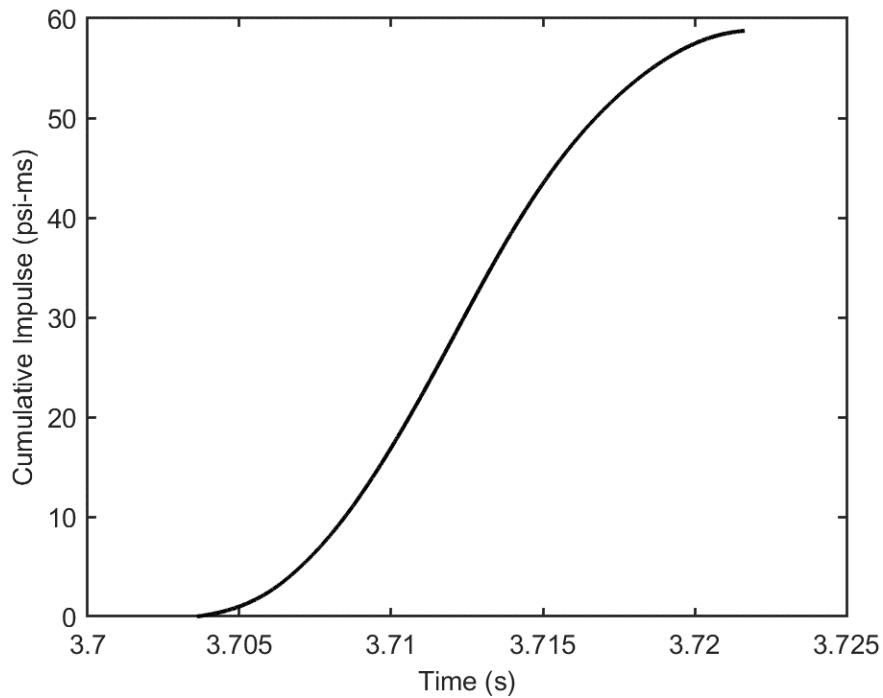


Figure 176. Impulse time history (from pressure data) for test EV3A during initial contact.

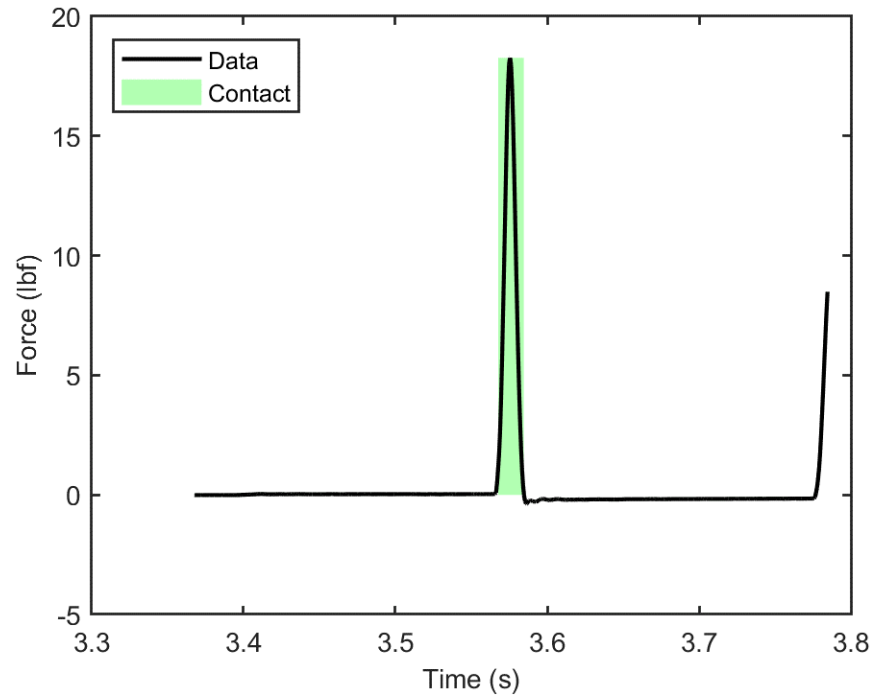


Figure 177. Force data for drop test EV4A, with contact time window marked.

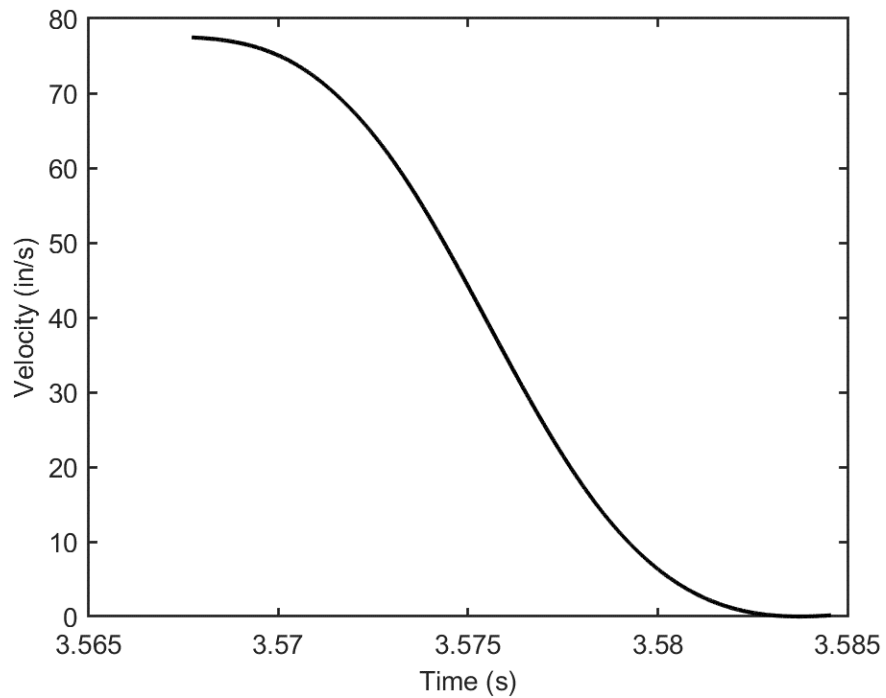


Figure 178. Velocity time history (from force data) for test EV4A during initial contact.

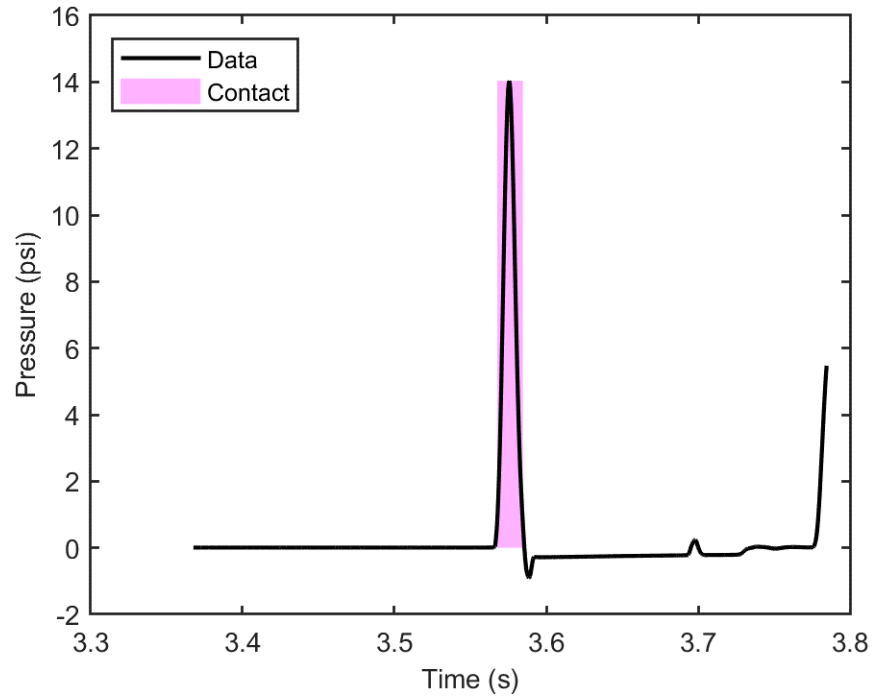


Figure 179. Pressure data for test EV4A, with contact time window marked.

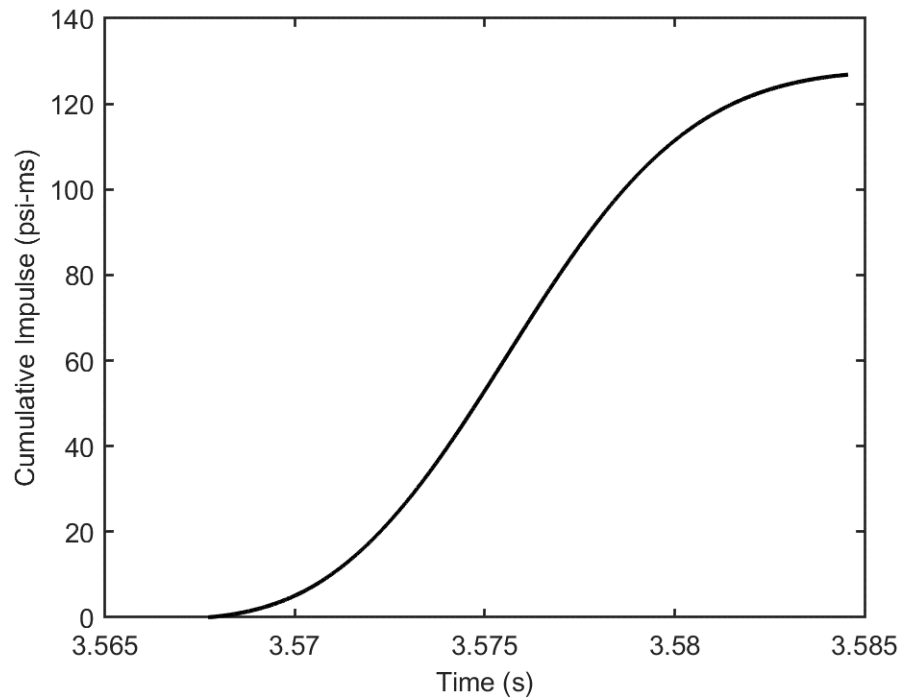


Figure 180. Impulse time history (from pressure data) for test EV4A during initial contact.

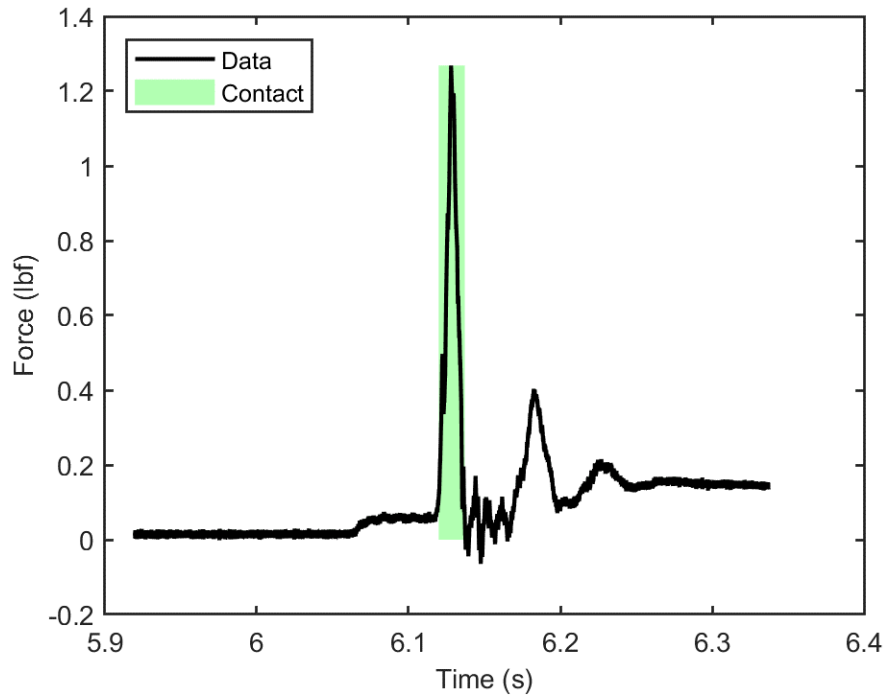


Figure 181. Force time history for drop test EV5A, with contact time window marked.

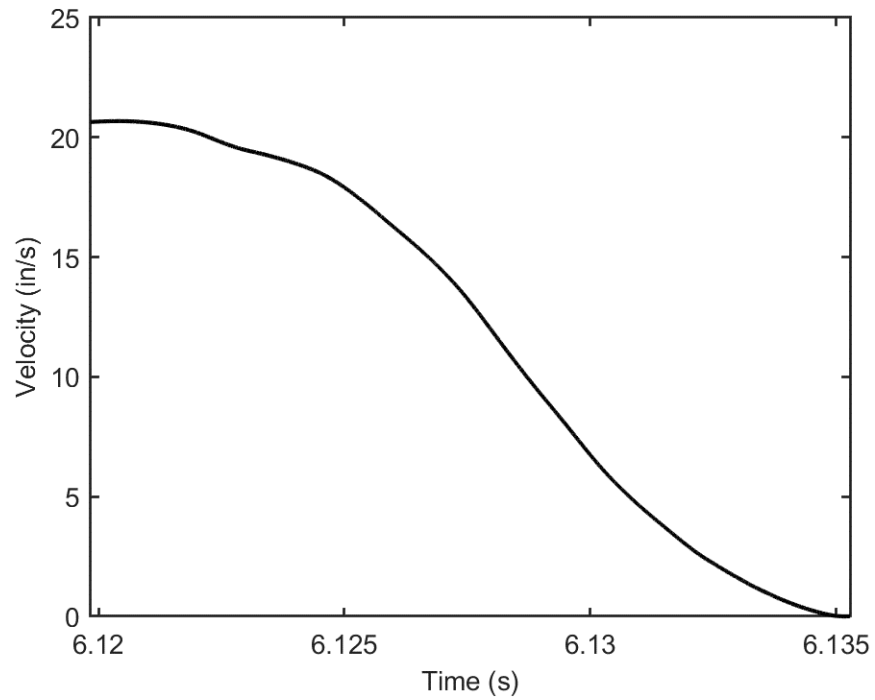


Figure 182. Velocity time history (from force data) for test EV5A during initial contact.

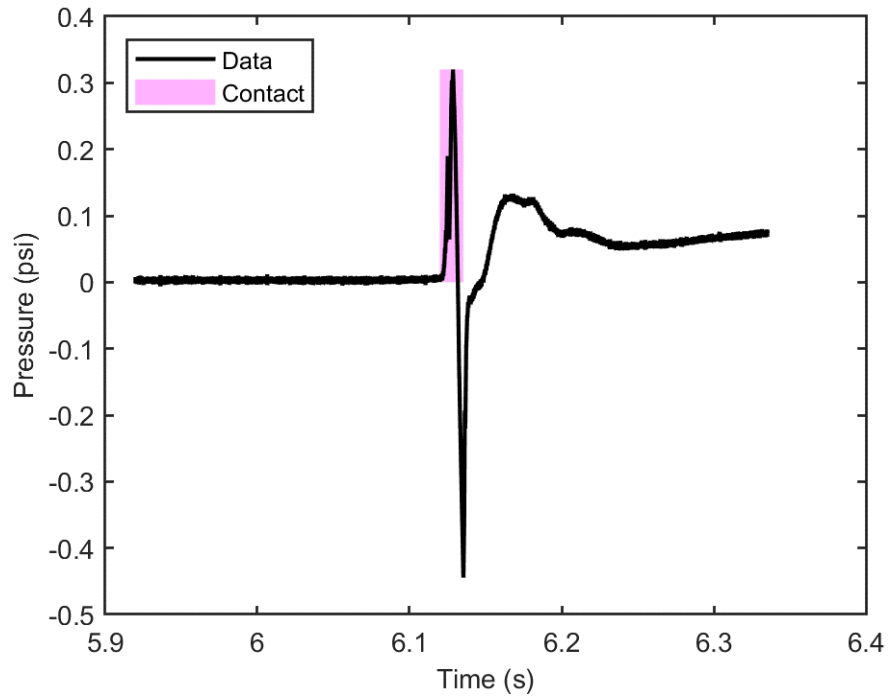


Figure 183. Pressure data for test EV5A, with contact time window marked.

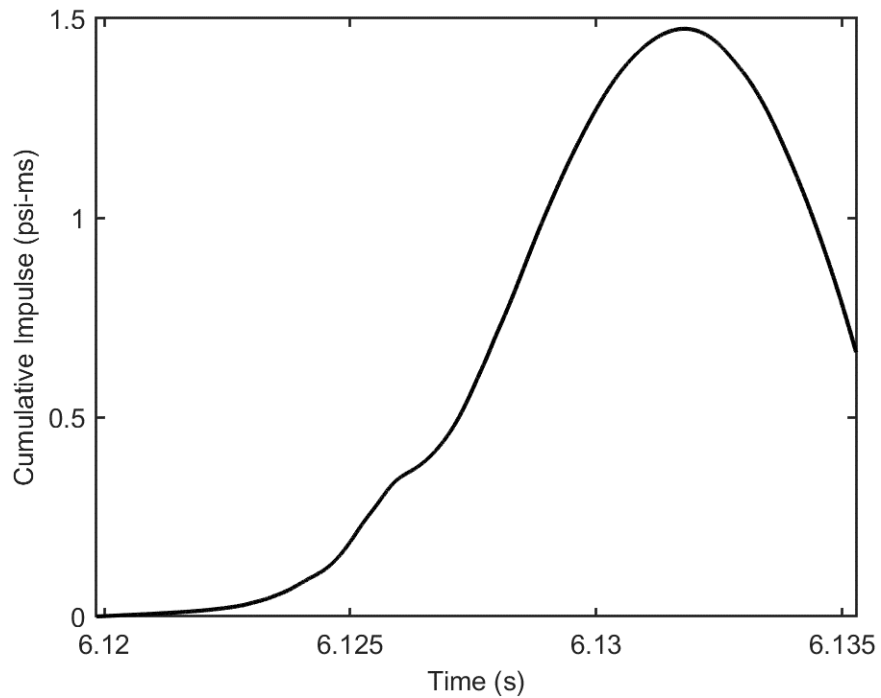


Figure 184. Impulse time history (from pressure data) for test EV5A during initial contact.

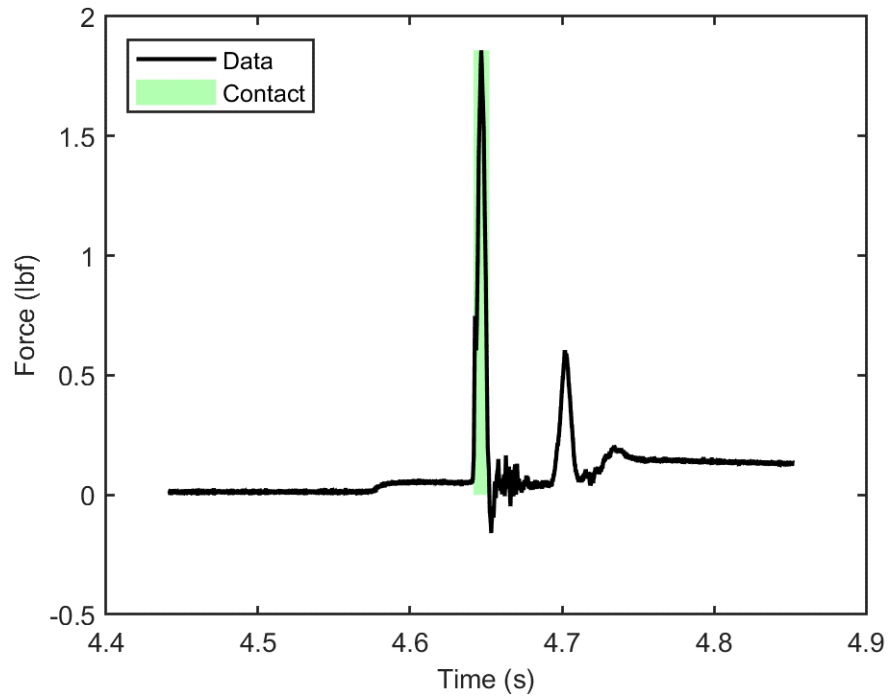


Figure 185. Force data for drop test EV8A, with contact time window marked.

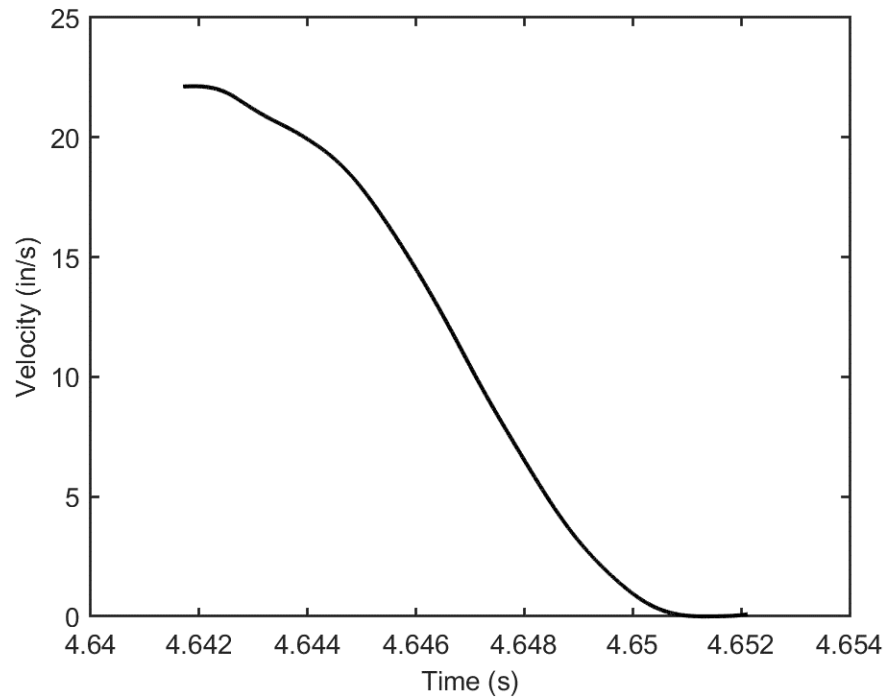


Figure 186. Velocity time history (from force data) for test EV8A during initial contact.

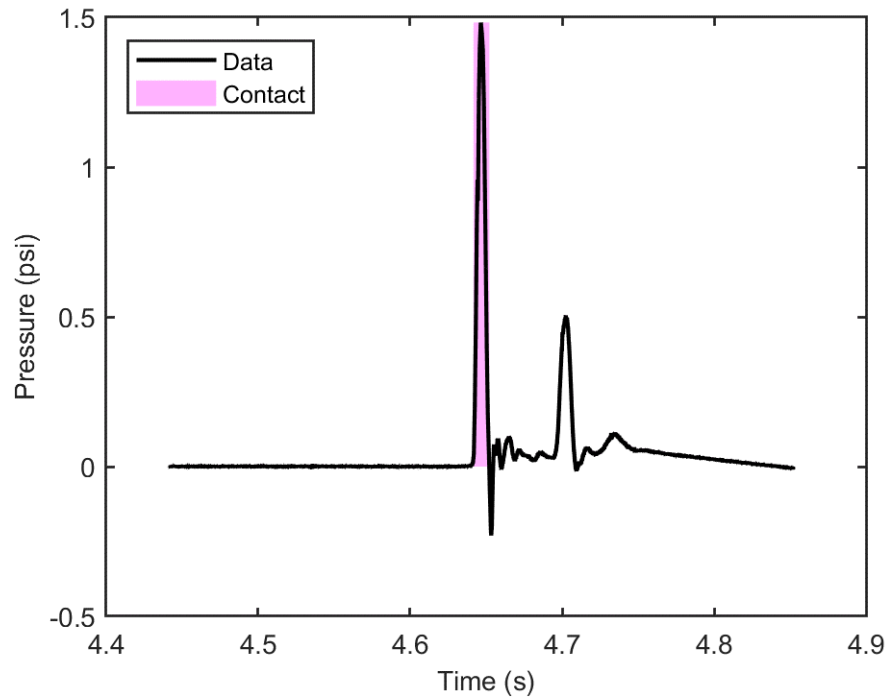


Figure 187. Pressure data for test EV8A, with contact time window marked.

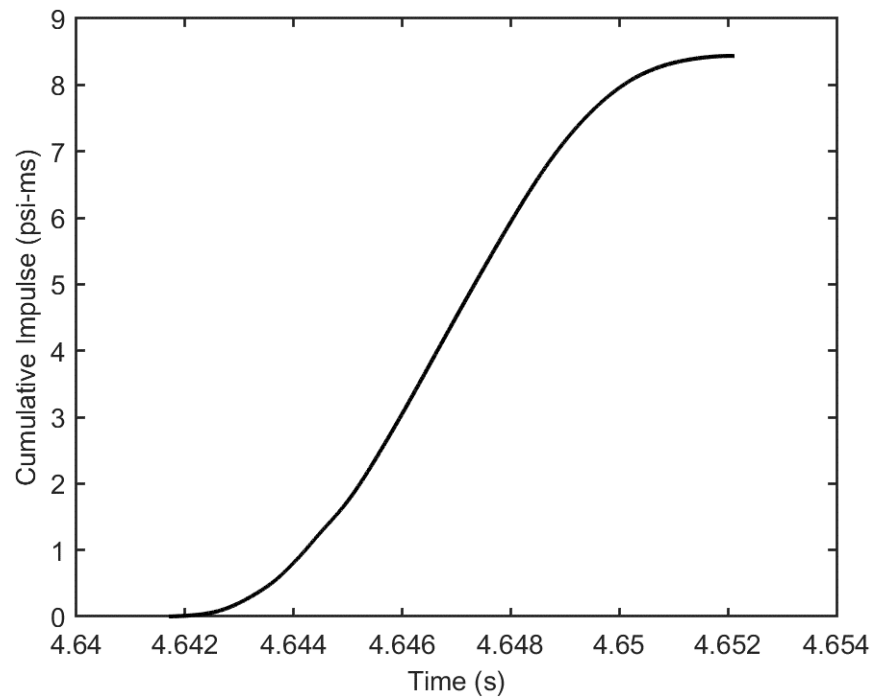


Figure 188. Impulse time history (from pressure data) for test EV8A during initial contact.

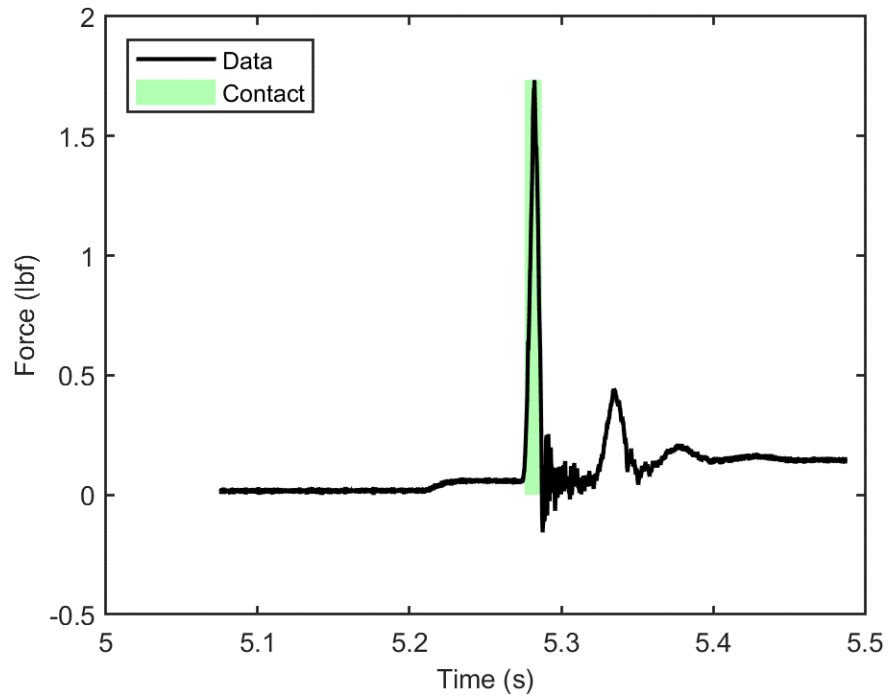


Figure 189. Force data for drop test EV9A, with contact time window marked.

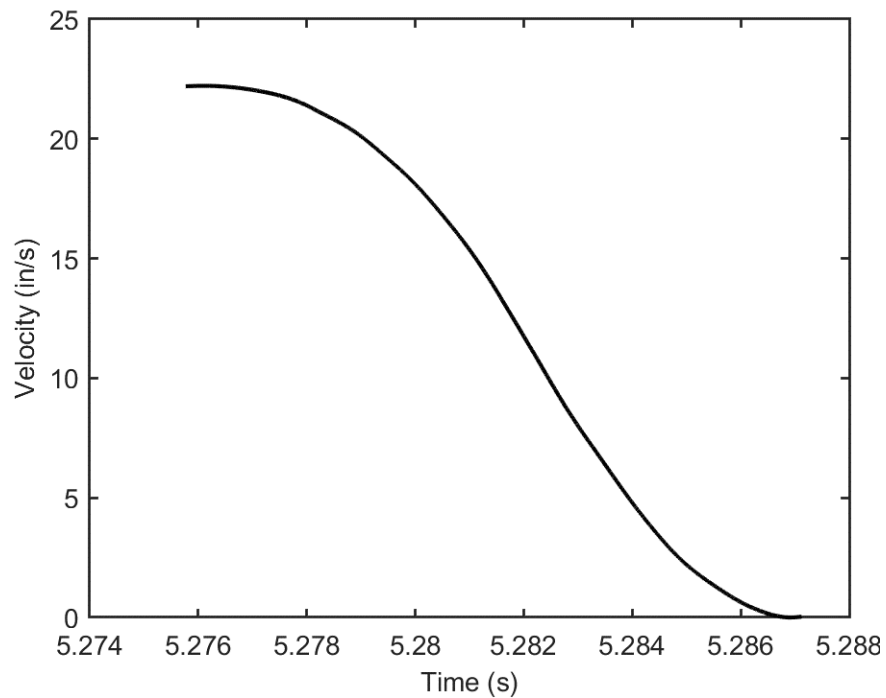


Figure 190. Velocity time history (from force data) for test EV9A during initial contact.

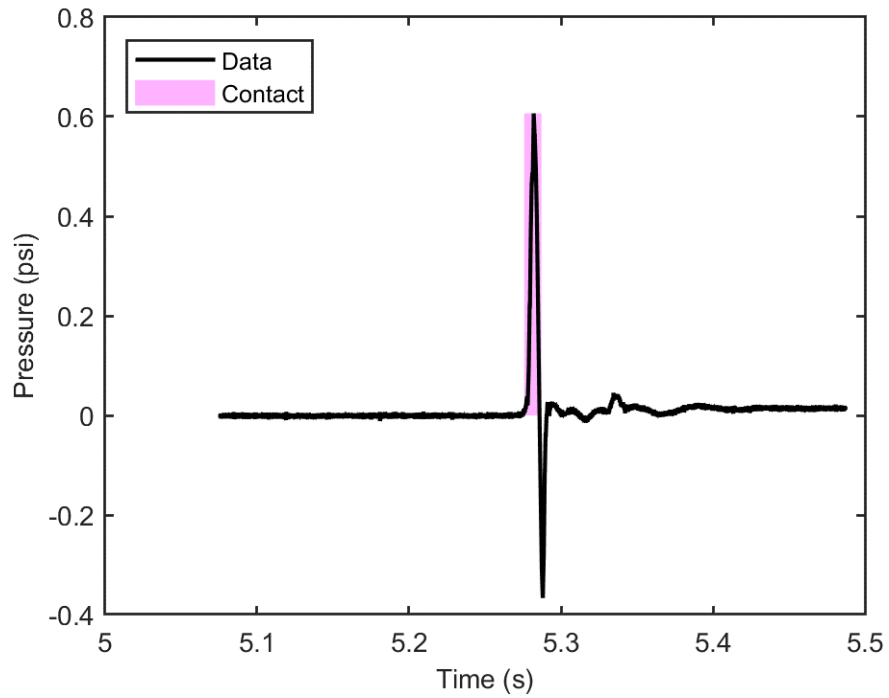


Figure 191. Pressure data for test EV9A, with contact time window marked.

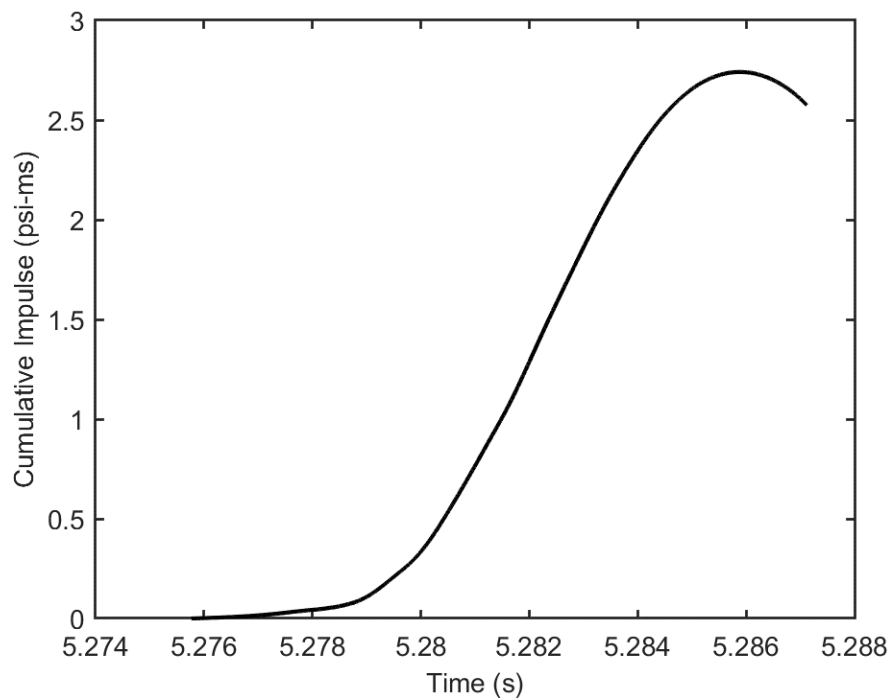


Figure 192. Impulse time history (from pressure data) for test EV9A during initial contact.

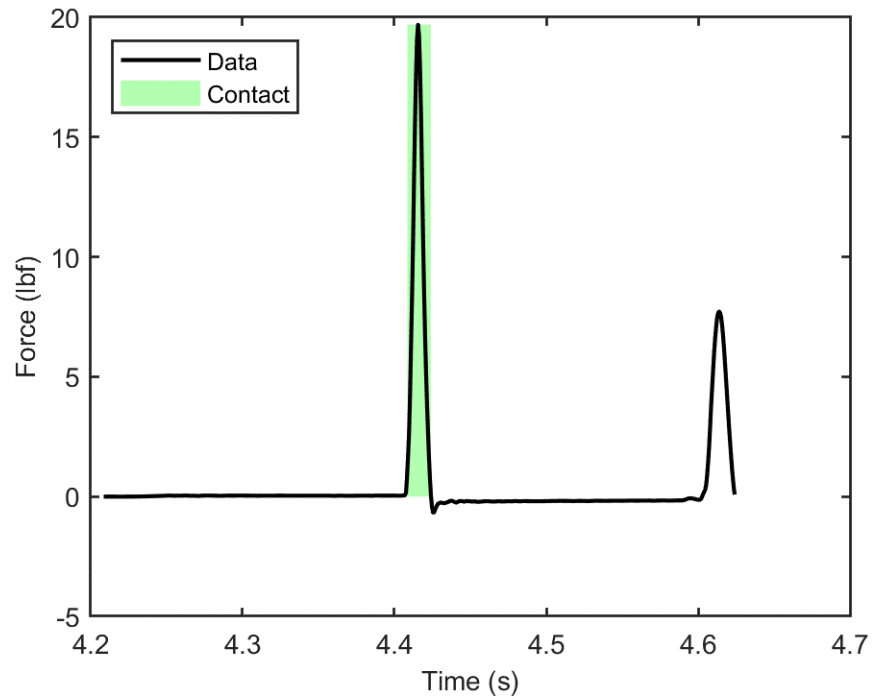


Figure 193. Force data for drop test EV9B, with contact time window marked.

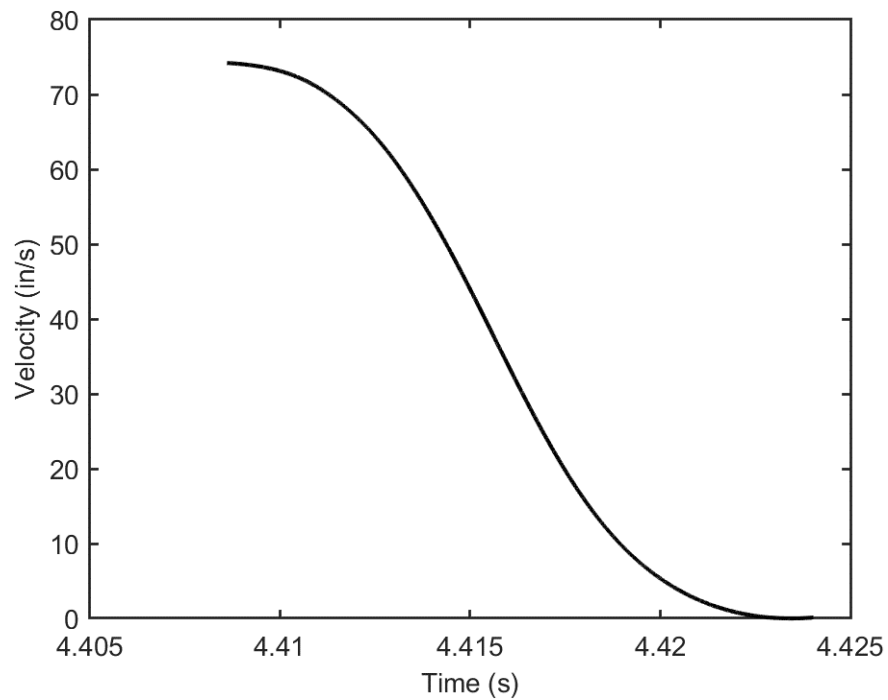


Figure 194. Velocity time history (from force data) for test EV9B during initial contact.

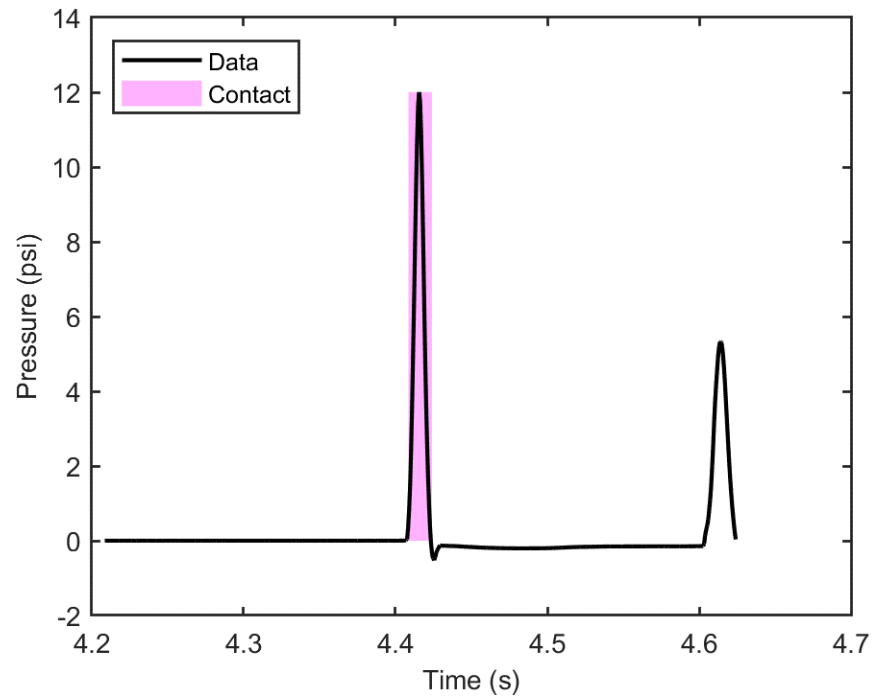


Figure 195. Pressure data for test EV9B, with contact time window marked.

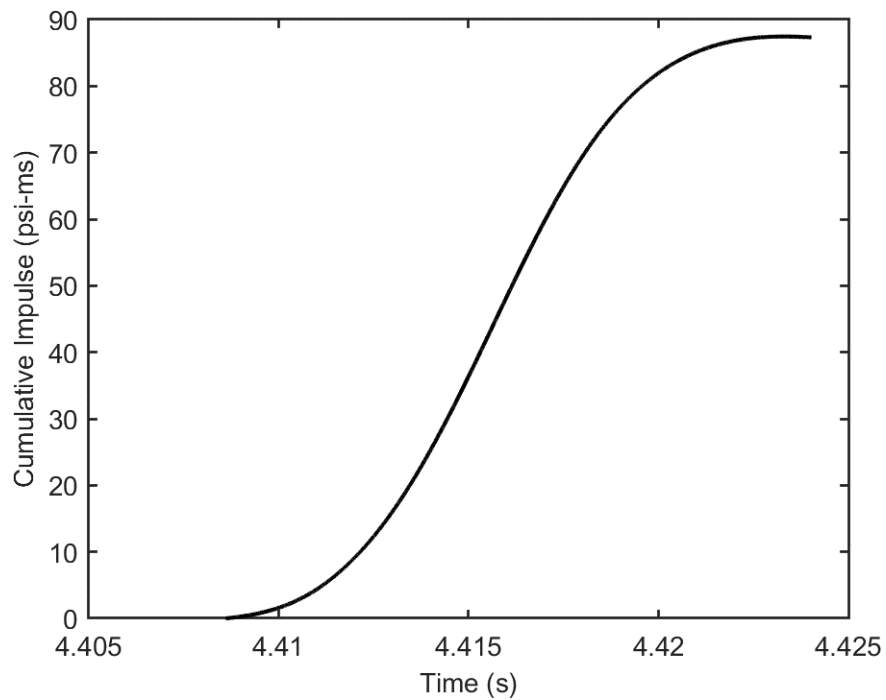


Figure 196. Impulse time history (from pressure data) for test EV9B during initial contact.

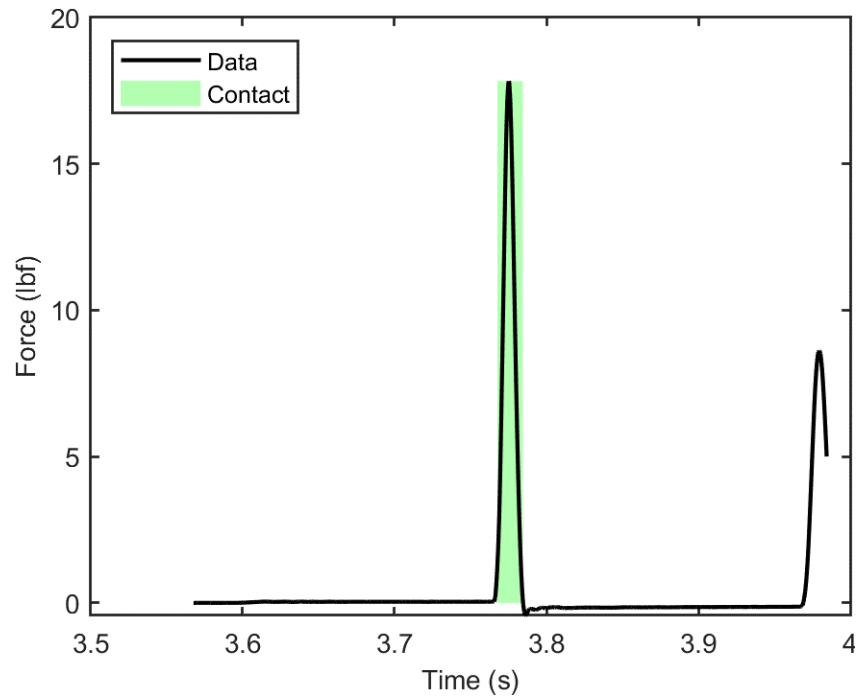


Figure 197. Force data for drop test EV10A, with contact time window marked.

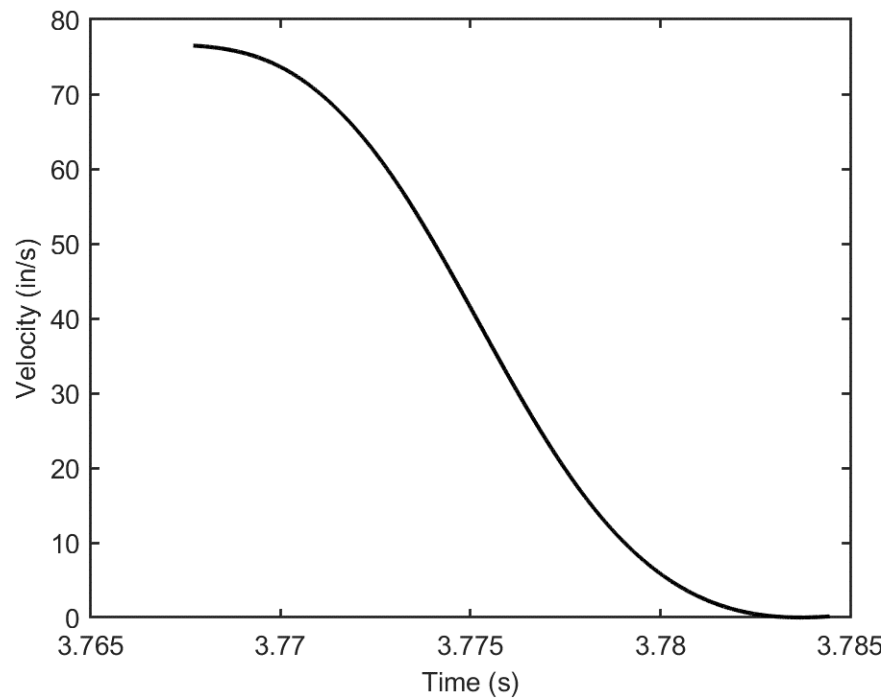


Figure 198. Velocity time history (from force data) for test EV10A during initial contact.

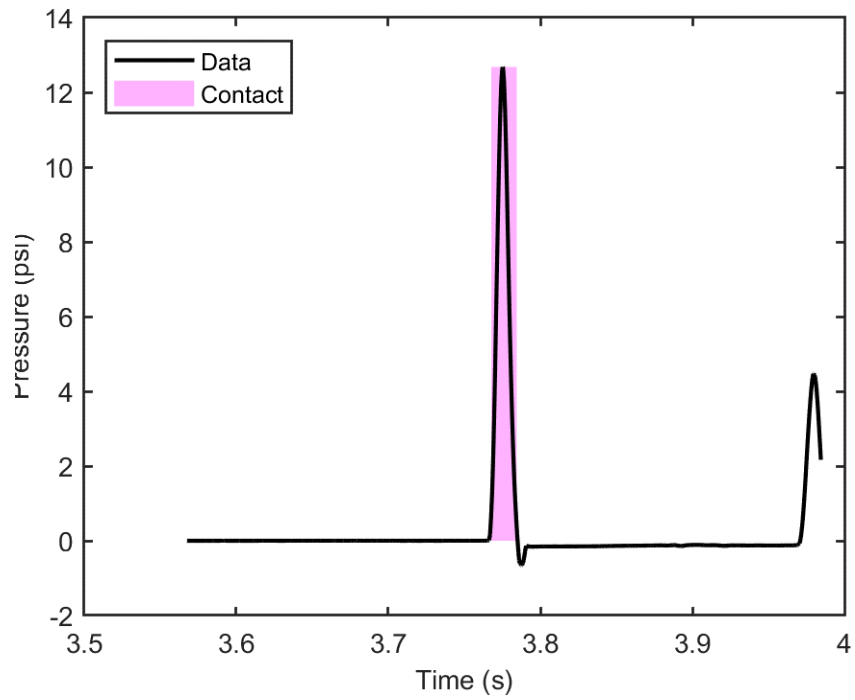


Figure 199. Pressure data for test EV10A, with contact time window marked.

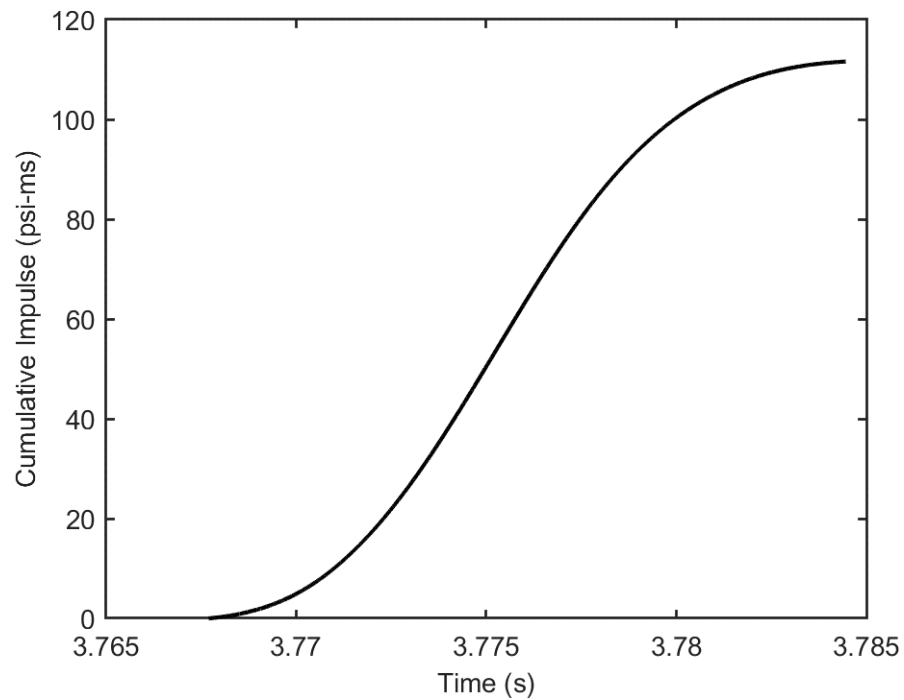


Figure 200. Impulse time history (from pressure data) for test EV10A during initial contact.

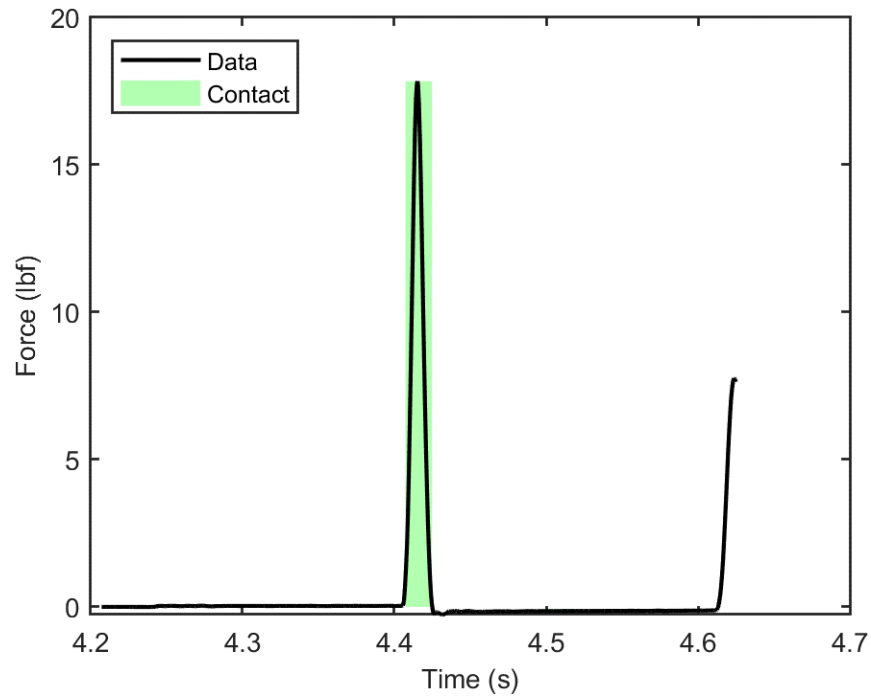


Figure 201. Force data for drop test EV10B, with contact time window marked.

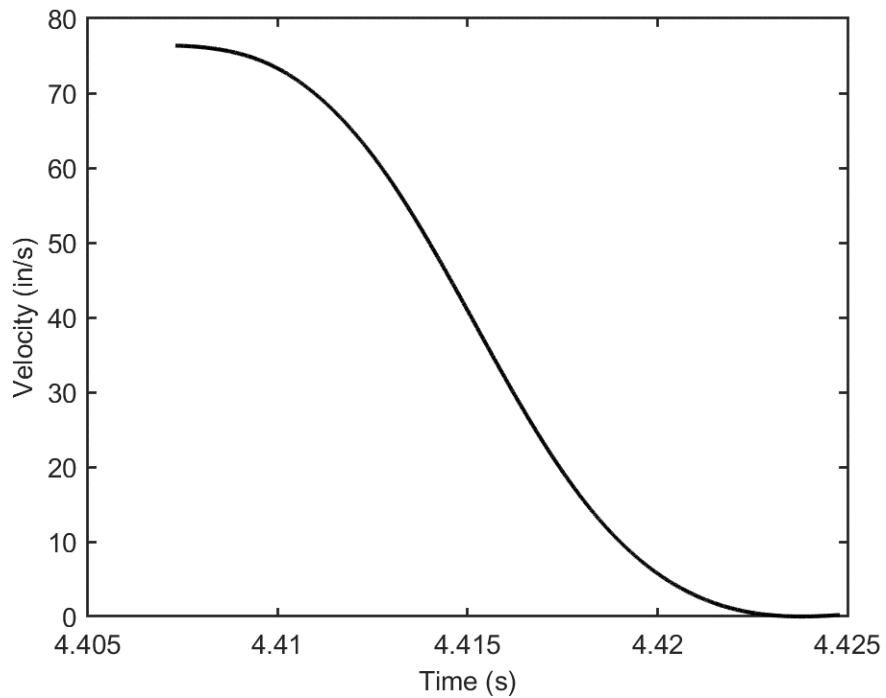


Figure 202. Velocity time history (from force data) for test EV10B during initial contact.

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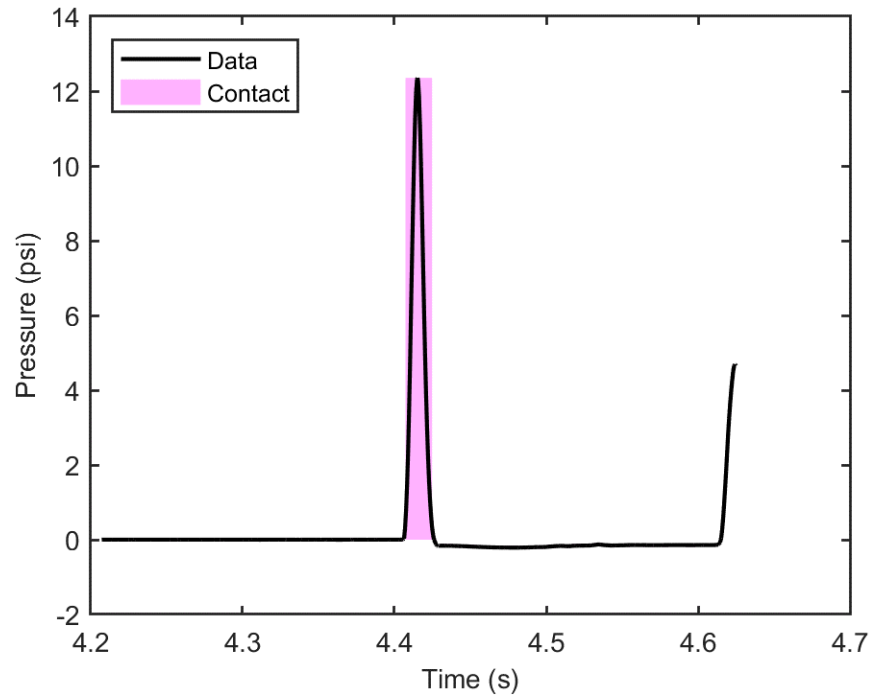


Figure 203. Pressure data for test EV10B, with contact time window marked.

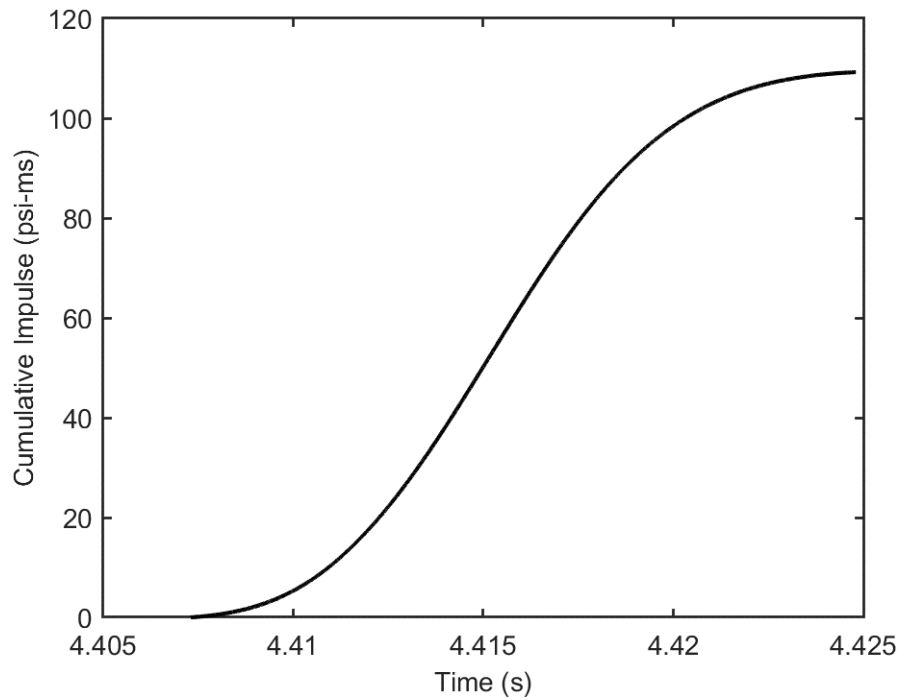


Figure 204. Impulse time history (from pressure data) for test EV10B during initial contact.

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