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A STUDY OF SHOCK MITIGATING MATERIALS IN A SPLIT HOPKINSON BAR CONFIGURATION PHASE II*

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A study to compare two thickness values, 0.125 and 0.250 in., of five materials, GE RTV 630, HS II Silicone, Polysulfide Rubber, Sylgard 184, and Teflon, for their shock mitigating characteristics with a split Hopkinson bar configuration has been completed. The five materials have been tested in both unconfined and confined conditions at ambient temperature and with two applied loads of 750 με peak (25 fps peak) with a 100 μs duration, measured at 10% amplitude, and 1500 με peak (50 fps peak) with a 100 μs duration, measured at 10% amplitude. The five materials have been tested at ambient, cold (-65°F), and hot (+165°F) for the unconfined condition with the 750 με peak (25 fps peak) applied load. Time domain and frequency domain analyses of the split Hopkinson bar data have been performed to compare how these materials lengthen the shock pulse, attenuate the shock pulse, reflect high frequency content in the shock pulse, and transmit energy.

INTRODUCTION

Sandia National Laboratories (SNL) designs mechanical systems with electronics that must survive high shock environments. These mechanical systems include penetrators that must survive soil and rock penetration, nuclear transportation casks that must survive transportation environments, and laydown weapons that must survive delivery impact. These mechanical systems contain electronics that may operate during and after the high shock environment and that must be protected from the high shock environments. A study has been started to improve the packaging techniques for the advanced electronics utilized in these mechanical systems because current packaging techniques are inadequate for these sensitive electronics. In many cases, it has been found that the packaging techniques currently used not only do not mitigate the shock environment but actually amplify the shock environment [1]. An ambitious goal for this packaging study is to avoid amplification and possibly attenuate the shock environment before it reaches the electronics contained in the various mechanical systems.

As part of the investigation of packaging techniques, a two-phase study of shock mitigating materials has been conducted. The purpose of the first phase is to examine the performance of a joint that consists of shock mitigating material sandwiched in between steel and to compare the performance of the shock mitigating materials. A split Hopkinson bar experimental configuration simulates this joint and has been used to study the shock mitigating characteristics of seventeen, unconfined materials [2]. The applied load for these tests was an incident compressive wave with 50 fps peak (1500 με peak) amplitude and a 100 μs duration, measured at 10% amplitude.

The second phase of the shock mitigating material study has continued with five materials from the first part of the

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study and is reported here. These materials were chosen because they demonstrated the desired characteristics of a shock mitigating material and for their ease of use in real structures. These materials are: GE RTV 630, HS II Silicone, Polysulfide Rubber, Sylgard 184, and Teflon, and have been tested in both unconfined and confined conditions at ambient temperature for two thickness values of 0.125 in. and 0.250 in. The five materials have been tested at ambient, cold (-65°F), and hot (+165°F) for the unconfined condition. The two applied loads as measured by strain gages on the incident Hopkinson bar are 750 με peak (25 fps peak) with a 100 μs duration, measured at 10% amplitude, and 1500 με peak (50 fps peak) with a 100 μs duration, measured at 10% amplitude, for these tests. The test matrix used for each material is shown in Table I and has ten different test conditions.

Time domain and frequency domain analyses of the split Hopkinson bar data have been performed to compare how these materials lengthen the shock pulse, attenuate the shock pulse, reflect high frequency content in the shock pulse, and transmit energy. No attempt has been made to compute stress-strain relationships or to develop constitutive relationships for these materials because of the variation of these materials' properties with stress. Additionally, since the impedance mismatch between the steel Hopkinson bars and the shock mitigating materials tested is so large, it is impossible to calculate the material properties from these data.

EXPERIMENTAL CONFIGURATION

This study compares five materials for their shock mitigating characteristics and has been completed with a split Hopkinson bar experimental configuration shown in Figure 1. Each sample was placed between two bars of hardened, maraging 300 steel. Samples with thickness of 0.125 in. and 0.250 in. were tested for each material

Table I: Test Matrix for Phase II Shock Mitigating Materials Study.

LOAD	THICKNESS	TEMPERATURE	CONFINEMENT	No. Samples
750 με	0.125 in.	Ambient	No	3
1500 με	0.125 in.	Ambient	No	3
750 με	0.250 in.	Ambient	No	3
1500 με	0.250 in.	Ambient	No	3
750 με	0.125 in.	Ambient	Yes	3
1500 με	0.125 in.	Ambient	Yes	3
750 με	0.250 in.	Ambient	Yes	3
1500 με	0.250 in.	Ambient	Yes	3
750 με	0.125 in.	Hot (+165°F)	No	3
750 με	0.125 in.	Cold (-65°F)	No	3

and are typical thickness values used in actual applications. The bars and material samples have a nominal 0.75 in. diameter. The incident bar is the bar impacted by the projectile. The transmission bar is the bar beyond the sample. The incident bar is 48 in. long with strain gages mounted in the middle of the bar at 24 in., and the transmission bar is 55.5 in. long with strain gages mounted 10 in. from the interface with the shock mitigating material. A kickoff bar (18 in. long) was placed at the end of the second bar to prevent the tensile pulse from entering into the transmission bar and interfering with the transmitted pulse. The kickoff bar was required for the shock mitigating materials testing because the transmitted pulses are very long in duration. The alternative to a kickoff bar is a transmission bar that is long enough to allow the measurement of the transmitted wave without interference from the tensile wave. This alternative was not practical for these materials. Strain gages were mounted on the bars with AE-10 epoxy. This epoxy was used because anomalies were observed in the data obtained with strain gages mounted with lower strength (and quicker curing) epoxies. The nominal applied load as the incident compressive wave are 750 με peak (25 fps peak) with a 100 μs duration (measured at 10% amplitude) and 1500 με peak (50 fps peak) with a 100 μs duration (measured at 10% amplitude) for these tests. Incident, reflected, and transmitted strains were measured for each material using the strain gages, and these measurements provided the basis for comparing the materials' responses.

DISCLAIMER

DISCLAIMER

Considerable effort was made during the initial portion of the experiments to align the two steel bars. The bars are positioned using two-axis alignment stages made by Newport. Each Hopkinson bar has a two-axis alignment stage on each end. The bars are aligned to minimize the reflection at the bar-to-bar interface without any shock mitigating material in between the bars. Figure 2 shows the incident and reflected wave achieved with the best alignment obtainable for this experimental configuration. Dow Corning 321 Dry Film Lubricant gave the least reflection at the interface. The reflected wave occurs at about 240 μs and has a magnitude of -0.45 fps or 0.93% of the incident stress wave. This alignment is considered acceptable for these experiments.

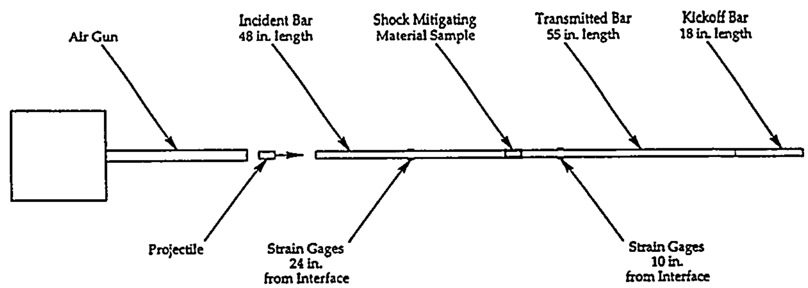


Figure 1: Split Hopkinson Bar Experimental Configuration for Shock Mitigating Materials.

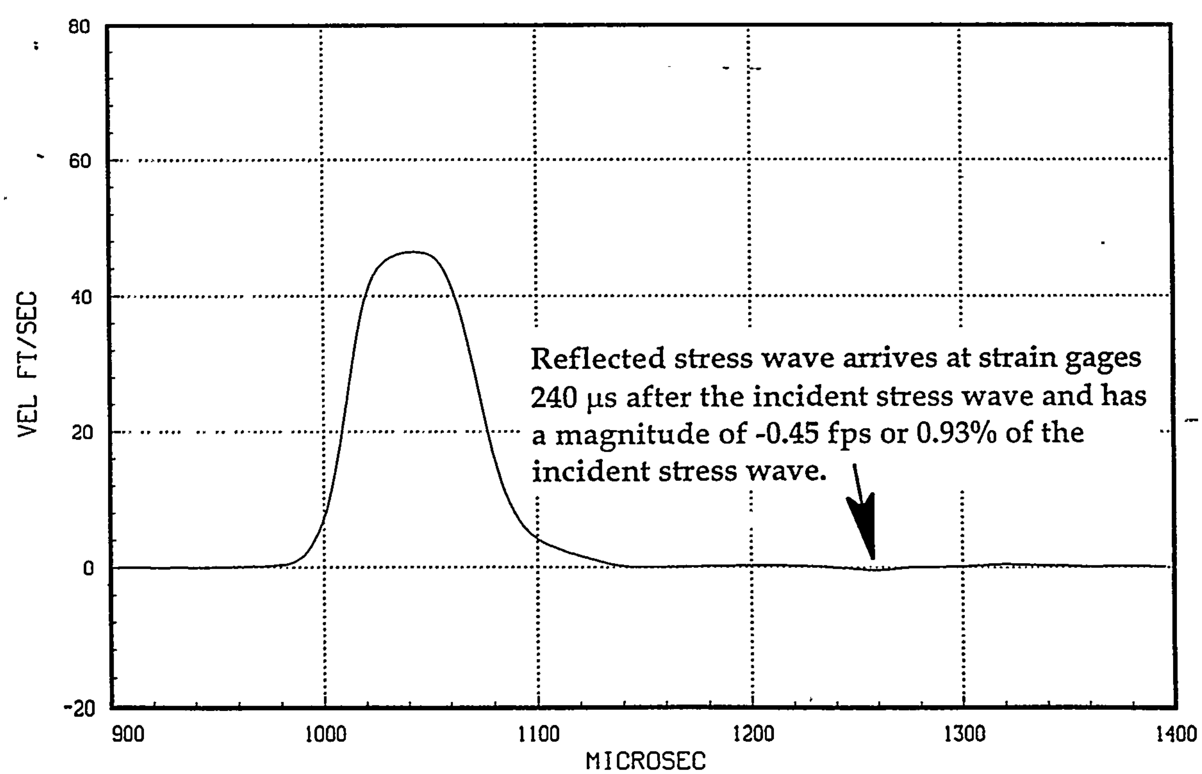


Figure 2: Incident and Reflected Stress Waves for Initial Bar to Bar Alignment.

SPLIT HOPKINSON BAR TIME DOMAIN DATA ANALYSES

The time domain, split Hopkinson bar data has been analyzed to evaluate the four different purposes of a shock mitigating material. Measured peak strain values from split Hopkinson bar testing of the shock mitigating materials have been tabulated in Tables II-VII. Any microstrain value can be converted to velocity in fps by dividing by 30. For example, the peak value on the incident compressive shock is 1500 $\mu\varepsilon$. or 50 fps.

The tabulated split Hopkinson bar data shows that for the same applied strain the amplitude of the transmitted shock pulse decreases with increasing thickness for all five materials. Shock transmission increases with confinement because these plastic materials stiffen and transmit more shock and smoother pulses. Polysulfide Rubber and Teflon transmit more shock at cold temperatures. GE RTV 630 Silicone, HSII Silicone, and Sylgard 184 show consistent characteristics for all temperatures. Figure 3 shows the incident, reflected and transmitted strain pulses for a good shock mitigator, Teflon. As shown in Figure 3, a good shock mitigator increases the time duration of the transmitted pulse and substantially attenuates the peak strain. Figure 4 compares the unconfined and confined response for HS II Silicone and illustrates that in confinement these materials stiffen and transmit shock pulses with higher peak strain values. Generally, the multiple samples were consistent with each other for the ten test conditions in the test matrix.

The equation that for the energy dissipated in the material samples is [3]:

$$E_{DISS} = E_{INC} - (E_{REF} + E_{TRANS}) \qquad (1)$$

where:

E_{DISS} = energy dissipated in the shock mitigating material,
E_{INC} = energy in the incident stress wave,
E_{REF} = energy in the reflected stress wave,
E_{TRANS} = energy transmitted to the second bar, and
$E = 0.5\ E_M\ \varepsilon^2$ with
E_M = modulus of elasticity (psi) and
ε^2 = the corresponding strain vector squared.

The units for E_{DISS} are psi because E_{DISS} represents energy per unit volume.

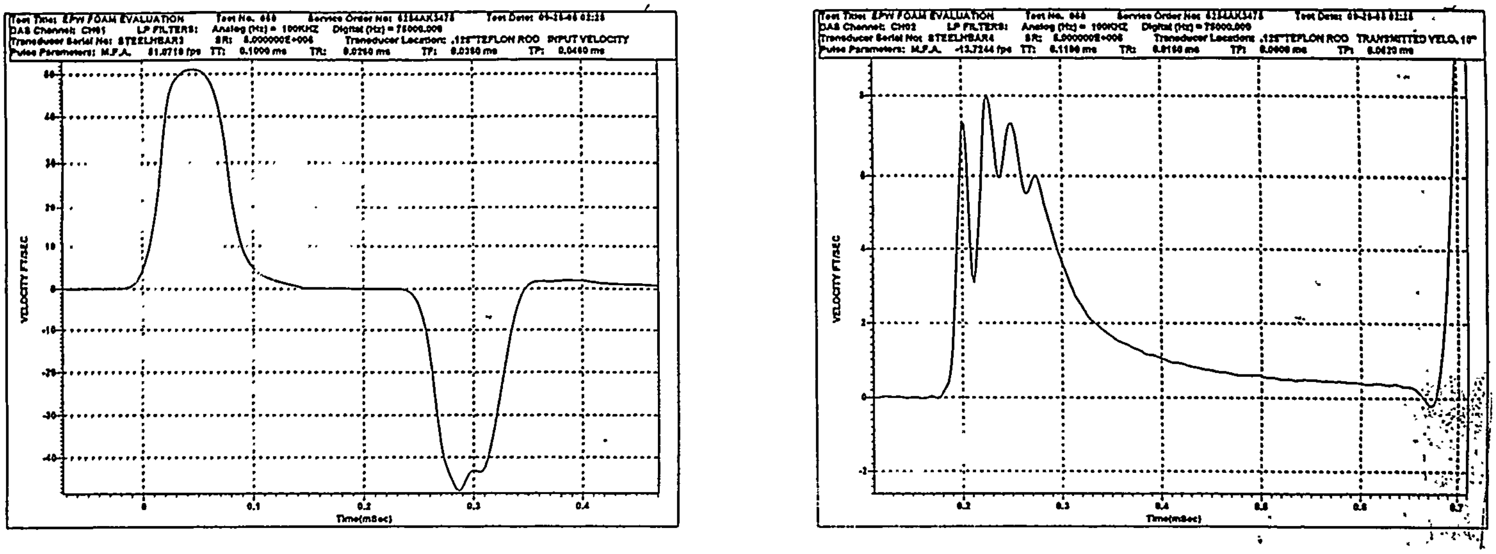
There are not significant differences in E_{DISS} for the different materials; E_{DISS} is the same low magnitude for all the materials. Ideally, E_{DISS}, as defined by the equation above, should be zero if the Hopkinson bars remain elastic [4]. In practical application, E_{DISS} will not be zero because of noise in the measurements. The low magnitude of E_{DISS} is indicative of low noise in the measurements.

In this split Hopkinson bar configuration, the strain gaged bars are transducers, and the transmitted bar measures the energy absorbed and transmitted by the material sample. The strain in the transmitted bar can be used to calculate the energy absorbed by the sample as per the equation:

$$E_{TRANS} = 0.5\ E_M\ \varepsilon^2_{TRANS} \qquad (2)$$

Since the stress wave has a velocity, then it cannot remain in the sample but must continue traveling on into the transmitted bar. As a consequence, the energy is calculated using equation (2). Table VIII summarizes the peak transmitted energies for the five materials.

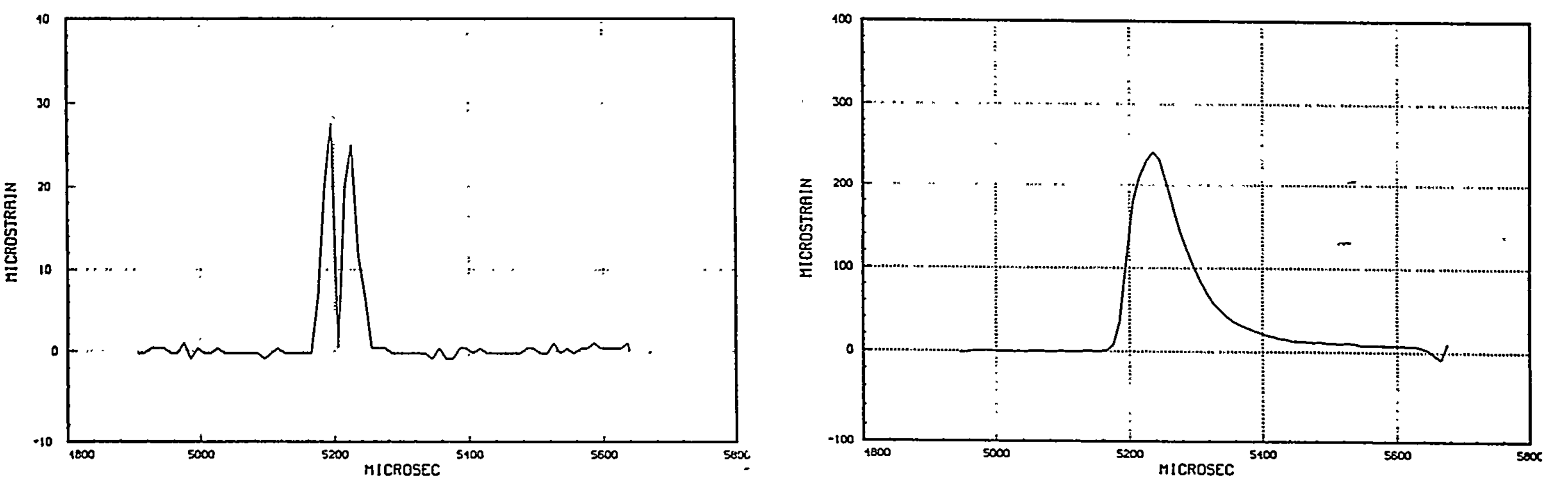
If the stress wave could be stopped in the sample, then equation (1) could be used to calculate the energy absorbed by the sample. An additional problem with the use of equation (1) is that the modulus of elasticity for these materials is not constant and is highly strain-rate dependent. This modulus variation also prevents the use of equation (1). Finally, to apply equation (1) using shock mitigating material response requires that the strain is measured on the material sample. This is a difficult, if not impossible, measurement with current techniques.



Incident and Reflected

Transmitted

Figure 3: Split Hopkinson Bar Data for A Good Shock Mitigator, Teflon Rod.



Unconfined*

Confined

Figure 4: Comparison of Transmitted Strain for HSII Silicone.
*Same Shape for Ambient, Hot (+165°F), and Cold (-65°F)

Table II: Peak Transmitted Strain for 0.125 in. Thick Samples.

Material	Load A (750 με)		Load B (1500 με)	
	Unconfined	Confined	Unconfined	Confined
GE RTV 630 Silicone	25 με	330 με	90 με	560 με
HSII Silicone	6 με	220 με	18 με	360 με
Polysulfide Rubber	39 με	330 με	64 με	600 με
Sylgard 184	55 με	350 με	220 με	700 με
Teflon	200 με	620 με	260 με	1180 με

Table III: Peak Transmitted Strain for 0.250 in. Thick Samples.

Material	Load A (750 με)		Load B (1500 με)	
	Unconfined	Confined	Unconfined	Confined
GE RTV 630 Silicone	7 με	250 με	22 με	420 με
HSII Silicone	4 με	110 με	14 με	200 με
Polysulfide Rubber	12 με	280 με	28 με	560 με
Sylgard 184	15 με	230 με	22 με	420 με
Teflon	135 με	500 με	170 με	1000 με

Table IV: Peak Transmitted Strain for Unconfined Samples.

Material	Load A (750 με)		Load B (1500 με)	
	0.125 in.	0.250 In.	0.125 in.	0.250 in.
GE RTV 630 Silicone	25 με	7 με	90 με	22 με
HSII Silicone	6 με	4 με	18 με	14 με
Polysulfide Rubber	39 με	12 με	64 με	28 με
Sylgard 184	55 με	15 με	220 με	22 με
Teflon	200 με	135 με	260 με	170 με

Table V: Peak Transmitted Strain for Confined Samples.

Material	Load A (750 με)		Load B (1500 με)	
	0.125 in.	0.250 in.	0.125 in.	0.250 in
GE RTV 630 Silicone	330 με	250 με	560 με	420 με
HSII Silicone	220 με	110 με	360 με	200 με
Polysulfide Rubber	330 με	280 με	600 με	560 με
Sylgard 184	350 με	230 με	700 με	420 με
Teflon	620 με	500 με	1180 με	1000 με

Table VI: Peak Transmitted Strain for Ambient and Hot (+165°F) Temperatures (0.125 in. Thick, Unconfined Samples at Load A of 750 με).

Material	Ambient	Hot (+165°F)
GE RTV 630 Silicone	25 με	28 με
HSII Silicone	6 με	10 με
Polysulfide Rubber	39 με	22 με
Sylgard 184	55 με	14 με
Teflon	200 με	135 με

Table VII: Peak Transmitted Strain for Ambient and Cold (-65°F) Temperatures (0.125 in. Thick, Unconfined Samples at Load A of 750 με).

Material	Ambient	Cold (-65°F)
GE RTV 630 Silicone	25 με	27 με
HSII Silicone	6 με	14 με
Polysulfide Rubber	39 με	565 με
Sylgard 184	55 με	25 με
Teflon	200 με	340 με

Table VIII: Comparison of Peak Transmitted Energy for a Nominal 0.125 in. Material Thickness and Incident Energy of 8.4375 psi (750 με Peak).

Material	Confinement	Temperature	Peak Transmitted Energy (psi)
GE RTV 630	No	Ambient	0.0094 (0.1%)
	No	+165°F	0.0118 (0.1%)
	No	- 65°F	0.0109 (0.1%)
	Yes	Ambient	1.6335 (19 %)
HSII Silicone Rubber	No	Ambient	0.0005 (0 %)
	No	+165°F	0.0015 (0 %)
	No	- 65°F	0.0029 (0 %)
	Yes	Ambient	0.7260 (8.6%)
Polysulfide Rubber PRC1422	No	Ambient	0.0228 (0.3%)
	No	+165°F	0.0073 (0.1%)
	No	- 65°F	4.7884 (57 %)
	Yes	Ambient	1.6335 (19 %)
Sylgard 184	No	Ambient	0.0454 (0.5%)
	No	+165°F	0.0029 (0 %)
	No	- 65°F	0.0094 (0.1%)
	Yes	Ambient	1.8375 (22 %)
Teflon Rod	No	Ambient	0.6000 (7 %)
	No	+165°F	0.2734 (3 %)
	No	- 65°F	1.7340 (21 %)
	Yes	Ambient	5.7660 (68 %)

SPLIT HOPKINSON BAR FREQUENCY DOMAIN DATA ANALYSES

Frequency response function (frf) magnitudes for a reflected frf, $H_{ref}(jw)$, and a transmitted frf, $H_{trans}(jw)$, were calculated for the five materials with equation (3) below.

$$H(j\omega) = \frac{H_1 + H_2}{2} \tag{3}$$

where,

$$H_1(j\omega) = \frac{\sum_{n=1}^{3} G_{xy}}{\sum_{n=1}^{3} G_{xx}} \tag{4}$$

and

$$H_2(j\omega) = \frac{\sum_{n=1}^{3} G_{yy}}{\sum_{n=1}^{3} G_{yx}} \tag{5}$$

where:

$H_1(j\omega) =$ frequency response function to minimize noise on the input, x,

$H_2(j\omega) =$ frequency response function to minimize noise on the output, y,

$G_{xx} =$ auto-spectrum for the input, x,

$G_{yy} =$ auto-spectrum for the output, y,

$G_{xy} =$ cross-spectrum between the input, x, and the output, y, and

$G_{yx} =$ cross-spectrum between the output, y, and the input, x.

For the reflected frf, $H_{ref}(jw)$, the input, x, is the incident wave, and the output, y, is the reflected wave. For the transmitted frf, $H_{trans}(jw)$, the input, x, is the incident wave, and the output, y, is the transmitted wave. These frf's are not normalized so that relative magnitudes may be compared. The frf magnitudes are plotted up to a maximum frequency of 10,000 Hz because the 100 μs pulse does not have adequate coherence beyond 10,000 Hz. The frequency resolution for HSII Silicone and Sylgard 184 is 24 Hz. The frequency resolution for the other three materials is 122 Hz.

The three samples tested for each thickness were averaged for the frf calculation. Further details of calculating the frf's have been reported previously and are not repeated here [5]. Materials such as HSII Silicone transmit a relatively short duration, low magnitude pulse, so their transmission frf magnitudes are essentially noise. Examples of frf magnitudes for unconfined and confined polysulfide rubber are shown in Figures 5 and 6, respectively. The frf magnitudes show that an unconfined material reflects more of the high frequency data than a confined material that tends to transmit flatter frequency content into the structure beyond the material. The shock mitigator reflects the high frequency back into the incident bar (or the penetrator case, for example) instead of absorbing the high frequency portion of the strain wave. This may not be an attractive feature since it may be damaging to other components in some cases. It would be best if the shock mitigating material actually absorbed the high frequency shock. A comparison of the shock mitigating materials frequency response function magnitudes at low frequency is given in Table IX. In general, the reflected frf magnitude increases with frequency, and the transmitted frf magnitude decreases with frequency.

Table IX: Comparison of Shock Mitigating Material Frequency Response Function Magnitudes for Incident Compressive Shock with 750 $\mu\varepsilon$ Peak.

Material (0.125 in. Thick)	Confined	Temperature	Low Frequency RFRF* Magnitude	Low Frequency TFRF** Magnitude
GE RTV 630	No	Ambient	0.96	0.11
	No	+165°F	0.99	0.06
	No	- 65°F	0.96	0.12
	Yes	Ambient	0.63	0.66
HSII Silicone	No	Ambient	1.00	0.04
Rubber	No	+165°F	0.99	0.02
	No	- 65°F	0.94	0.03
	Yes	Ambient	0.54	0.47
Polysulfide	No	Ambient	0.94	0.20
Rubber PRC1422	No	+165°F	0.95	0.12
	No	- 65°F	0.28	0.85
	Yes	Ambient	0.62	0.63
Sylgard 184	No	Ambient	0.92	0.35
	No	+165°F	0.89	0.08
	No	- 65°F	0.91	0.09
	Yes	Ambient	0.56	0.70
Teflon Rod	No	Ambient	0.70	0.45
	No	+165°F	0.80	0.35
	No	- 65°F	0.65	0.54
	Yes	Ambient	0.33	0.82

* RFRF is the reflected frequency response function and increases in magnitude with frequency.
** TFRF is the transmitted frequency response function and decreases in magnitude with frequency.

CONCLUSIONS

A study to compare two thickness values, 0.125 and 0.250 in., of five materials, GE RTV 630, HS II Silicone, Polysulfide Rubber, Sylgard 184, and Teflon, for their shock mitigating characteristics with a split Hopkinson bar configuration has been completed. These materials were chosen because they demonstrate the desired characteristics of a shock mitigating material as shown in Phase I of this study and for their ease of use in real structures. The analysis of the time domain, split Hopkinson bar data shows that the amplitude of the transmitted shock pulse decreases with increasing thickness for all five materials for the same applied strain. Shock transmission increases with confinement because these plastic materials stiffen and transmit more shock and smoother pulses when confined. PSR and Teflon transmit more shock at cold temperatures. GE RTV 630 Silicone, HSII Silicone, and Sylgard 184 show consistent characteristics for all temperatures. The peak incident energy and peak transmitted energy has been calculated and tabulated for each material. Frequency response function magnitudes have been calculated for these materials. The high frequency content is reflected at the interface between the Hopkinson bars and the shock mitigating material because of the large impedance mismatch. However, the reflection of high frequency portion of the shock at the interface with the shock mitigating material may not be desirable in some applications because the reflected shock may damage some other components or portions of a structure.

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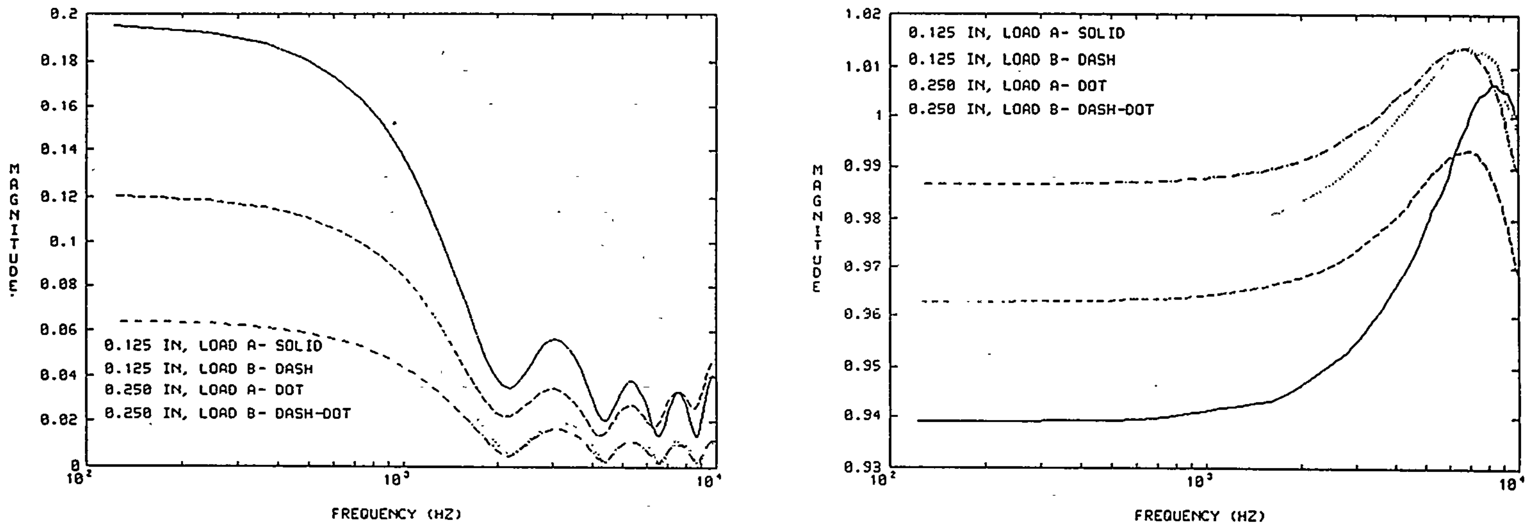
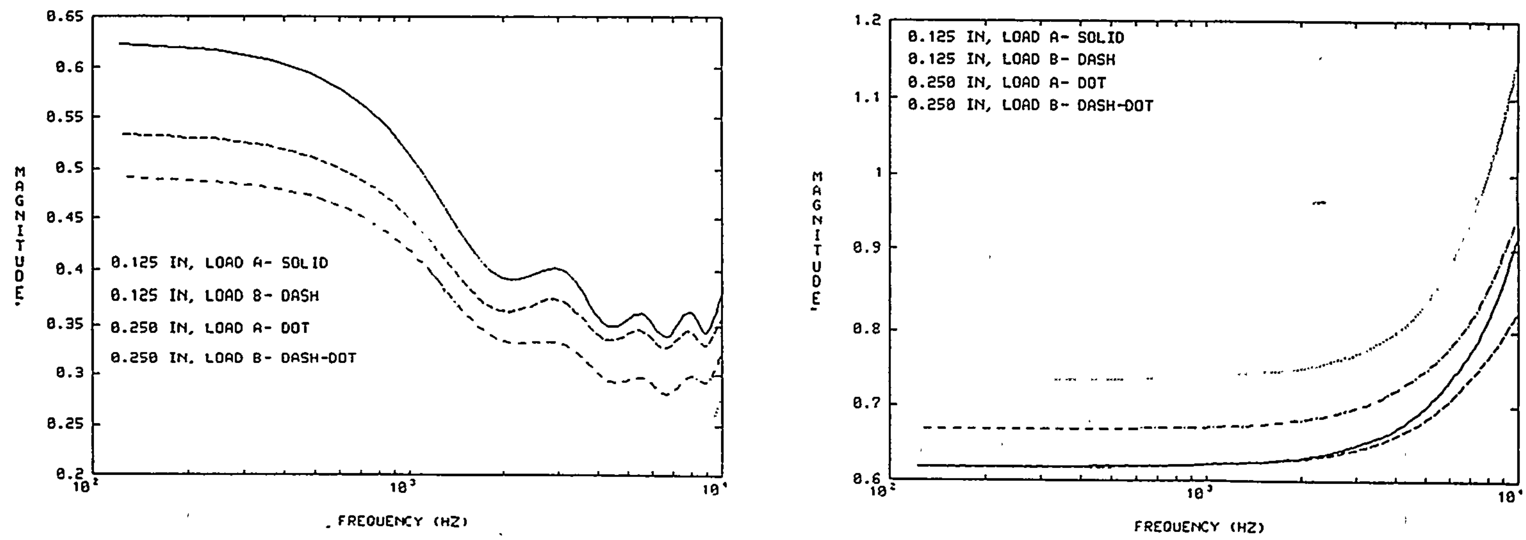


Reflected FRF

Transmitted FRF

Figure 5: Comparison of Frequency Response Functions for *Unconfined Polysulfide Rubber.*



Reflected FRF

Transmitted FRF

Figure 6: Comparison of Frequency Response Functions for *Confined Polysulfide Rubber.*