SAND2016-12696PE

[redacted]-Isolation Material Selection for Electronic Packages in Hard-Target Penetration Environments

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November 21, 2016

Acknowledgments:
Dr. Jamie Kimberley (Adviser)
Dr. Seokbin Lim
Dr. Paul Taylor
Erik Nishida
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- Introduction and Motivation
- Purpose and Thesis Topics
- Isolation Models
- Viscoelastic Materials and Material Selection
- High Strain Rate Testing with Split Hopkinson Bar (SHPB)
- Energy Transmission Analysis
- Transmissibility Modeling
- Procedure Example
- Impact and Conclusions
- Enhancements

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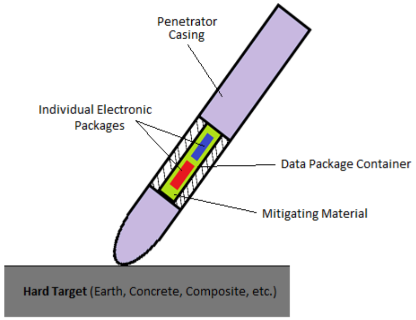
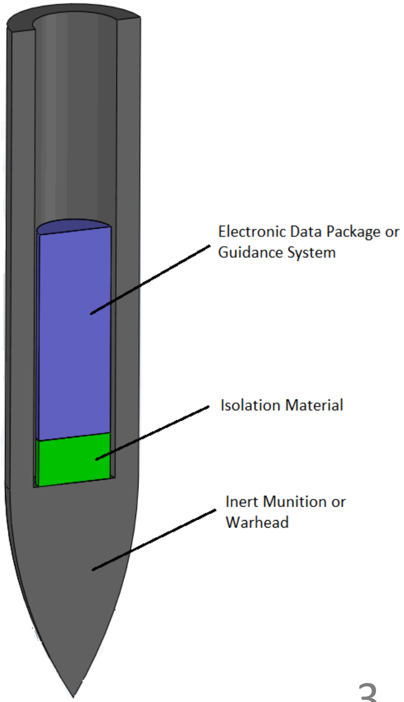
- High velocity munitions and kinetic penetrators
- Complex internal guidance, electronics, or mechanical systems
- Extreme shock, impulse, and cyclical loading due to impact
- Isolation system research to reduce:
  - Shock acceleration
  - Frequency modes
  - Resonance
  - Stress





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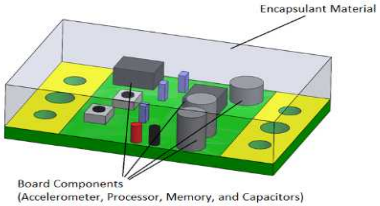
- Increase survivability and functionality of sensitive electronic recorders and systems including printed circuit board (PCB) components
  - Maximum stress: ~ 76MPa
  - Maximum displacement: ~ 10mm
- Primary methods include:
  - ☐ Load-Path-Management through surroundings
  - ☐ Solder adhesion and hardening of electrical components
  - ✓ **Encapsulation of components in *Mitigating Material***



- **Material selection** of commercial encapsulants through high strain rate testing and investigation of viscoelastic materials response

- **Energy attenuation**, strain rate, and thickness effects

- Experimentally based **modeling and procedure development** from findings for initial design categorization

http://www.epoxysetinc.com/product-reviews/potting-encapsulating-compounds/

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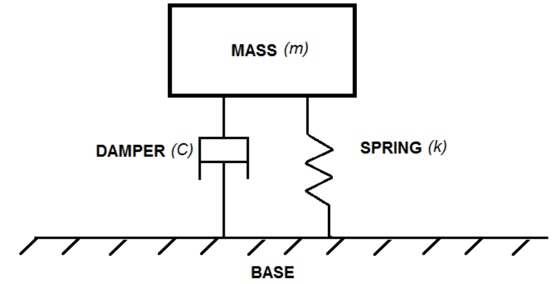
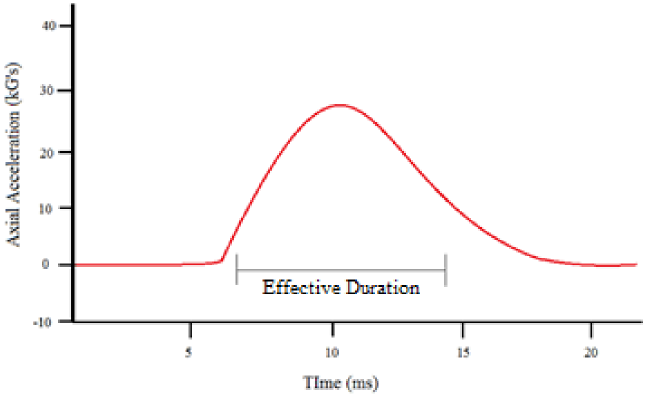
- Isolation system based on single degree of freedom (SDOF) assumptions for idealized structure



$$m\ddot{x} + c\dot{x} + kx = F_o \sin(2\pi f_f t)$$

- Simple Harmonic Characteristics:
  - Mass *m* (Package)
  - Spring *k* and Damper *c* (Isolation Material)
  - Excitation Event with System Reponses



- Half-Sine pulse wave form with pulse duration and amplitude of displacement, velocity or acceleration

- Damped Natural and Excitation Frequency ratio plays important role

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k'g}{F}} \qquad r = \frac{f_n}{f_f} \neq 1\ (resonance)$$

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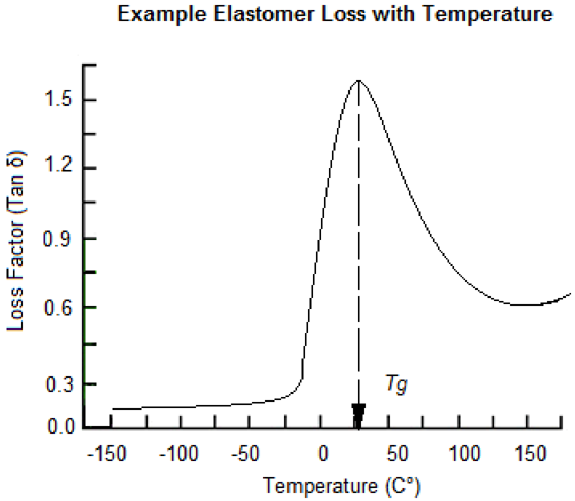
- Temperature, frequency, and time dependent
- Hardening or softening effects
- Glass transition temperature T_g
- Complex modulus: $E^* = E' + iE''$
  - Storage (Elastic): $E' = \frac{\sigma_0}{\varepsilon_0} \cos\delta$
  - Loss (Viscous): $E'' = \frac{\sigma_0}{\varepsilon_0} \sin\delta$
  - Phase Angle: δ
- Master-Curves and Time-Temperature relation through DMA testing at low strain rates

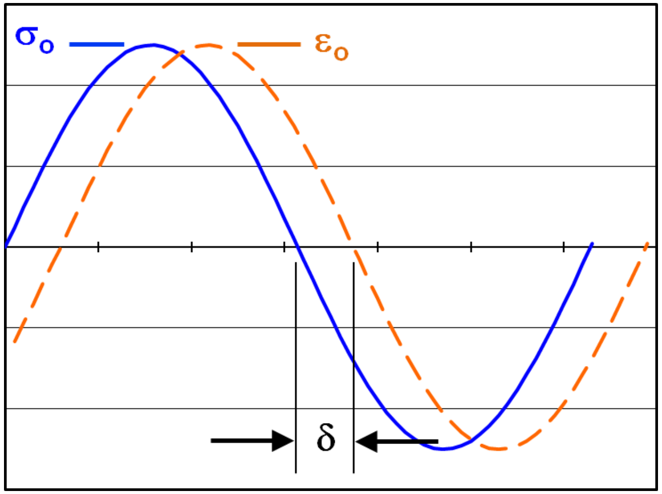


[redacted]Tan δ)

- Tan δ is a useful parameter to determine the effectiveness of a polymer based material for damping applications
- Tan (δ) = Loss/Storage $= \frac{E''}{E'} = \frac{G''}{G'}$
- Other Loss parameters:
  - Damping or Critical Ratio ζ
  - Figure of Merit Q
  - Coefficient of Restitution (*COR*)
  - Viscosity μ
- Relation to common isolation quantities

$$2\zeta \approx \tan\delta \approx 1/Q$$

- Generally, maximum Tan δ means material will perform well in dissipation and transmission



http://www.continuummechanics.org/cm/images/stress-strain-sines.png

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- Common potting and isolation materials:
  - Soft Elastomers
  - Hard plastics
  - Epoxies
  - Foams
- Cost, manufacturing, behavior, existing DMA data

- Selected Materials:
  - ***Dow® Sylgard®-184* Silicone**
    - Soft Elastomer
  - ***Conathane® EN-4/9* Polyurethane**
    - Medium Strength Elastomer
  - **E&C™ Stycast™-2651 Epoxy**
    - Hard Epoxy Resin

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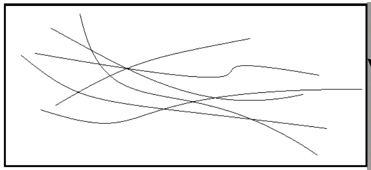
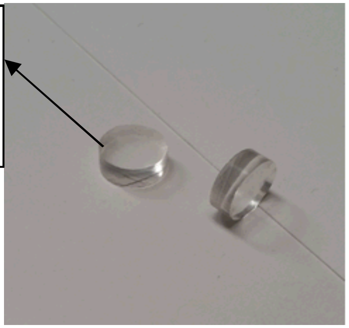
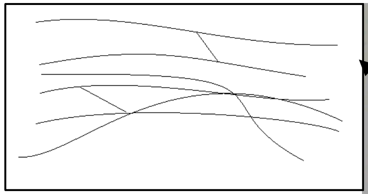
Specimen Dimensions:
Diameter: 3/8”
Thickness: 1/8”

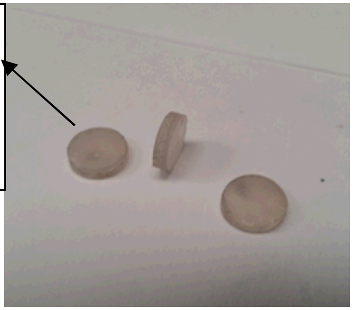
- ***Dow® Sylgard®-184*** **Silicone**
  - Shore Hardness: 45A
  - Mixing Ratio(Wt.) 10/100
  - *Tg*= -45°C
  - Soft segments-Low Strength



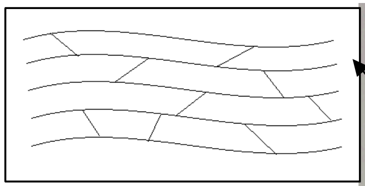


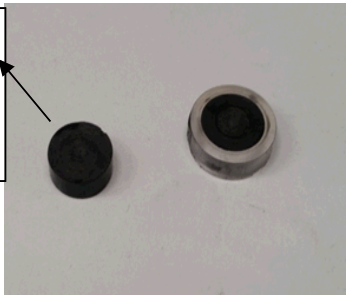
- ***Conathane® EN-4/9*** **Polyurethane**
  - Shore Hardness: 85-90A
  - Mixing Ratio(Wt.) 17.5/100
  - *Tg*= -55°C
  - Hard and Soft segments-Medium Strength





- **E&C™ Stycast™-2651/9 Epoxy**
  - Shore Hardness: 88D
  - Mixing Ratio(Wt.) 8.5/100
  - *Tg*= 75°C
  - Carbon black filler included
  - Hard segments with High Cross-linking and Strength





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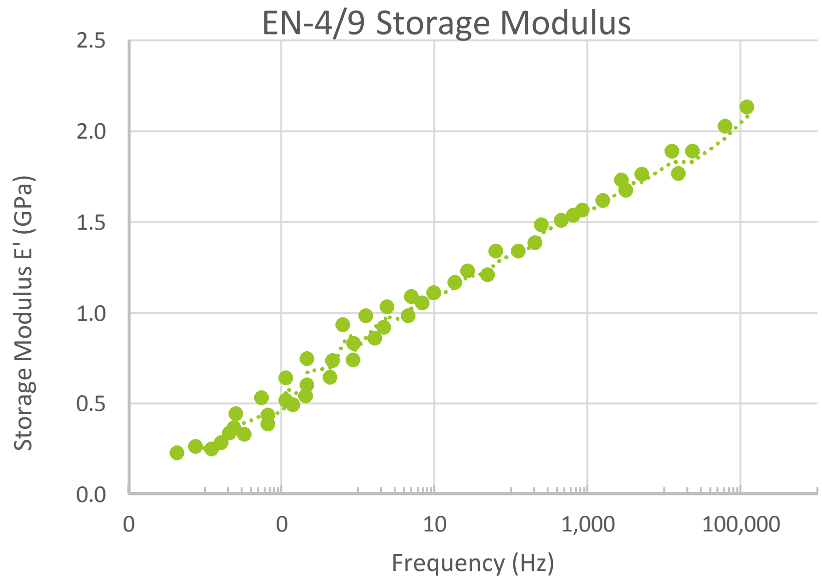
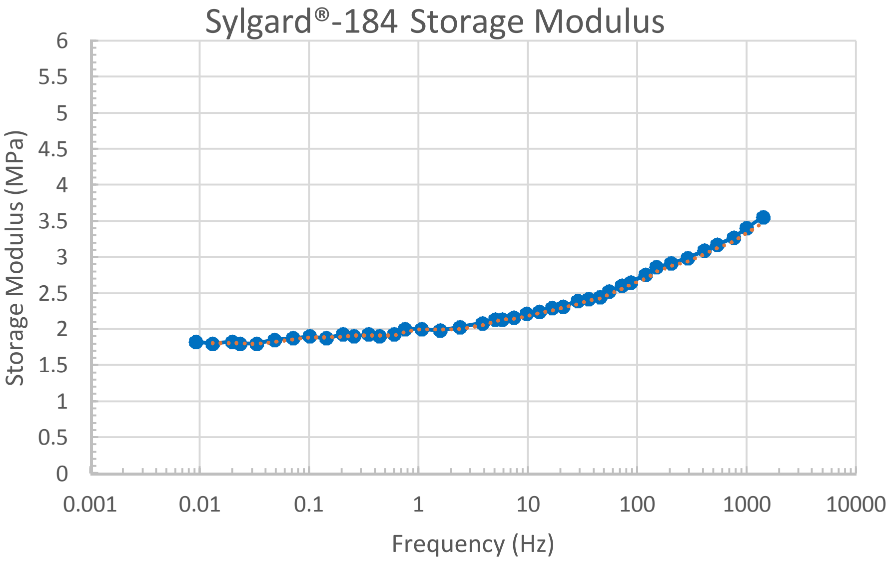
- Ambient Temperature: 25°C (298K)
- Sine-Wave input
- Stycast-2651 (Constant Modulus $\approx 3 - 4\ \mathrm{GPa}$)





$$\log(a_T) = -\frac{C1\ (T - T_0)}{C2 +\ (T - T_0)} = -\frac{10.3(298 - 283.15)}{(95.6 + 298 - 283.15)}$$

Capps 1989-DMA and Acoustic Testing

Rouzic et al. 2010-DMA testing

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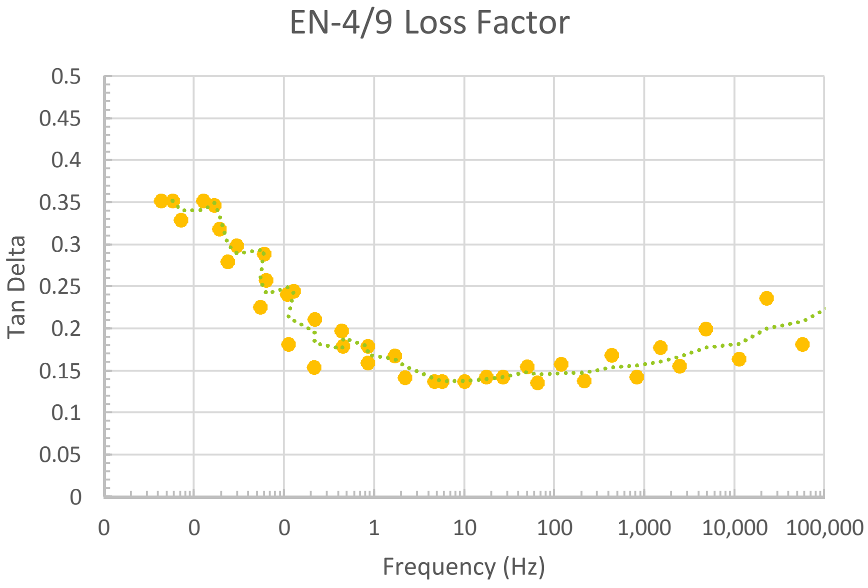
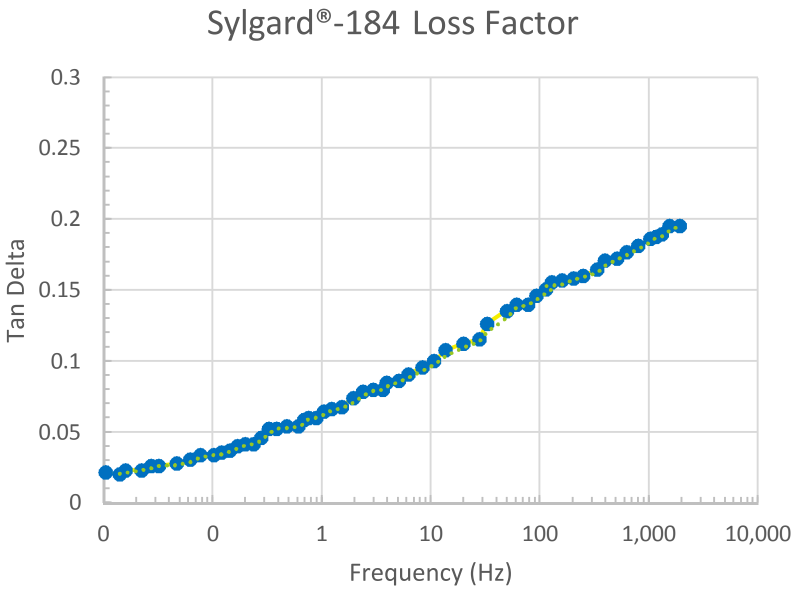
- Ambient Temperature: 25°C (298K)
- Stycast-2651 Loss Factor $\approx 0.015 - 0.020$


EN-4/9 Loss Factor

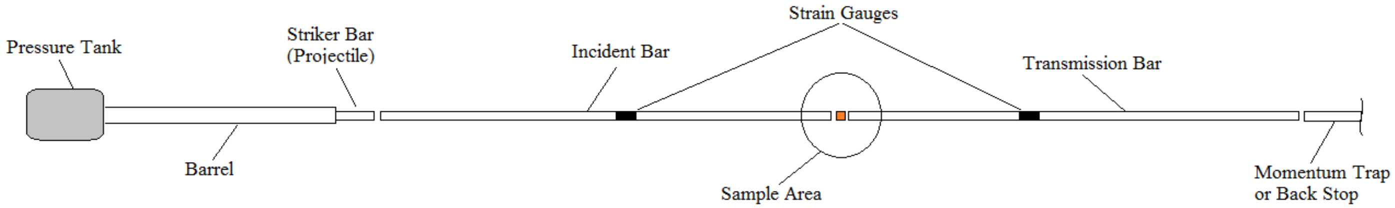

Sylgard®-184 Loss Factor

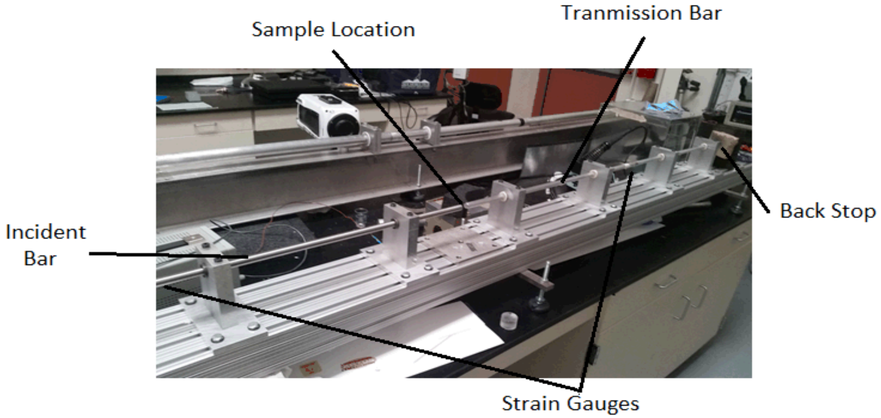
Capps 1989-DMA and Acoustic Testing

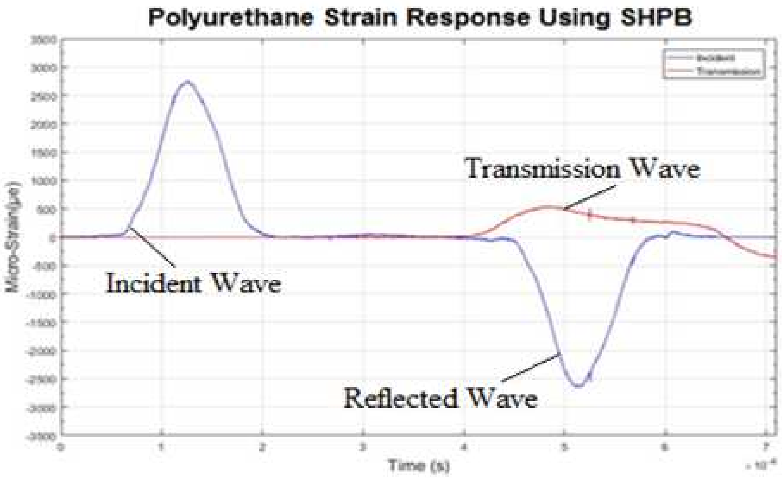
Rouzic et al. 2010-DMA testing

[redacted]-Strain Rate SHPB Testing

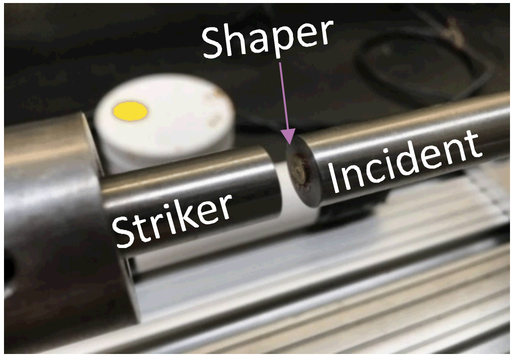
- Split Hopkinson Pressure Bar or Kolsky Bar
- Simple dynamic testing at high strain rates (100-10000/s)
- Linear elastic bar and 1D-wave mechanics assumptions



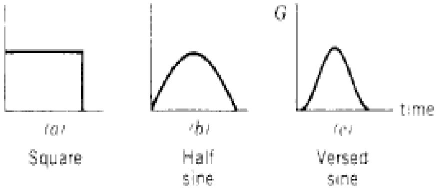


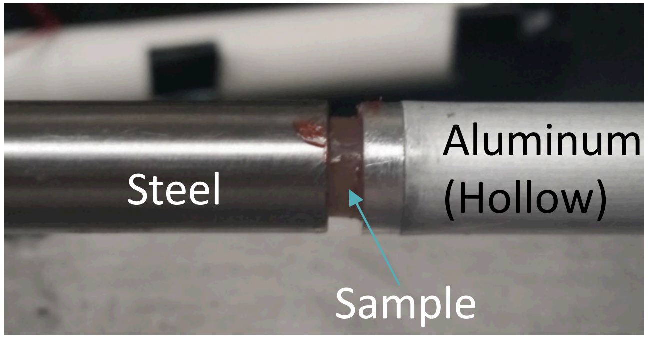


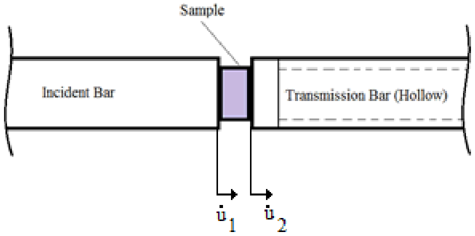
[redacted]-Strain Rate SHPB Testing Continued



- Dynamic Equilibrium Loading (DEL)
- Pulse Shaping for sine-wave and DEL
- Modified for soft materials Testing
  - Steel Incident Bar (C300)
  - Hollow Aluminum Transmission Bar (6061-T6)
- Modified Strain Rate, Strain and Three-Wave Stress in sample







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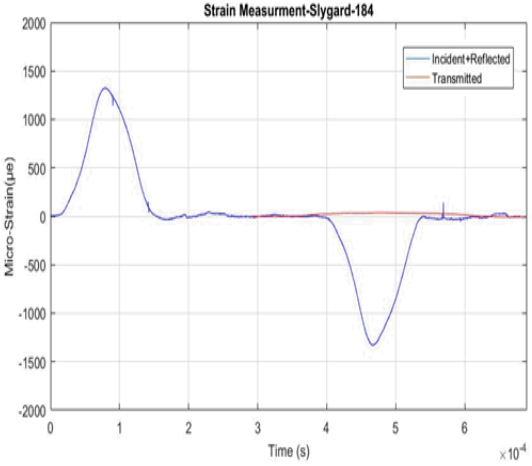
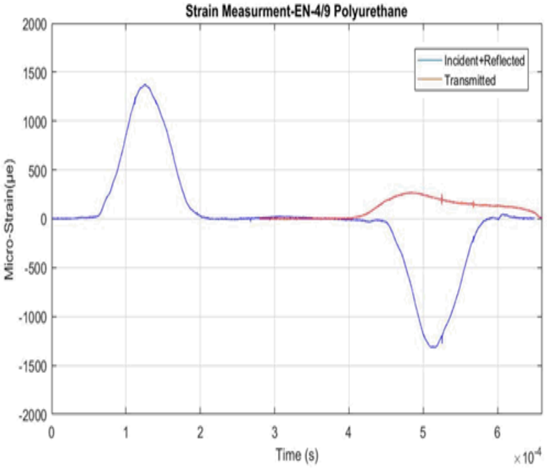
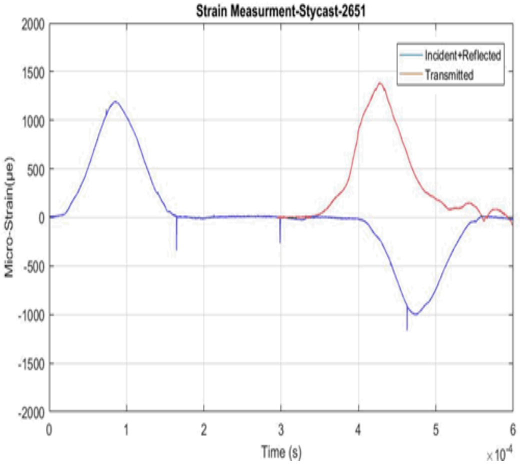
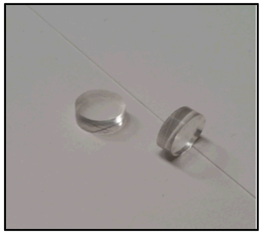
Sample Type	Nominal Thickness (inch)	Peak Incident Strain (με)	Peak Transmission Strain (με)
Sylgard®-184	0.140	1350	34
Conathane® EN-4/9	0.110	1450	250
Stycast™-2651	0.140	1300	1500

- ○ Five (5) samples per test
- ○ Peak Incident Strain ≈ 1400 μ-strain
- ○ Incident Pulse Width ≈ 140 μ-seconds
- ○ No confinement (Poisson's Effect)
- ○ Dynamic equilibrium achieved but not complete constant strain rate









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- Different Ratios depending on material attributes
- Peak Strain Energy Density (w_i, w_r, w_t)

$$\boldsymbol{w} = \frac{1}{2} E \varepsilon^2 \qquad \boldsymbol{w_R} = \frac{0.5 E_t \varepsilon_{t-max}^2}{0.5 E_i \varepsilon_{i-max}^2} = \left(\frac{w_t}{w_i}\right)$$

- Simple and conservative comparison for energy transmission at maximum point in time

Sample Type	**Incident Strain Energy $\boldsymbol{U_i}$ (J)**	**Strain Energy Transmitted $\boldsymbol{U_t}$ (J)**	**Peak Strain Energy Density Ratio, $(\mathbf{100\%})\ (\boldsymbol{w_R})$**
Sylgard®-184	4.859	0.00126	**0.0293%**
Conathane® EN-4/9	5.129	0.0436	**1.31%**
Stycast™-2651	4.728	.752	**20.9%**

[redacted]

- ○ Sylgard-184 high-strain rate energy density transmission compared to Bateman et al. (Part 1-1988,Part 2-1992)
- ○ Reduction in pulse amplitude and increase in duration

- ○ Thickness and strain rate dependence (General Trend)

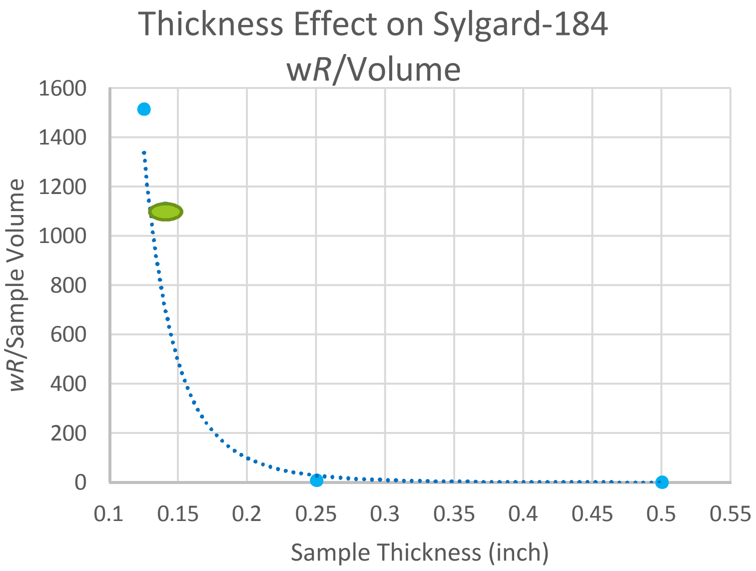
$$\uparrow Thickness \quad = \quad \downarrow Energy\ Tranmission$$

$$\uparrow Strain\ Rate \quad = \downarrow Energy\ Tranmission$$

- ○ Discrepancy with Part 2 data

- ○ Comparison by Volume w_R/V_s (Part 1)

Nominal Thickness (inch)	w_R Part 1 4700/s	w_R Part 2 4700/s	w_R This Study ≈4000/s	w_R Part 2 2350/s
0.125	0.1372%	2.151%	0.0293%	0.54%
0.25	0.0016%	0.0215%	-	0.04%
0.5	3.70E-04%	-	-	-



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- Total Strain Energy Transmission from bar strains (U_i, U_r, U_t)

$$\boldsymbol{U} = \int_0^t \frac{1}{2} A_i C_i \, E_i \, \varepsilon_i^2 \, dt \qquad Total\ Transmission\ Ratio = \ U_t / U_i$$

- Best way to examine energy transmission based on entire pulse history

Sample Type	Incident Strain Energy U_i (J)	Strain Energy Transmitted U_t (J)	Total Strain Energy Transmitted $(100\%)(U_t/U_i)$
Sylgard®-184	4.859	0.00126	**0.026%**
Conathane® EN-4/9	5.129	0.0436	**1.10%**
Stycast™-2651	4.728	0.752	**13.9%**

[redacted]

- Difficult to determine from actual sample

$$\boldsymbol{U_D} = U_i - (U_r + U_t)$$

- Energy Dissipation from materials (U_D)

- Slight variation in dissipation from material and loading

Sample Type	Incident Strain Energy U_i (J)	Strain Energy Transmitted U_t (J)	Energy Dissipated U_D (J)
Sylgard®-184	4.859	0.00126	0.0326
Conathane® EN-4/9	5.129	0.0436	0.412
Stycast™-2651	4.728	.752	**0.547**

[redacted]

- Comparison of DMA data to SHPB data

- Loss Factor in terms of Dissipation and Max Elastic Energy <u>per cycle</u> (U_E)

$$\tan\delta = \frac{E''}{E'} = \frac{U_D}{2\pi\, U_E} \qquad \boldsymbol{U_E} = \int w\, dV = V\int \sigma d\varepsilon\ (nonlinear) = \frac{1}{2}E\varepsilon_{sample}^{2}(linear)$$

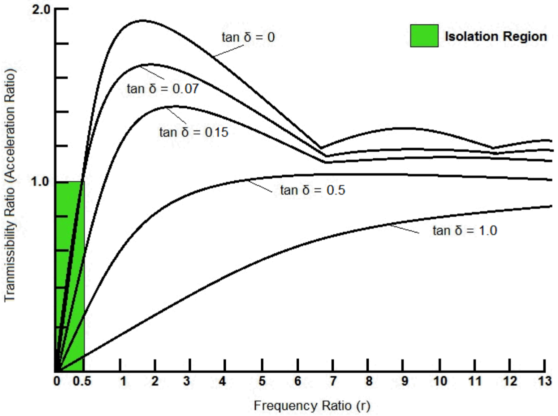
- Stress-Strain relationship from specimens
- Input frequency: 3300Hz
- Ambient temperature: 25°C

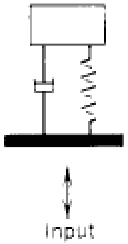
Material	**DMA Loss Factor ($\tan\delta$)**	**SHPB Energy Based Loss Factor ($\tan\delta$)**
Sylgard®-184 Non -Linear	0.09 - 0.17	0.0829
Conathane® EN-4/9 Non-Linear	0.145 -0.17	0.136
Stycast™-2651 Linear	0.015 - 0.020	0.0173

Response Functions

- Transmissibility of simple system: response/input
- Use of energy based loss factor for determining system loss
- Simple means to estimate performance of structure for transient excitation through shock amplification

$$m\ddot{x} + c\dot{x} + kx = F_p \sin(\pi\, t/\tau)$$





Response from Vibration Analysis for Electronic 3ED Steinberg Chp. 11

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- Estimation of transmission ratio seen by SHPB testing

Inputs:	Outputs:
Pulse Frequency of Excitation f_f	Dynamic Stiffness of Specimen ***k’***
Specimen Dimensions and Constants ***A, t, SP***	Natural Frequency of System (Specimen) f_n
Material Properties at Natural and Excited States **E,** $\tan\delta$	Displacement, Force, and Energy Transmissibility ***T***
Incident Force on Specimen ***F***	Comparison to Experimental Data Ratios

- Combination of Displacement and Force transmissibility using natural frequency of specimens and pulse characteristics

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K'g}{F}} \qquad f_f = \frac{1}{2\tau} \qquad r = \frac{f_n}{f_f}$$

- Resulting work comparison relies on loss factor and dynamic properties

$$k' = \frac{E_n'(1 + 2SP^2)A}{t} \qquad DF = E_n'/E_f'$$

$$Transmitted\ Energy\ Ratio\ (Force \cdot Displacemet) = r^2 \frac{1 + (\tan\delta r)^2}{(1 - r^2\ DF) + (\tan\delta r)^2}(Work)$$

- Relations lead to application in shock amplification for standard design procedure

[redacted]

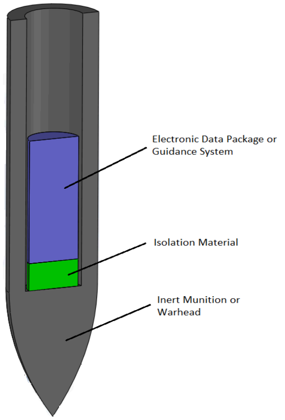
- Procedure using three investigated materials
- Simple SDOF setup in linear impact orientation with package
- Material selection based on shock amplification and standard mechanical analysis

Performance Envelope:

Stress, ksi (Mpa)	Axial Acceleration, g	Lateral Acceleration, g	Duration, ms	Velocity Step, ft/s (m/s)	Temp.,°C
5-70 (34.5-480)	1000-25,000	1000-50,000	0.5-20	500-5000 (152-1520)	(-)25-200

Example Problem:

Peak Acceleration	25,000 G
Waveform	Half-Sine
Duration	20 ms
Available Diameter	2 inches [0.0508m]
Package Mass	2 kg
Package Material	Aluminum shell with silicon board (encapsulated)
Ambient Temperature	25°C



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Step 1: *Determine the Shock transmission function based on pulse shape and duration expected as well as loss factor attributes. Determine pulse frequency.*

$$f_f = \frac{1}{(2)(0.020)} = 25\text{hz}$$

Step 2: *Determine applicable materials based on expected shock levels with regards to deceleration amplitude, topological constraints, and frequency concerns. Determine package frequency.*

$$Shape\ Factor\ (SP) = \frac{Diameter}{(4t)} = \frac{(0.0508)}{(4)(.0064)} = 1.98$$

Material	k'
Sylgard-184	6.30 MN/m
EN-4/9	19.7 MN/m
Stycast-2651	179 MN/m

$$k'_{eq} = \frac{E'_n(1 + 2SF^2)Impact\ Area}{t}$$

$$f_n = \frac{\sqrt{k'_{eq}g\left(1 - (0.5\tan\delta_n)\right)^2 / F}}{2\pi}$$

Material	fn
Sylgard-184	5 Hz
EN-4/9	9 Hz
Stycast-2651	20 Hz

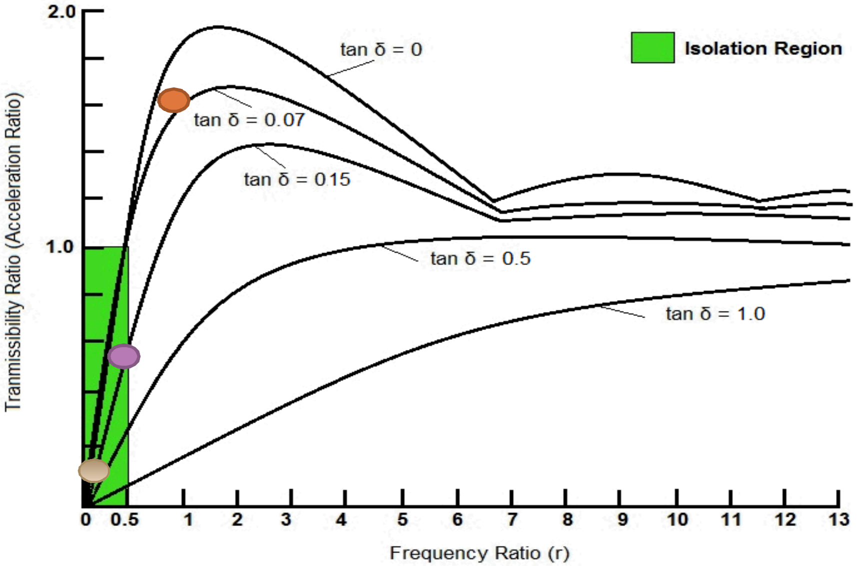
[redacted]

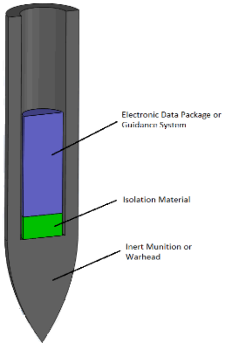
Step 3: *Using transmissibility chart, obtain amplification of factor for acceleration using materials selected and the simplified package characteristics.*

- Dissipation has major role in response at excitation frequency

$$r = \frac{f_n}{25\ Hz}$$

Material	Frequency Ratio	Loss Factor	Amplification Factor
Sylgard-184	0.2	0.12	0.1
EN-4/9	0.4	0.16	0.5
Stycast-2651	0.8	0.017	1.6





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Step 4: *Determine stress values to compare to maximum allowable values for the most sensitive components in the design.*

Material	Amplification Factor
Sylgard-184	0.1
EN-4/9	0.5
Stycast-2651	1.6

EN-4/9: $\sigma_{max} = 76\ \text{MPa}^{*}$ $\sigma_y \approx \underline{38\ \text{MPa}}$

$$\sigma = \frac{(mass)\ (\text{G}'\text{s})(Amplification\ Factor)}{Loaded\ Area} = \frac{(2\text{kg})(25{,}000\text{G})(0.5)}{(2.0E-3)} = \mathbf{12.5\ MPa}$$

$$Safety\ Factor = \frac{\sigma_y}{\sigma} = \frac{38\ \text{MPa}}{12.5\ MPa} = \mathbf{3.0} > 1.0$$

Material	Safety Factor
Sylgard-184	7.60
EN-4/9	3.00
Stycast-2651	0.95

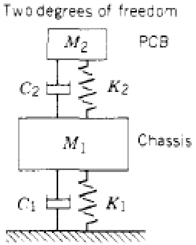
- Silicone and Polyurethane adequate for isolation
- Epoxy would risk failure of electronic pack at t = 0.25 and Loss factor of 0.017

*Thermomechanical Impact of Polyurethane Potting on Gun Launched Electronics-Haynes,Cordes, Krug 2013 10% Failure @76 MPa
Lead Free Solder and Flex Cracking Failures in Ceramic Capacitors
Database for Solder Properties with Emphasis on New Lead-free Solders 0.2% offset yield at 27 MPa

[redacted]

***Step 5:** Depending on system complexity, add degrees of freedom for additional components or subassemblies.*

- Further iteration can be performed by increasing the amount of sub-assemblies, combing the stiffness and loss factors, or iterating for different components in the package.



***Step 6:** Choose the most applicable materials in accordance to results as well as concerns of machining, manufacturing, procurement, cost, and physical attributes.*

- **Use with PCB components**
  - Adhesion of potting to components and resistivity
  - **Mechanical Impedance**
  - Temperature of reaction
  - Volume expansion
  - Fatigue and degradation to environment
  - Manufacturing
  - Cost

$$Z_{Isolator} < Z_{Structure}$$

Response from Vibration Analysis for Electronic 3ED Steinberg Chp. 11

[redacted]

- Showed correlation of Loss Factor from low-strain rate to high-strain rate dynamic testing at similar frequency and temperature conditions
- Developed experimentally based model for initial selection of materials based on complex material parameters, total strain energy transmission U and dissipation U_D, and general loading conditions
- Narrowed down a library of materials based on dynamic information obtained from experimental sources such as DMA and SHPB for impact enviorments

[redacted]

- Idealized SDOF structure for setting up response and testing of packages
- Explored connections between viscoelastic material properties and response in impact environments
- Use of modified SHPB for dynamic material testing of three (3) commercial potting agents at high strain rates to investigate material parameters
- Direct comparison to other published material including Bateman et al. (1988,1992) and Song et al. (2009,2014,2015)
- Development of simple energy and shock response spectrums
- Application to example shock mitigation problem

[redacted]

- Addition of confinement and composite layering for impedance and stiffness comparison in testing
- Use of pre-load to simulate compression to avoid bouncing of isolated components in testing
- Introduction of porous layers/engineered voids in the host material alters the behavior and dynamic response in impact environments for testing
- Statistical energy analysis investigation for coupling of loss factors to impedance, multi-material systems, and MDOF in modeling appraoch

[redacted]

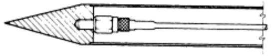
Thank You

[redacted]

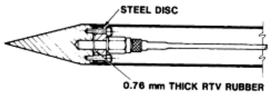
- Thermomechancial Impact of Polyurethane Potting on Gun Launched Electronics-A.S.Haynes,J.A. Cordes and J.Krug 2012
- Shock Mitigation by Soft Condensed Matter- Vitali F. Nesterenko 2003
- Vibration Analysis for Electronic 3ED Steinberg Chp. 11
- Pt1/Pt2-A Study of Shock mitigating Materials in a SHBC-SNL 1996,1997
- A Study of Shock mitigating Materials in a SHBC-SNL 1996
- Electronic Components for High-G Hardened Packaging-Berman
- High-G Ruggedization Methods for Gun Projectile Electronics-Jeff Burd ION GPS '99, 14-17 September 1999, Nashville, TN
- Zapotec: A Coupled Euler Lagrange Program for Modeling Earth Penetration Greg C. Bessette, Courtenay T. Vaughan, and Raymond L. Bell SNL
- Experimental Determination of applied forces during penetration: L.M.Lee,M.J.Forresta SNL

[redacted]

- Create relevant and standard responses of material parameters for high frequency and impact excitation using:
  - SHPB and Acceleration bar with visual strain recording of sample to compare energy dissipated
  - Drop Impact of example systems and materials with attached accelerometer
  - Vibration Table for determination of frequency response and modal behavior
  - Ride Along tests with actual K.E. munition



a) RIGIDLY MOUNTED ACCELEROMETER



b) SHOCK ISOLATED ACCELEROMETER

Experimental Determination of applied forces during penetration: L.M.Lee,M.J.Forresta SNL

[redacted]

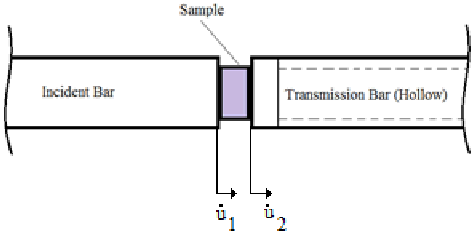
- Sylgard-184 High Strain Rate Energy Dissipation using relation proposed by Song et al. 2014

$$\delta(t) = \frac{U_D}{U_i - U_r}$$

Study	Energy Dissipation Ratio $\delta(t)$
Bateman et al. (1988) **w**	0.963
Current Test Specimens **w**	0.951

- Also provides another means of determining acceleration attenuation through foams by taking FFT of strain signals

[redacted]-Strain Rate SHPB Testing Continued:



$$\dot{\varepsilon} = \frac{\dot{u}_2 - \dot{u}_1}{L_s}$$

- ○ Friction and Dynamic Equilibrium Loading

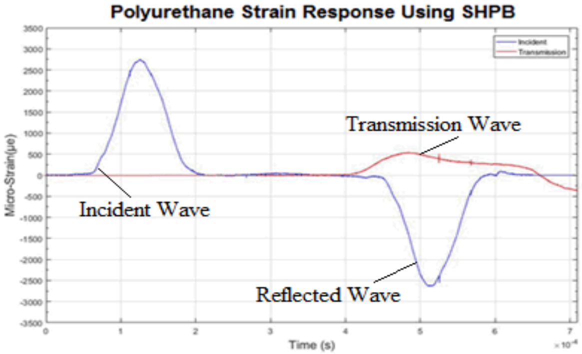
$$A_iE_i(\varepsilon_i + \varepsilon_r) \approx A_tE_t(\varepsilon_t)$$

- ○ Modified Strain Rate, Strain and Three-Wave Stress in sample

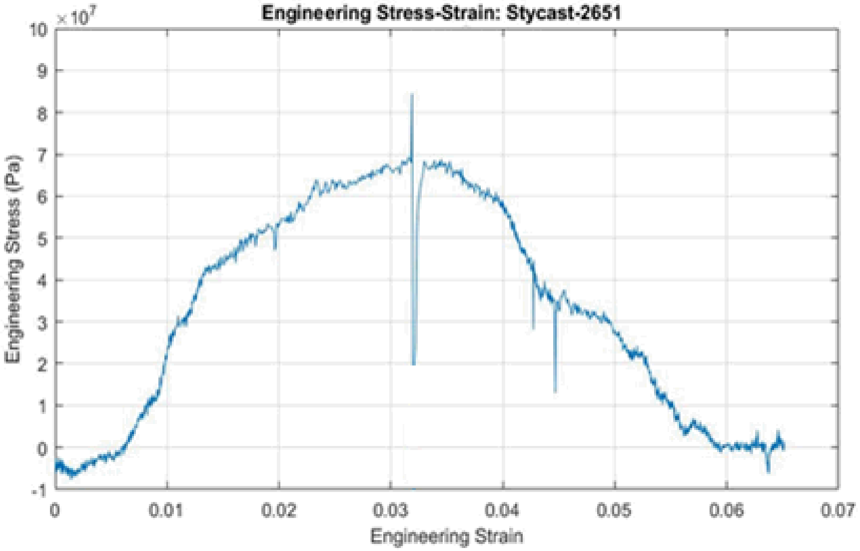
$$\dot{\varepsilon} = \frac{(C_i - C_tA_i E_i/A_t E_t)\varepsilon_i(t) - (C_i + C_tA_i E_i/A_t E_t)\varepsilon_r(t)}{L_s}$$

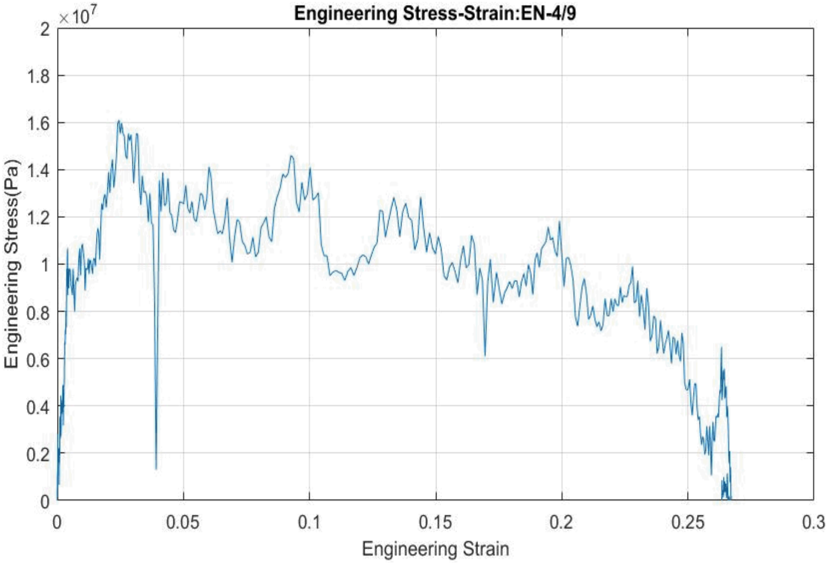
$$\varepsilon = \int_0^t \dot{\varepsilon}\, dt$$

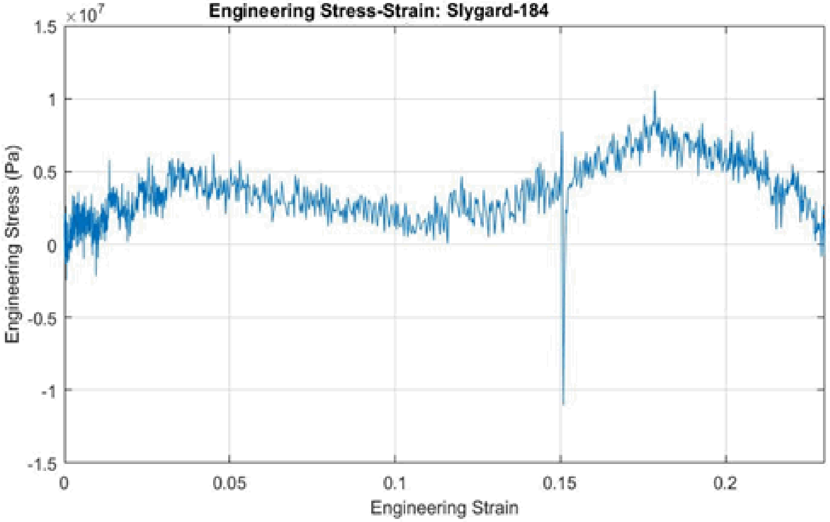
$$\sigma = \frac{A_iE_i[\varepsilon_i(t) + \varepsilon_r(t)] + A_tE_t\varepsilon_t(t)}{2A_s} = \frac{F_1(t) + F_2(t)}{2A_s}$$

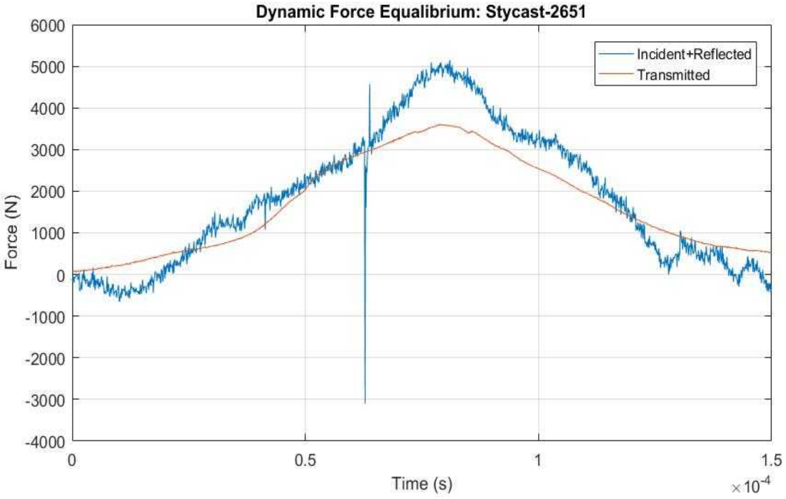


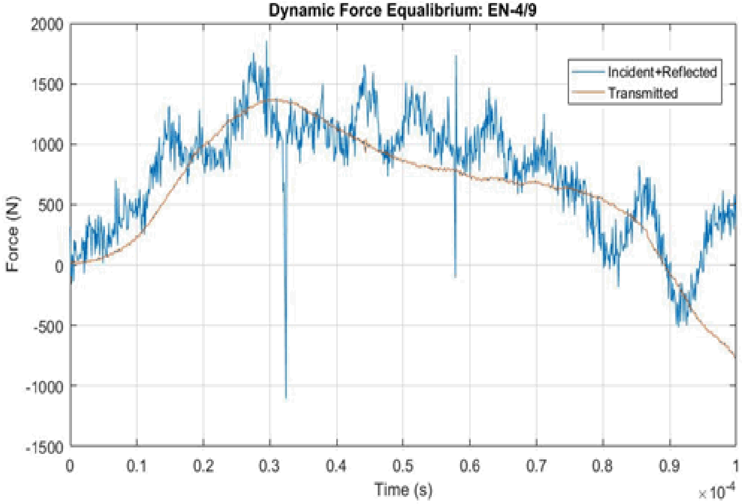
[redacted]-Strain Response

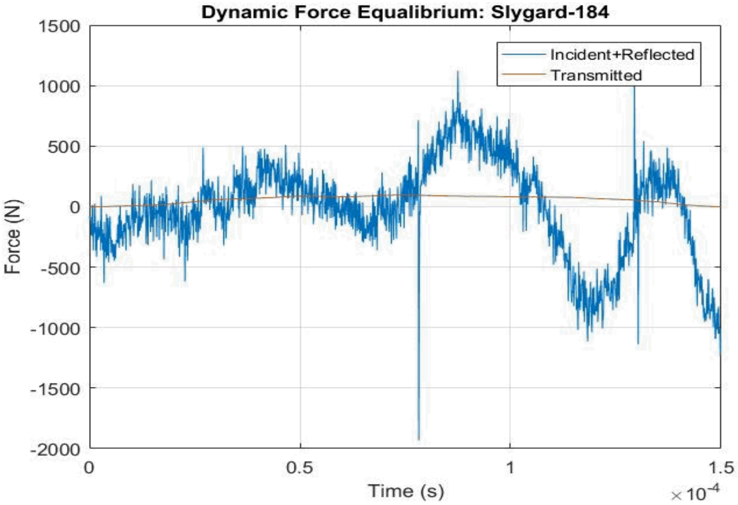


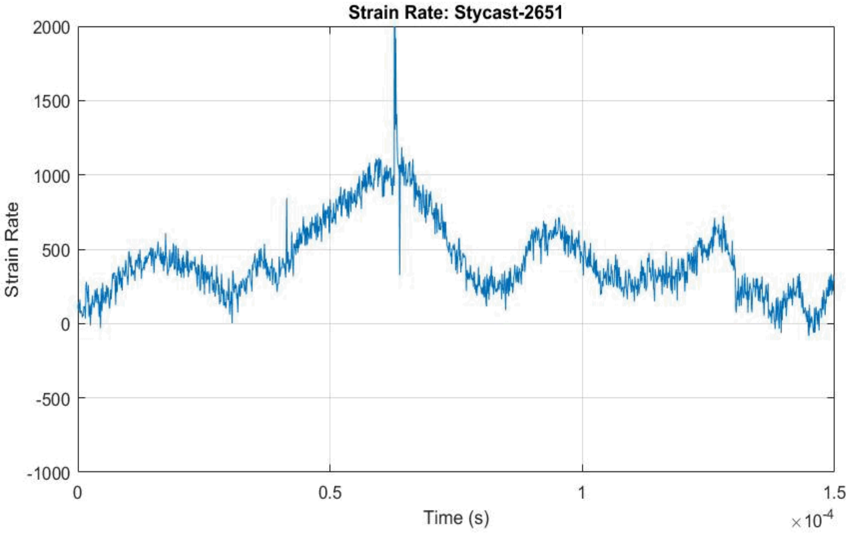


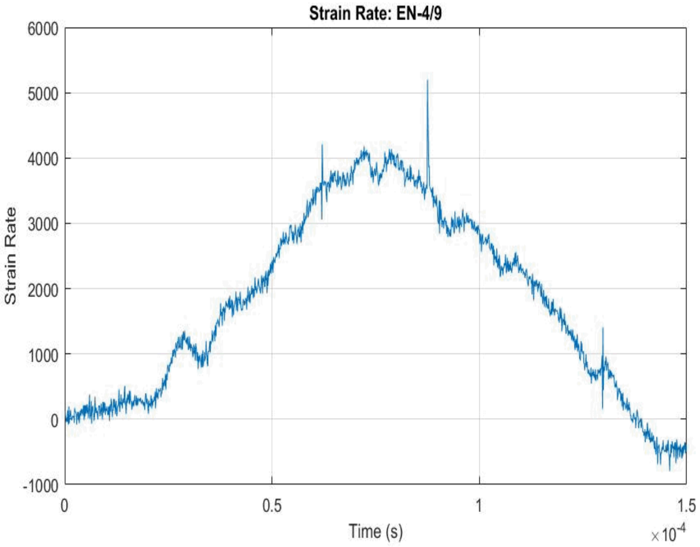


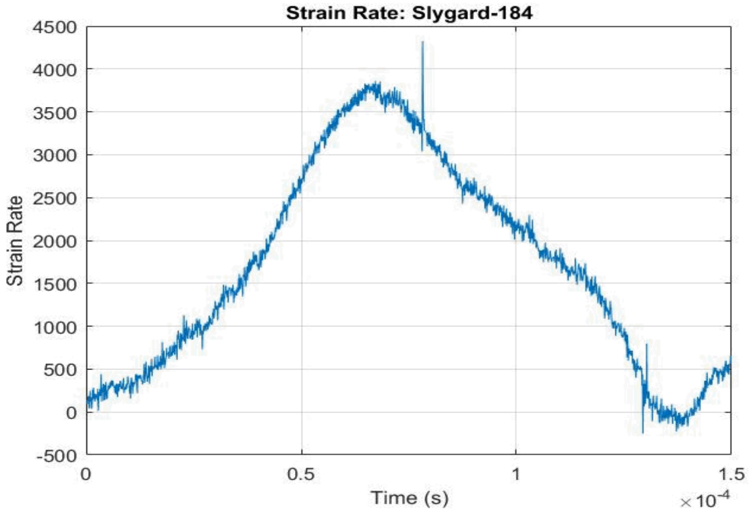

Dynamic Force Equalibrium: Stycast-2651
Incident+Reflected
Transmitted
Force (N)
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
0
0.5
1
1.5
Time (s)
×10^-4


Dynamic Force Equalibrium: EN-4/9
Incident+Reflected
Transmitted
Force (N)
2000
1500
1000
500
0
-500
-1000
-1500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (s)
×10^-4


Dynamic Force Equalibrium: Slygard-184
Incident+Reflected
Transmitted
Force (N)
1500
1000
500
0
-500
-1000
-1500
-2000
0
0.5
1
1.5
Time (s)
×10^-4

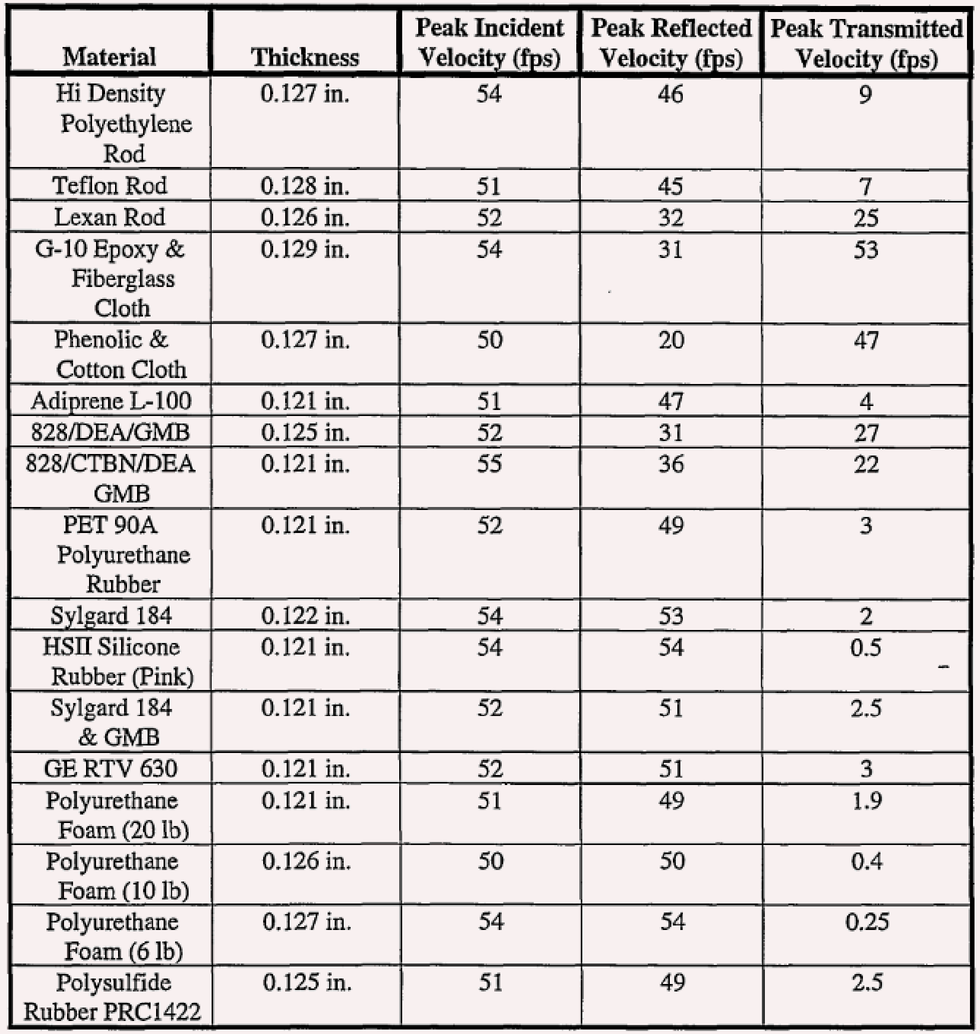

Strain Rate: Stycast-2651


Strain Rate: EN-4/9


Strain Rate: Slygard-184

Material Species (Cured):	Sylgard®-184	Conathane® EN-4/9	Stycast™-2651/9
Hardness, Shore Durometer	43-50A	85-90A	88D
Viscosity, cP	3500	N/A	25000
Specific Gravity	1.03	1.01	1.50
Compressive Strength, ksi (MPa)	7.5 (51.7)	N/A	17.1 (118)
Compressive Modulus, ksi (MPa)	27.1 (186.9)	N/A	N/A
Tensile Strength, ksi (MPa)	0.98 (6.7)	1.9-2.5 (13.1-17.2)	6.5 (45)
Poisson’s Ratio (υ)	0.499	0.499	0.323
100% Modulus, ksi (MPa)	0.191 (1.32)	0.8 (3.52-6.21)	145 (1000)
300% Modulus, ksi (MPa)	N/A	1.6 (8.28-12.8)	N/A
Shear Modulus, ksi (MPa)	0.064 (0.44)	N/A	N/A
Bulk Modulus, ksi (MPa)	319 (2200)	N/A	N/A
Ultimate Elongation (%)	N/A	380-500	N/A
Water Absorption (%)	N/A	0.2	0.25
Thermal Expansion Coefficient ppm/°C	340	N/A	43.3
Glass Transition Temperature (°C)	-45	-55	75

Sample Type	Nominal Thickness (inch)	Peak Incident Strain (με)	Peak Transmission Strain (με)	Incident Strain Energy U_i (J)	Strain Energy Transmitted U_t (J)	Energy Dissipated U_D (J)	Total Strain Energy Transmitted $(100\%)(U_t/U_i)$	Peak Strain Energy Density Ratio, $(100\%)\ (w_R)$
Conathane® EN-4/9	0.110	1450	250	5.129	0.0436	0.412	1.10%	1.31%
Slygard®-184	0.140	1350	34	4.859	0.00126	0.0326	0.026%	0.0293%
Stycast™-2651	0.140	1300	1500	4.728	.752	0.547	13.9%	20.9%



Material	Thickness	Peak Incident Velocity (fps)	Peak Reflected Velocity (fps)	Peak Transmitted Velocity (fps)
Hi Density Polyethylene Rod	0.127 in.	54	46	9
Teflon Rod	0.128 in.	51	45	7
Lexan Rod	0.126 in.	52	32	25
G-10 Epoxy & Fiberglass Cloth	0.129 in.	54	31	53
Phenolic & Cotton Cloth	0.127 in.	50	20	47
Adiprene L-100	0.121 in.	51	47	4
828/DEA/GMB	0.125 in.	52	31	27
828/CTBN/DEA GMB	0.121 in.	55	36	22
PET 90A Polyurethane Rubber	0.121 in.	52	49	3
Sylgard 184	0.122 in.	54	53	2
HSII Silicone Rubber (Pink)	0.121 in.	54	54	0.5
Sylgard 184 & GMB	0.121 in.	52	51	2.5
GE RTV 630	0.121 in.	52	51	3
Polyurethane Foam (20 lb)	0.121 in.	51	49	1.9
Polyurethane Foam (10 lb)	0.126 in.	50	50	0.4
Polyurethane Foam (6 lb)	0.127 in.	54	54	0.25
Polysulfide Rubber PRC1422	0.125 in.	51	49	2.5

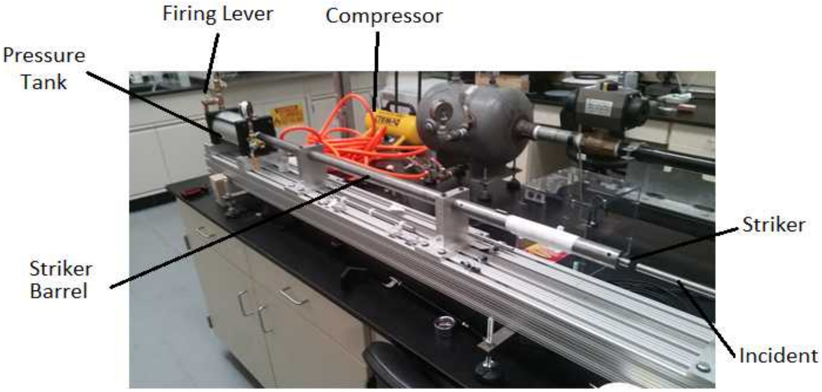
Thickness (Inch)	Incident Peak Strain (μ-strain)	Transmitted Peak Strain (μ-strain)	Peak Energy Transmitted Ratio
0.122	1620	60	0.0184
0.249	1500	22	2.15E-04
0.501	1560	3	3.70E-06

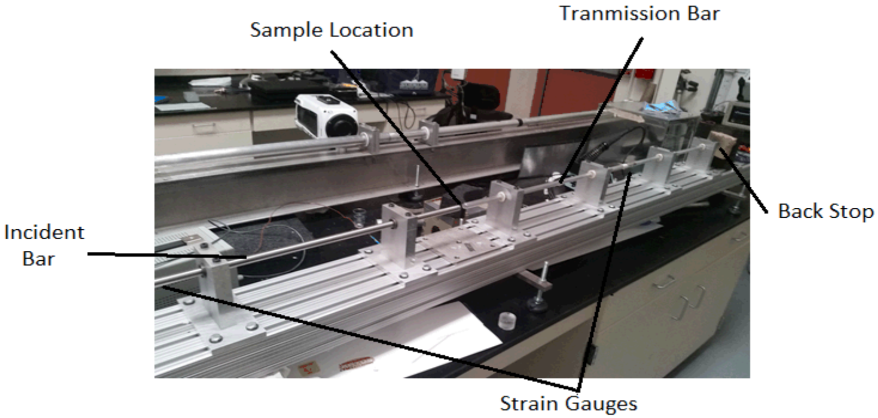
Parameter	Sylgard®-184	Conathane® EN-4/9	Stycast™ -2651/9	Aluminum 6061-T6	C300 Maraging Steel
Density, g/cc	1010	1030	1500	2700	8100
Sound Speed (Longitudinal), m/s	120	734	1155	5051	4850
Impedance, kg/(sqm s)	1.20E+05	7.56E+05	1.73E+06	1.36E+07	3.92E+07

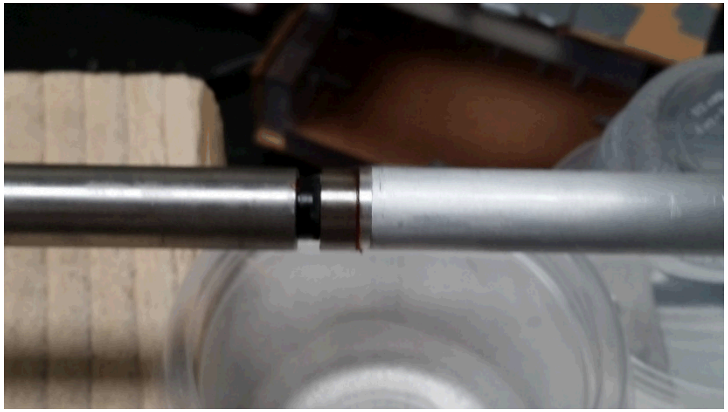
Nominal Thickness (inch)	w_R/V_s Part 1 4700/s	w_R/V_s Part 2 4700/s	w_R/V_s This Study 4000/s	w_R/V_s Part 2 2350/s
0.125	1516	23769	1114	5943
0.25	8.86	119	-	222
0.50	1.02	-	-	-

Nominal Thickness (inch)	w_R Part 1 4700/s	w_R Part 2 4700/s	w_R This Study 3700/s	w_R Part 2 2350/s
0.125	0.1372%	2.151%	0.0293%	0.54%
0.25	0.0016%	0.0215%	-	0.04%
0.5	3.70E-04%	-	-	-

[redacted]

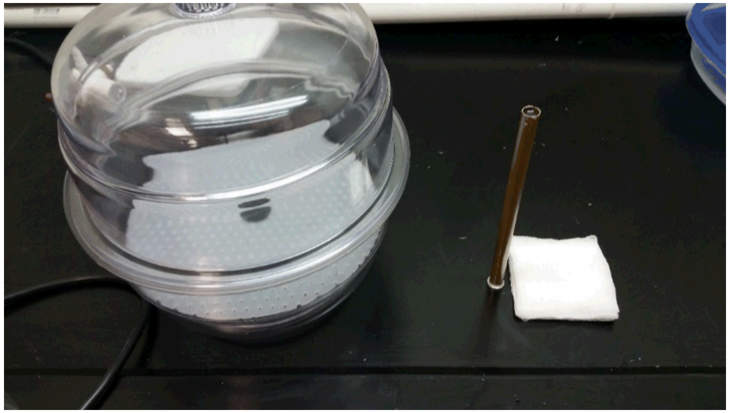


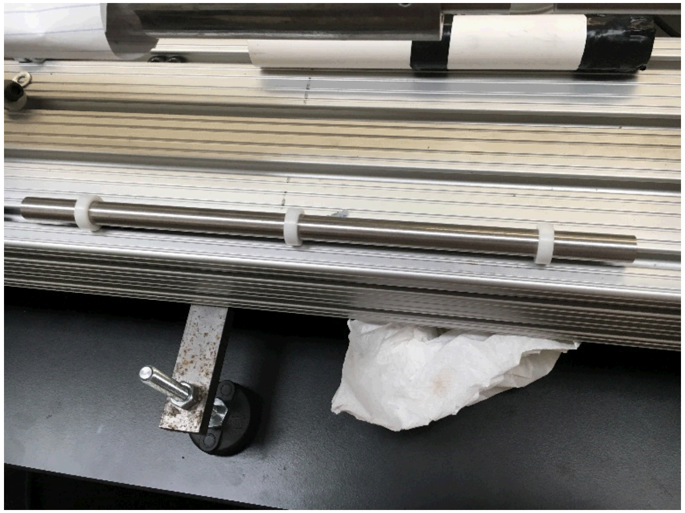




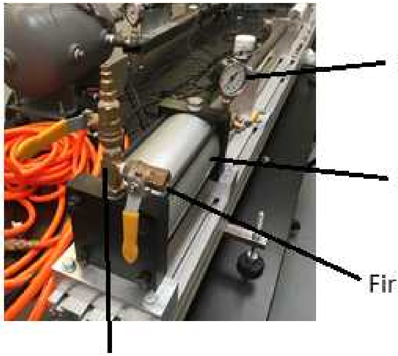
Stycast

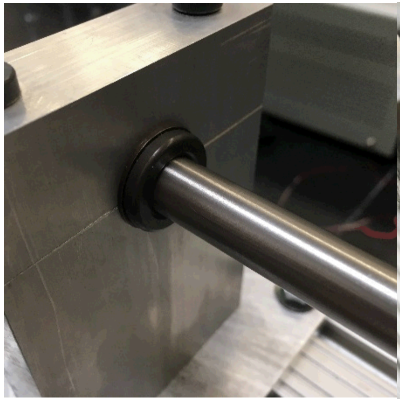
EN-9

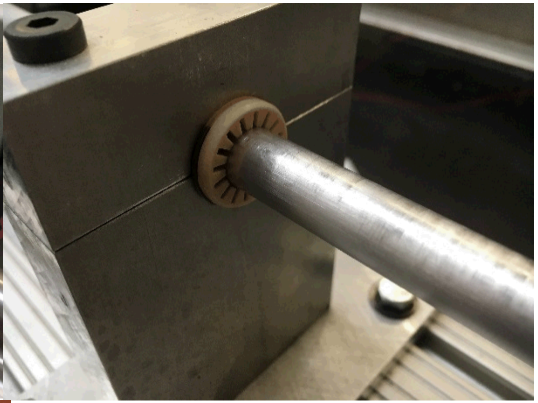


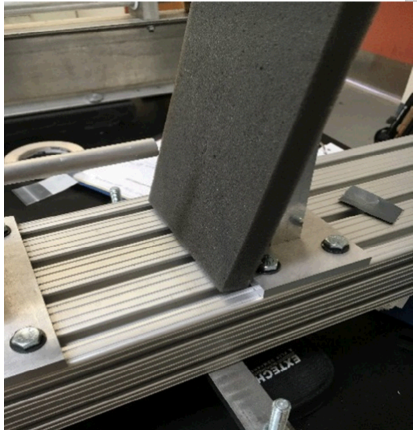


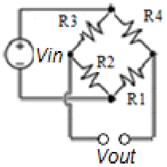

Air Compressor

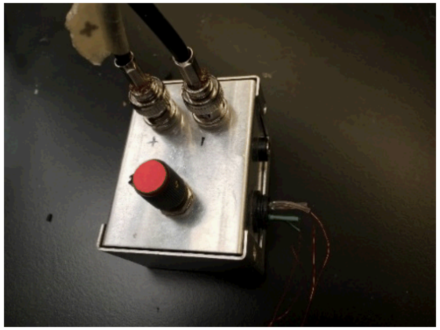

Pressure Gauge (psi)
Pressure Tank
Firing Lever
Gas Input

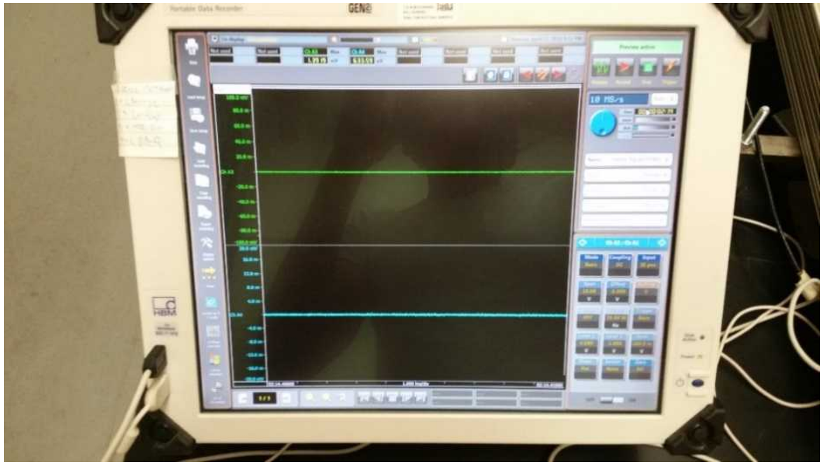







R3
R4
Vin
R2
R1
Vout

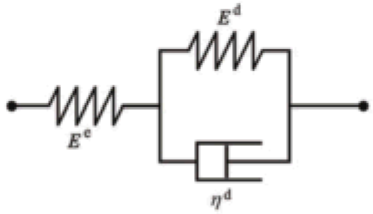




```
%% Dynamic Values pertaining of frequency are captured at 25°C (ambient)
fi=3333;    %% Pulse frequency
g=9.81;     %% Gravitational Constant SI
t=.0030988;  %% Specimen thickness in meters
D=.01905;    %% Specimen diameter in meters
SF=D/(4*t)      %% Shape factor for cylindrical sample
m=1030*.25*pi*D^2*t;    %% Mass of sample from density (kg)

tandN=0.10           %%Initial natural frequency loss factor
tandNC=(sqrt(1+tandN)-sqrt(1-tandN)) %% Series correction of natural loss factor
tandEx=0.21;        %%Loss factor at excitation frequency
tandCEX=(sqrt(1+tandEx)-sqrt(1-tandEx))     %% Series correction of natural loss factor

E0=2.25e6;          %% Storage modulus value at natural frequency
W=1335;             %% Load experienced by incident bar

%%  Dynamic Properties of Damped System using Loss factor
K=E0*(1+2*SF^2)*(.25*pi*D^2)/t    %% Dynamic Stiffness of Specimen
fn=sqrt(K*g*(1-(.5*tandNC))^2/W)/(2*pi)     %%Natural frequency of specimen(must be iterated with E0)

F=fi/fn             %%Ratio of pulse to natural frequency
G=E0/(4.2e6)        %% Ratio of natural to excitation storage modulus
%% Displacement Transmission
T1=sqrt((1+tandCEX^2)/((1-(F^2)*G)^2+(tandCEX^2)))

%% Force Transmission
F1= (F^2)*sqrt((1+tandCEX^2)/((1-(F^2))^2+(tandCEX^2)))

%% Work (Energy) Transmission
E1=(F^2)*(T1^2)
```

Identifying Materials with SHPB (Mousavi, Saed 2007)

SLS-Standard Linear Solid: Derived from hyper-elasticity model but includes both creep and relaxation effects



$$\frac{\Delta W}{W} = 2\pi\left(\frac{E''}{E'}\right) = 2\pi \tan(\delta_E) \,,$$

where ΔW and W are the energy dissipated and the maximum elastic energy stored per cycle of deformation, respectively, and δ_E is the phase angle by which the strain lags behind the stress. Thus, $\tan(\delta_E)$ is a measure of the relative energy dissipation in the material. From a parametrically identified complex modulus, one can obtain the energy dissipation peak and the relaxation strength, quantities which provide insight into the physical processes and structures of the materials.

-Mousavi, Saed 2007

Transfer function:

$$X(s) = H(s)\,F(s) \qquad H(s) = \frac{X(s)}{F(s)}$$

$$H(s) = \frac{1}{ms^2 + cs + k}$$

Statistical Energy Analysis and Power Transmission

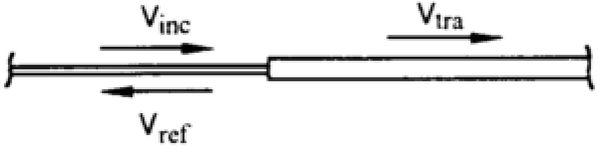
$$\Pi_{\mathrm{tra}} = \Pi_{1\,\rightarrow\,2} = 2\pi f \eta_{12} E_1$$

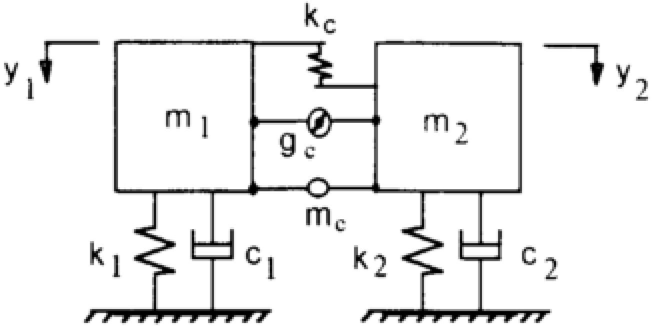
$$\eta_{12} = \frac{\overline{\delta f_1}}{\pi f}\,\frac{\tau_{12}}{2 - \tau_{12}} \qquad \eta_{12} = \frac{\eta_2 E_2}{E_1 - \overline{\delta f_2} E_2 / \overline{\delta f_1}}$$

1. Divide the system into a number of coupled subsystems.
2. Determine the mode counts and damping loss factors for the subsystems.
3. Determine the coupling factors between connected subsystems.
4. Determine the subsystem input powers from external sources.
5. Solve the energy equations to determine the subsystem response levels.

Mechanical Impedance and Transmission Coefficient:

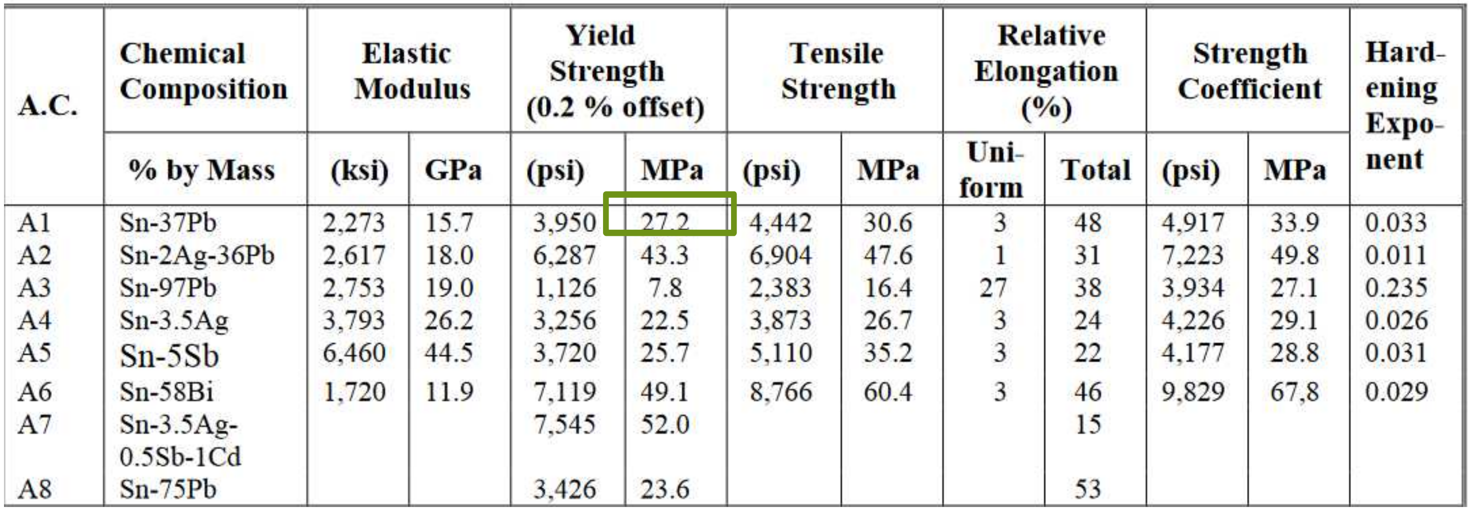
$$\tau_{12} = \frac{4R_1R_2}{|Z_1 + Z_2|^2}$$





Harris and Piersol:2002 Chapter 11

Database for Solder Properties with Emphasis on New Lead-free Solders National Institute of Standards and Technology & Colorado School of Mines



A.C.	Chemical Composition	Elastic Modulus		Yield Strength (0.2 % offset)		Tensile Strength		Relative Elongation (%)		Strength Coefficient		Hardening Exponent
	% by Mass	(ksi)	GPa	(psi)	MPa	(psi)	MPa	Uniform	Total	(psi)	MPa	
A1	Sn-37Pb	2,273	15.7	3,950	27.2	4,442	30.6	3	48	4,917	33.9	0.033
A2	Sn-2Ag-36Pb	2,617	18.0	6,287	43.3	6,904	47.6	1	31	7,223	49.8	0.011
A3	Sn-97Pb	2,753	19.0	1,126	7.8	2,383	16.4	27	38	3,934	27.1	0.235
A4	Sn-3.5Ag	3,793	26.2	3,256	22.5	3,873	26.7	3	24	4,226	29.1	0.026
A5	Sn-5Sb	6,460	44.5	3,720	25.7	5,110	35.2	3	22	4,177	28.8	0.031
A6	Sn-58Bi	1,720	11.9	7,119	49.1	8,766	60.4	3	46	9,829	67,8	0.029
A7	Sn-3.5Ag-0.5Sb-1Cd			7,545	52.0				15			
A8	Sn-75Pb			3,426	23.6				53			

Lead Free Solder and Flex Cracking Failures in Ceramic Capacitors
-N. Blattau, D. Barker, and C. Hillman CALCE Electronic Products and Systems Center