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

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A study to compare three thicknesses (0.125, 0.250, and 0.500 in.) of seventeen, unconfined materials for their shock mitigating characteristics has been completed with a split Hopkinson bar configuration. The nominal input as measured by strain gages on the incident Hopkinson bar is 50 fps @ 100 μs for these tests. It is hypothesized that a shock mitigating material has four purposes: to lengthen the shock pulse, to attenuate the shock pulse, to mitigate high frequency content in the shock pulse, and to absorb energy. Both time domain and frequency domain analyses of the split Hopkinson bar data have been performed to compare the materials' achievement of these purposes.

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, rock, and ice penetration, nuclear transportation casks that must survive transportation environments, and laydown weapons that must survive delivery impact of 125 fps. 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 more 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.

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As part of the investigation of packaging techniques, a two part study of shock mitigating materials is being conducted. This paper reports the first part of the shock mitigating materials study. In this part of the study, seventeen, unconfined materials have been compared for their shock mitigating characteristics with a split Hopkinson bar configuration. It is hypothesized that a shock mitigating material has four purposes: to lengthen the shock pulse, to attenuate the shock pulse, to mitigate high frequency content in the shock pulse, and to absorb energy. Both time domain and frequency domain analyses of the split Hopkinson bar data have been performed to evaluate the materials' achievement of these purposes. No attempt has been made to compute stress-strain or to develop constitutive relationships for these materials because of the variation of these materials' properties with stress.

EXPERIMENTAL TEST CONFIGURATION

This study to compare seventeen, unconfined materials for their shock mitigating characteristics has been completed with a split Hopkinson bar configuration shown in Figure 1. Each sample was placed between two bars of hardened, 4340 steel. The thicknesses of 0.125 in., 0.250 in., and 0.500 in. were tested for each material. The thickness values were chosen because they are typical thickness used in actual applications. The bars and material samples have a 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, and the transmission bar is 55.5 in. long. 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 critical for the shock mitigating materials testing because the transmitted pulses are very long in duration. 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 input as the incident wave was 50 fps @ 100 μs for these tests. Incident, reflected, and transmitted velocity were measured for each material using the strain gages, and these measurements provided the basis for comparing the materials' responses.

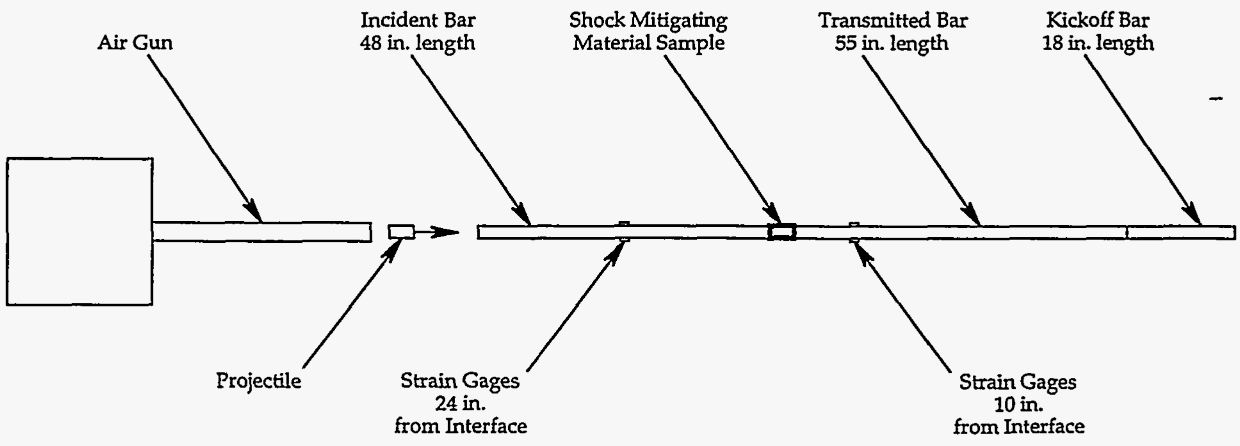


Figure 1: Split Hopkinson Bar Configuration for Shock Mitigating Materials.

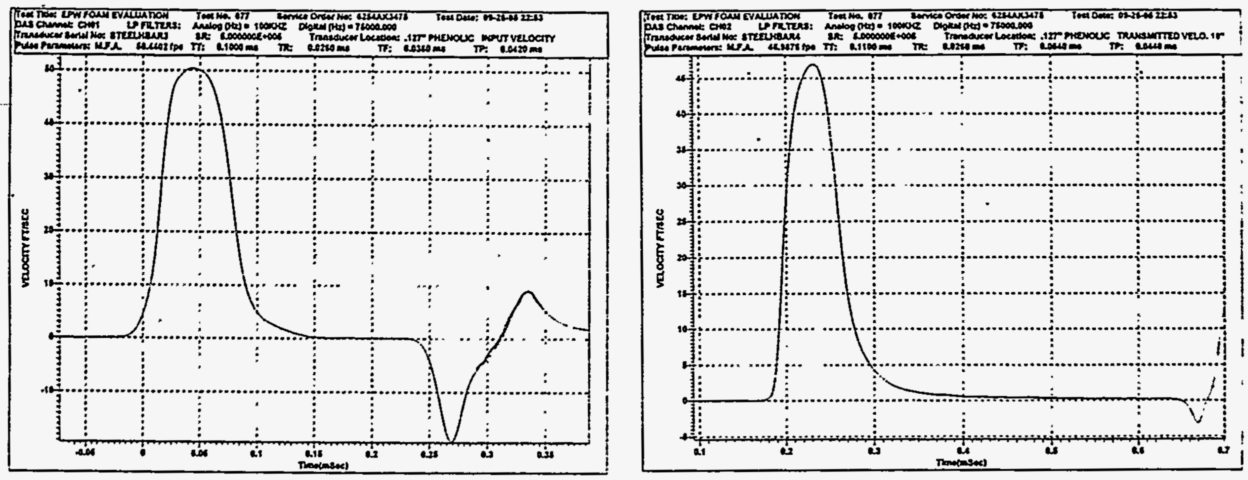
SPLIT HOPKINSON BAR DATA ANALYSES

The split Hopkinson bar data has been analyzed to evaluate the four different purposes of this shock mitigating materials. Measured velocity values from split Hopkinson bar testing of the shock mitigating materials have been tabulated. Table 1 provides a comparison of the peak velocity magnitudes for seventeen shock mitigating materials with one thickness of approximately 0.125 in. Exact thickness values are shown. As can be seen in Table 1, materials, such as Lexan, G-10 Epoxy, Phenolic, 828 DEA GMB, and 828 CTBN DEA GMB, transmitted a large

Table 1: Comparison of Material Responses for a Nominal 0.125 in. Thickness.

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

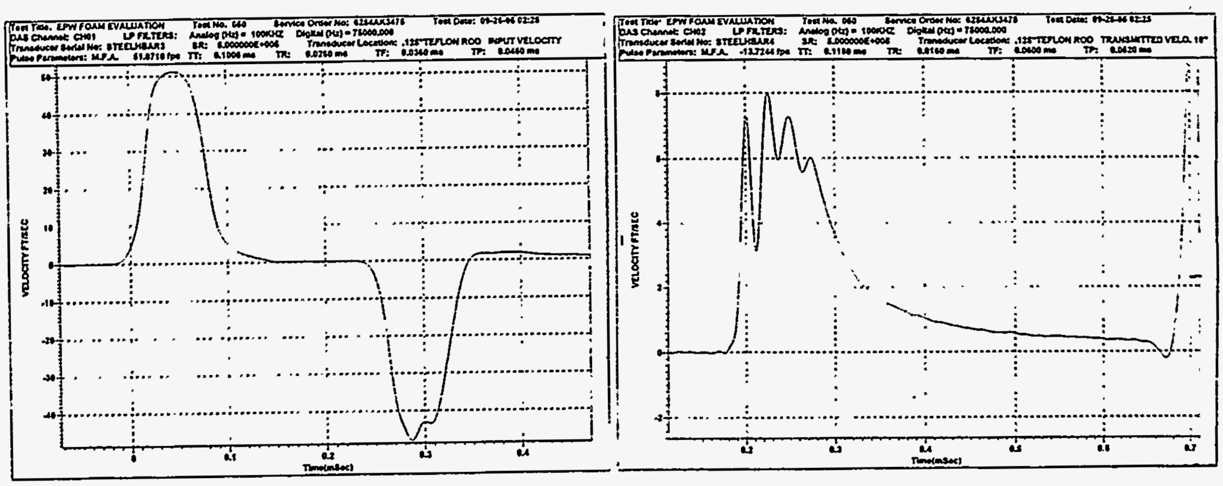
percentage of the shock pulse. Other materials, such as Teflon rod, drastically attenuated the shock pulse. Figures 2 and 3 show the incident, reflected and transmitted velocity pulses for a good shock transmitter, phenolic and cotton cloth, and for a good shock mitigator, Teflon rod, respectively. The time duration of the transmitted pulse is increased several times by a good shock mitigator as shown in Figure 3.



Incident and Reflected

Transmitted

Figure 2: Split Hopkinson Bar Data for A Good Shock Transmitter, Phenolic and Cotton Cloth.



Incident and Reflected

Transmitted

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

The shock mitigating materials did not perform the same for the nominal thicknesses tested of 0.125 in., 0.250 in. and 0.500 in. Tables 2-18 show the variation of the peak velocities as a function of thickness for each material shown in Table 1. These results are not surprising because the materials are not expected to have linear characteristics. The results for one sample at each thickness value are shown, but two or three samples were tested for each material and each thickness. Generally, the multiple samples were consistent with each other.

Table 2: Peak Responses for Hi Density Polyethylene Rod.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.127 in.	54	46	9
0.252 in.	54	46	8
0.501 in.	54	47	6.4

Table 3: Peak Responses for Teflon Rod.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.128 in.	51	45	7
0.252 in.	51	46	4.5
0.502 in.	53	49	4.1

Table 4: Peak Responses for Lexan Rod.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.126 in.	52	32	25
0.252 in.	52	40	22
0.501 in.	54	45	18

Table 5: Peak Responses for G-10 Epoxy & Fiberglass Cloth.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.129 in.	54	31	53
0.251 in.	51	20	48
0.501 in.	52	32	43

Table 6: Peak Responses for Phenolic & Cotton Cloth.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.127 in.	50	20	47
0.250 in.	51	29	42
0.502 in.	53	36	34

Table 7: Peak Responses for Adiprene L-100

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	51	47	4
0.248 in.	50	48	2
0.497 in.	52	51	1.3

Table 8: Peak Responses for 828/DEA/GMB.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.125 in.	52	31	27
0.251 in.	52	39	23
0.502 in.	54	46	22

Table 9: Peak Responses for 828/CTBN/DEA/GMB.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	55	36	22
0.251 in.	53	41	21
0.500 in.	54	47	20

Table 10: Peak Responses for PET 90A Polyurethane Rubber.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	52	49	3
0.250 in.	54	52	1.2
0.499 in.	54	53	0.7

Table 11: Peak Responses for Sylgard 184.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.122 in.	54	53	2
0.249 in.	50	50	0.2
0.501 in.	52	52	0.1

Table 12: Peak Responses for HSII Silicone Rubber (Pink).

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	54	54	0.5
0.250 in.	52	52	0.2
0.501 in.	50	50	0.05

Table 13: Peak Responses for Sylgard 184 with GMB.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	52	51	2.5
0.249 in.	54	54	0.5
0.497 in.	54	54	0.2

Table 14: Peak Responses for GE RTV 630.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	52	51	3
0.250 in.	50	50	0.2
0.497 in.	52	52	0.2

Table 15: Peak Responses for Polyurethane Foam (20 lb).

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.121 in.	51	49	2.8
0.250 in.	52	50	2.3
0.500 in.	50	49	1.6

Table 16: Peak Responses for Polyurethane Foam (10 lb).

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.126 in.	50	50	0.50
0.251 in.	54	54	0.45
0.500 in.	54	53	0.40

Table 17: Peak Responses for Polyurethane Foam (6 lb).

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.127 in.	54	54	0.30
0.253 in.	54	54	0.30
0.503 in.	54	54	0.25

Table 18: Peak Responses for Polysulfide Rubber PRC1422.

Thickness	Incident (fps)	Reflected (fps)	Transmitted (fps)
0.127 in.	51	49	2.5
0.253 in.	51	50	0.8
0.503 in.	52	51	0.4

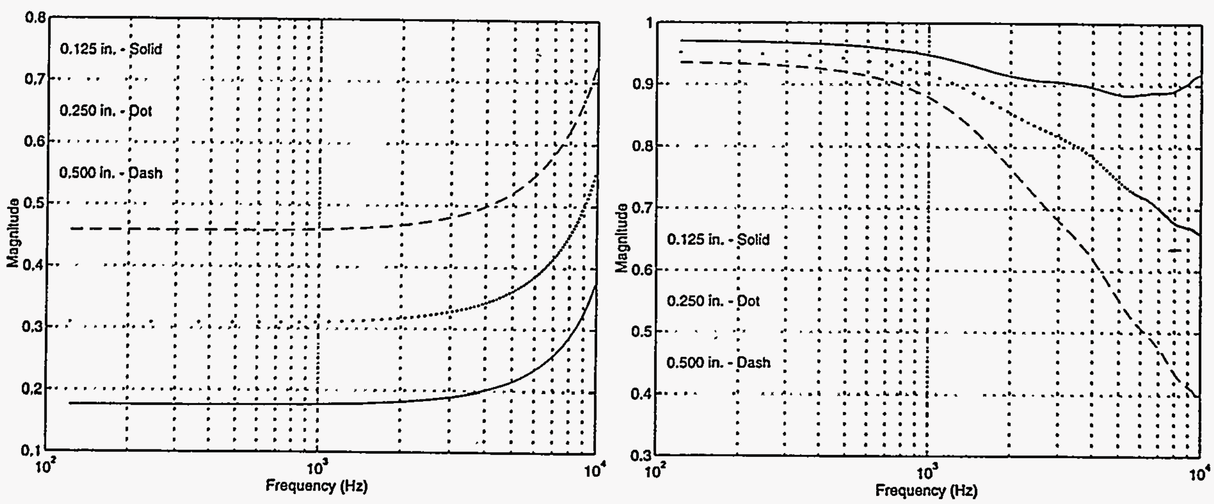
Frequency response function (frf) magnitudes, a reflected frf and a transmitted frf, were calculated for the seventeen materials listed in Table 1. Both functions use the incident velocity pulse as the input. For the reflected frf, the velocity pulse reflected at the interface between the incident Hopkinson bar and the material being tested is the output. For the transmission frf, the velocity pulse transmitted through the material to the second Hopkinson bar is the output. Three samples were tested for each thickness and averaged for the frf calculation except for the Sylgard 184 and GMB material that only had two samples at each thickness. The details of calculating the frf's have been reported previously and are not repeated here [2]. Materials such as Sylgard and HSII Silicone transmit a relatively short duration, low magnitude pulse, so their transmission frf's are essentially noise. Examples of frf's for a good shock transmitter, phenolic and cotton cloth, and for a good shock mitigator, teflon rod, are shown in Figures 4 and 5, respectively. The frf's show that a good shock mitigator reflects more lower frequency data than a good shock transmitter that tends to transmit flatter frequency content into the structure beyond the material.

The shock mitigator appears to reflect the high frequency back into the incident bar (or the penetrator case, for example) instead of absorbing the high frequency portion of the velocity wave. This may not be an attractive feature since it may be damaging in some cases. It would be best if the shock mitigating material actually absorbed the high frequency shock.

An energy analysis is being performed with the data presented in this paper but is not complete at this time. For this analysis, energy, U, is defined as

$$U = AEc_o\int_0^T \varepsilon^2 dt \qquad (1)$$

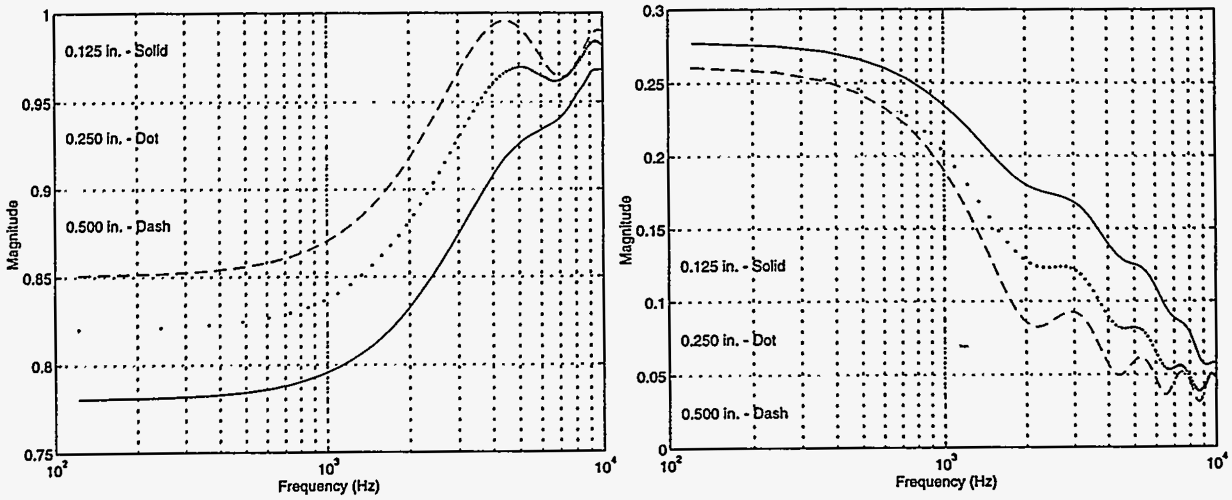
where A, E, and c_o, are the bar area, modulus, and wave speed and ε is the instantaneous strain



Reflected FRF

Transmitted FRF

Figure 4: Frequency Response Functions for a Good Shock Transmitter, Phenolic and Cotton Cloth.



Reflected FRF Transmitted FRF

Figure 5: Frequency Response Functions for a Good Shock Mitigator, Teflon Rod.

amplitude [3]. The energy loss in the material being tested must be equal to the plastic work done on the specimen and is given by:

$$\text{Energy Loss} = U(\varepsilon_I) - [U(\varepsilon_R) + U(\varepsilon_T)] \tag{2}$$

where ε_I, ε_R, and ε_T are the incident strain, reflected strain and the transmitted strain, respectively [3]. The results of this energy analysis will be reported with the second phase of this shock mitigating material study.

CONCLUSIONS

The first part of a study to evaluate seventeen, unconfined materials for four shock mitigating characteristics has been completed. The analysis of the split Hopkinson bar data shows that the amplitude of the transmitted shock pulse decreases with increasing thickness for all seventeen materials. A good shock mitigating material is one that transmits a substantially lower amplitude shock than the incident shock. Additionally, the pulse duration is lengthened by a good shock mitigating material so that the shock pulse becomes a low frequency pulse. Frequency response function magnitudes have been calculated for these materials. At this point in the data analyses, it appears that the high frequency content is reflected at the interface between the Hopkinson bars and the shock mitigating material. An energy analysis may show if any high frequency content is absorbed by the material. 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.

FUTURE WORK

The second portion of the shock mitigating material study will continue with five materials from the first part of the study. 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: Teflon, Sylgard 184, GE RTV 630, HS II Silicone, and Polysulfide Rubber. These materials will be evaluated at ambient, -65°F, and +165°F. Two thickness of 0.125 and 0.250 in. will be used. Both confined and unconfined samples will be evaluated at the two load conditions of 25 fps and 50 fps with a 100 µs pulse duration for both amplitudes. The energy analysis of the split Hopkinson bar data will be completed for both parts of the study.

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