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SHOCK TRANSMISSIBILITY OF THREADED JOINTS

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This paper summarizes an analytical study and an experimental evaluation of compressive, one-dimensional, shock transmission through a threaded joint in a split Hopkinson bar configuration. Thread geometries were scaled to simulate large diameter threaded joints with loadings parallel to the axis of the threads. Both strain and acceleration were evaluated with experimental measurements and analysis. Analytical results confirm the experimental conclusions that in this split Hopkinson bar configuration, the change in the one-dimensional shock wave by the threaded joint is localized to a length equal to a few diameters' length beyond the threaded joint.

INTRODUCTION

Sandia National Laboratories (SNL) designs mechanical systems with threaded joints that must survive high shock environments. These mechanical systems include penetrators that must survive soil and rock penetration; drilling pipe strings that must survive rock-cutting, shock environments; and laydown weapons that must survive delivery impact shock. 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.

As part of the investigation of packaging techniques, a shock transmissibility study of thread joints has been conducted. In general, threaded rings segregate the masses internal to mechanical structures. Consequently, the threaded rings are a load path between the internal masses and the external structure. A split Hopkinson bar experimental configuration provides a method to apply a one-dimensional, compressive shock wave to a threaded joint in an orientation parallel to the axis of the threads. In this configuration the distortion of the one-dimensional shock wave may be examined. Additionally, any high frequency response created by threads rattling may be measured. joints conducteded at the Sandia National Laboratories Mechanical Shock Laboratory. Both strain and acceleration were evaluated in a four part experimental evaluation measurements and with analysis.

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SPLIT HOPKINSON BAR EXPERIMENTAL CONFIGURATION

This evaluation has been completed with a split Hopkinson bar experimental configuration shown in Figure 1 [2]. Each joint insert was placed between two bars of 7075-T6 aluminum. A threaded joint insert and a solid joint insert are shown in Figure 2 and 3, respectively. Figure 2 has two specifications for the threads. One is 2.3-10ACME-4C for tight threads; the other specification is 2.3-10ACME-2G for loose threads. The threaded joint is designed so that the only way the applied shock can pass through the insert is through the threads. The two solid joints in Figure 3 were made to imitate the gaps and cavities in the threaded joint but without the threads. Both the incident bar and the response bar are 96 in. long, and the strain gages are mounted in the middle of each bar, or 48 in. from either end. Projectiles with lengths of 12 in. and 24 in. were used during this evaluation. All Hopkinson bars, inserts, and projectiles have a nominal 3 in. diameter.

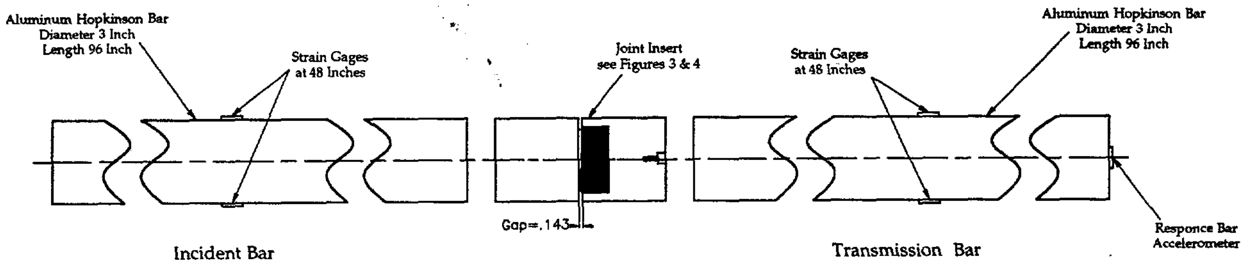


Figure 1: Split Hopkinson Bar Experimental Configuration.

Considerable effort was made during the initial portion of the experiments to align the two aluminum bars so that the reflection is minimized at the bar-to-bar interface without a joint insert. Figure 4 shows the incident and reflected wave achieved with the best alignment obtainable for this experimental configuration. The reflected wave returns to the strain gages at 480 μs after the beginning of the incident wave and has a 3000 lb. magnitude or about 3.5% of the incident wave. Dow Corning 4, a Silicone-based electrical insulating compound, was used in between the Hopkinson bars and the joint inserts for some of the experiments.

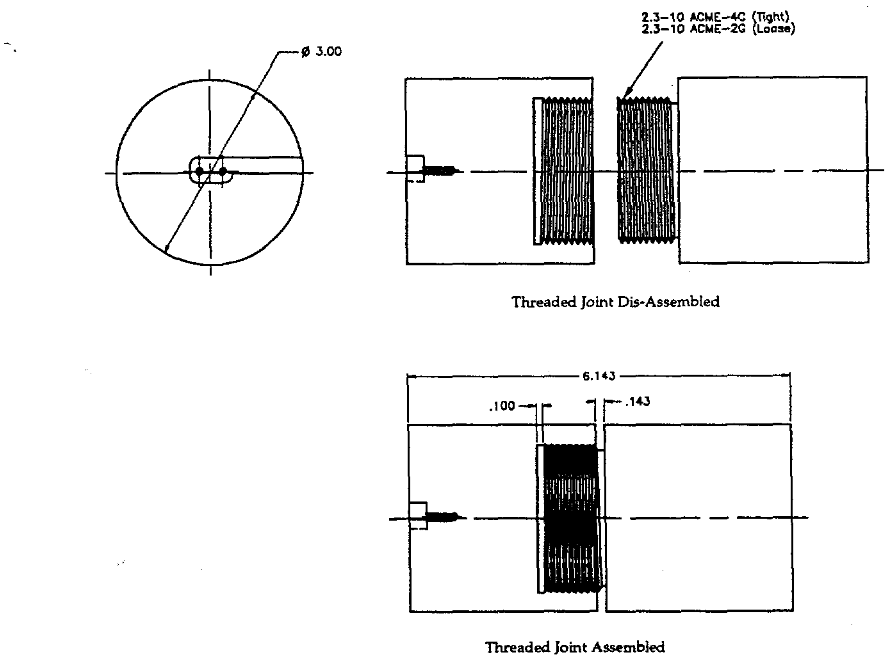
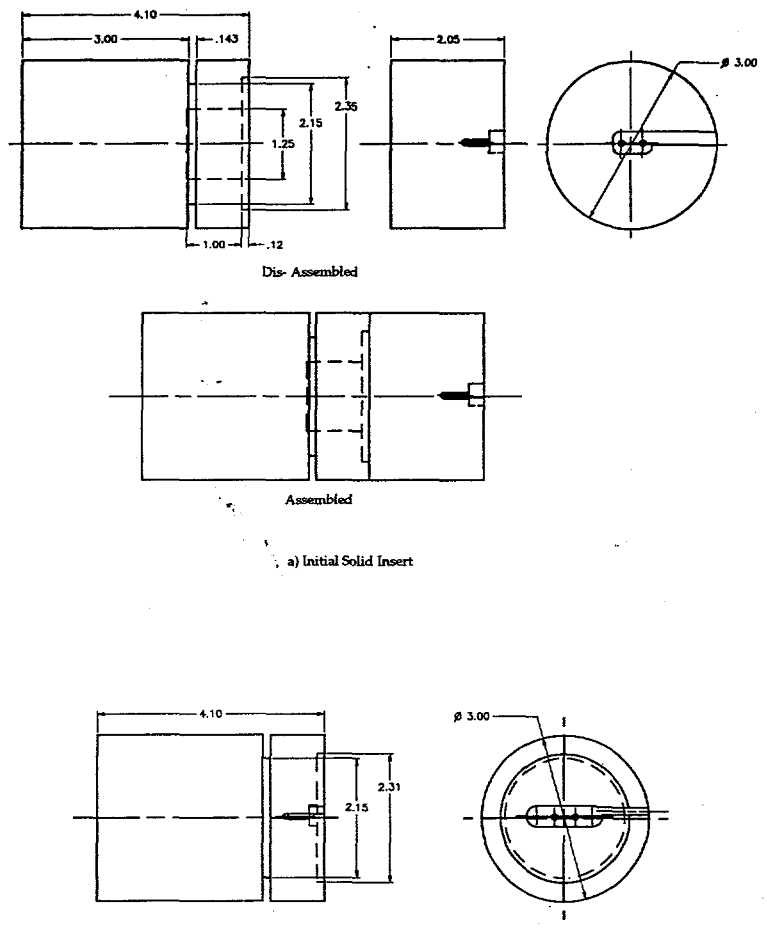


Figure 2: Threaded Joint Insert for Split Hopkinson Bar Configuration.



a) Initial Solid Insert

b) Modified Solid Insert

Figure 3: Solid Joint Insert for Split Hopkinson Bar Configuration.

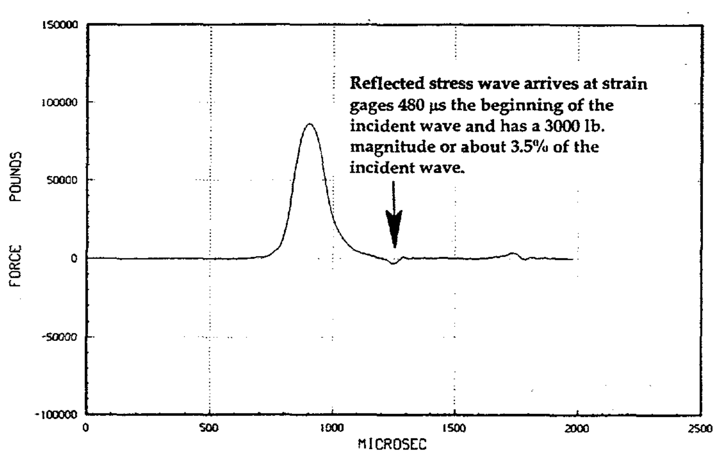


Figure 4: Incident and Reflected Stress Waves for Initial Bar to Bar Alignment.

MECHANICAL SHOCK LAB EXPERIMENT SERIES

The evaluation of the shock transmissibility of threaded joints consisted of four parts. In the first part, the strain gage responses from the Hopkinson bars with threaded joint inserts with loose threads and with tight threads as specified in Figure 2 were evaluated. In the second part, the strain gage responses from the Hopkinson bars with threaded joint inserts with loose threads and with solid joint inserts were evaluated. In the third part of the study, acceleration responses measured on the joint inserts are compared for the solid insert, the threaded insert with loose threads, and the threaded insert with tight threads. In the fourth and final part of the study, the strain gage responses from the Hopkinson bars created with two different projectile lengths, 12 in. and 24 in., are compared. Before the evaluations began, nominal incident force magnitudes were chosen after the yield force magnitude for the ACME threads was established. An incident force magnitude of 123,000 lbs. caused significant rubbing between the ACME threads; 139,000 lbs. caused the ACME threads to totally lockup. The duration (measured at 10%) for these tests was 250 μs, and is the longest duration possible with the Hopkinson bar lengths and the location of the strain gages as shown in Figure 1. This duration is non-dispersive according to the criterion below [3].

$$\lambda \geq 10D \tag{1}$$

or

$$T \geq 150\,\mu\text{s} \tag{2}$$

where:

λ = Wavelength in the Hopkinson bar or (wave speed, c)(pulse duration, T), and
D= Diameter of the Hopkinson bar.

The force magnitude values that caused thread yielding in this dynamic shock experiment were surprisingly close to the static shear strength value of 135,000 lbs. for ACME threads. Nominal force magnitudes were chosen as 40,000 lbs., 70,000 lbs., and 120,000 lbs. for the four parts of the evaluation that followed.

The first part of the evaluation used a force pulse shape and a nominal duration of 250 μs, as shown in Figure 4, with the three magnitudes of 40,000 lbs., 70,000 lbs., and 120,000 lbs. A projectile with a length of 12 in. and a 0.25 in. thick, felt pad were used to create this non-dispersive pulse shape. DC-4 grease was used between the insert and the Hopkinson bars. The experiment methodology was to test one threaded joint insert at all three force magnitudes in order of increasing magnitude. The sample was then discarded and not used for any subsequent testing because localized yielding could have occurred at the 120,000 lbs. magnitude. Five threaded inserts with loose threads and five threaded inserts with tight threads were tested with this methodology. The strain response data measured on the incident bar and the transmission bar were used to calculate a shock reflection efficiency and a shock transmission efficiency as defined below [4,5].

$$\rho = \frac{\sum_{n=1}^{5} psd(reflectedwave)}{\sum_{n=1}^{5} psd(incidentwave)} = \text{reflection efficiency} \tag{3}$$

and

$$\tau = \frac{\sum_{n=1}^{5} psd(transmittedwave)}{\sum_{n=1}^{5} psd(incidentwave)} = \text{transmission efficiency} \tag{4}$$

The results of the calculation of the reflection efficiency and the transmission efficiency are shown in Figures 5 and 6 for 40,000 lbs. and compare these quantities for the tight threads and the loose threads and the three force magnitude values. The results for the other force magnitudes, 70,000 lbs and 100,000 lbs, are essentially the same. Figures 6-11 show very little difference in the reflection efficiency and the transmission efficiency for the two thread types, loose and tight. This result was not expected. It was hypothesized that the non-dispersive incident force wave did not have a rise-time short enough to rattle the threads sufficiently. Consequently, a projectile with a 24 in. length was used to impact the incident bar metal-to-metal (i.e., no pulse shaping material such as felt) and create a dispersive, square pulse shape. In this case, the dispersion is not caused by the pulse length but the pulse rise-time.

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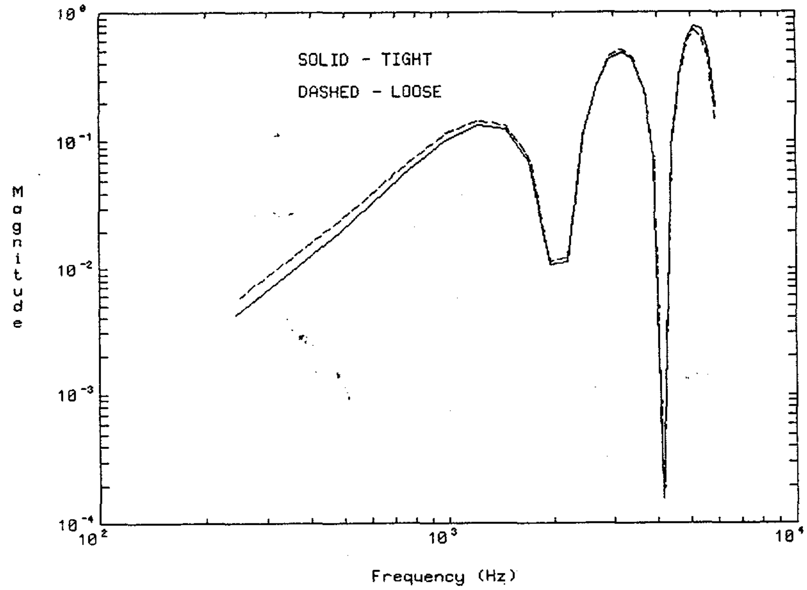

Figure 5: Shock Reflection Efficiency at 40,000 lbs.

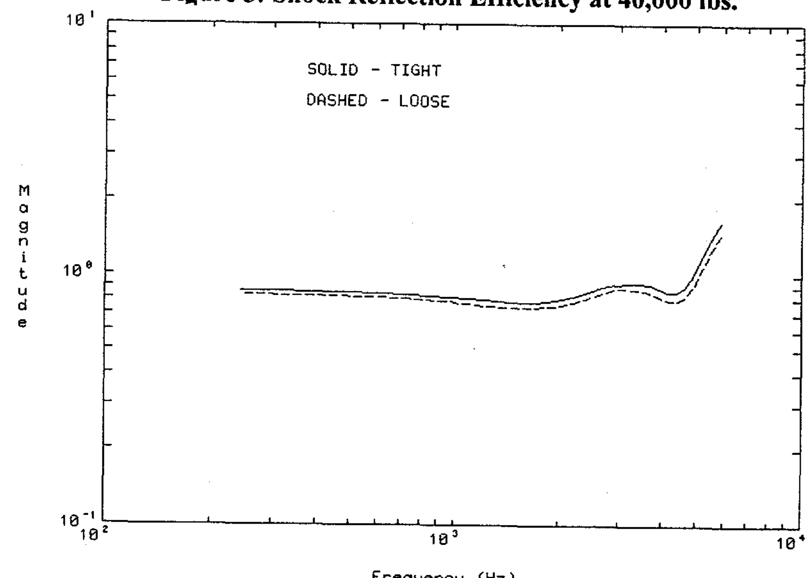

Figure 6: Shock Transmission Efficiency at 40,000 lbs.

The square pulse shape shown in Figure 7 has a rise-time similar to an actual penetration force pulse and was used for the second part of the evaluation. The DC-4 grease was not used for this part of the evaluation because it caused excessive reflections of the high frequency portion of the incident wave at the Hopkinson bar-insert interface. The inserts evaluated are the threaded joint insert with loose threads and the solid joint insert shown in Figure 3a.

The experiment methodology was to test one threaded joint insert at all three force magnitudes in order of increasing magnitude as in part one. The sample was then discarded and not used for any subsequent testing because localized yielding could have occurred at the 120,000 lbs. magnitude. Five threaded inserts with loose threads were tested with this methodology. Five pulses were applied to the solid insert at each force magnitude. The strain response data measured on the incident bar and the transmission bar were used to calculate a shock reflection efficiency and a shock transmission efficiency as defined above in equations (3) and (4).

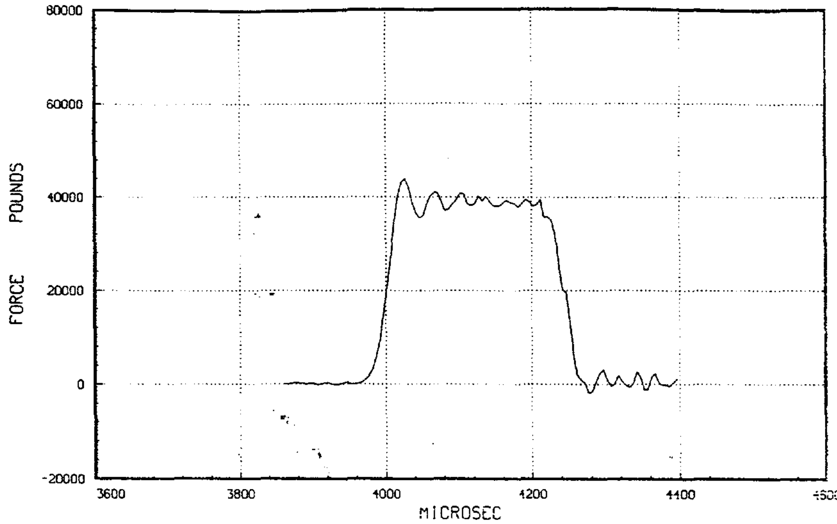

Figure 7: Dispersive Incident Wave Used for Part 2 Evaluation.

The dispersive character of the incident wave in Figure 12 appears to be a frequency superimposed on the square wave pulse. However, dispersion occurs because all frequencies in the shock wave are not travelling at the same speed which results in a phase difference between the frequency components [3]. The phase difference increases with frequency. The dispersive wave measured at the strain gages may be corrected so that the phase difference is that applied to the insert and the bar-insert interface. This correction was originally solved for discrete values of material properties [6]. More recent work has interpolated from the tabulated data of Bancroft so that the force pulse can be reconstructed using Fourier transform techniques and the equation for the resulting phase shift, φ, for a propagation distance, z, [7] below.

$$\varphi = 2\pi n \omega z \left(\frac{1}{c_o} - \frac{1}{c_n} \right) \tag{5}$$

where:

- z = Propagation distance, positive for distance further down the bar,
- $n\omega$ = Number, n, times the frequency resolution, ω,
- c_o = Nominal wave speed,
- c_n = Wave speed values interpolated from Bancroft [6].

The procedure for correcting the data is to calculate the complex Fourier transform for the measured force in magnitude and phase. The phase correction in equation (5) is added to the phase, and the inverse Fourier transform is performed to return the signal to the time-domain. All measurements during the second part of the evaluation were corrected for the distance between the bar-insert interface and the measurement point. The corrected strain response data from the incident bar (incident and reflected force) and the transmission bar were used to calculate a shock reflection efficiency and a shock transmission efficiency as defined above in equations (3) and (4).

The transmission efficiency results are shown in Figure 8 and compare the efficiency for the loose threads and the solid insert and for 40,000 lbs. force magnitude value. The results for the other force magnitudes, 70,000 lbs. and 100,000 lbs., are essentially the same and show that the threaded joint transmitted more of the force than the solid insert, which was an unexpected result. The reason for the lower transmission by the solid insert was hypothesized to be caused by reflections from the hollow cavity in solid insert. The finite element model confirmed this hypothesis.

In the third part of the evaluation, the inserts and the transmitted (response) bar were instrumented with ENDEVCO 7270A-200K accelerometers so that the results could more easily be correlated with the finite element model. The locations of accelerometers are shown in Figures 1-3. The same dispersive input force shown in Figure 7 (the transmitted force is essentially the same) was used in this third part of the threaded joint evaluation that compared acceleration responses for the modified solid insert in Figure 4b, the tight threaded joint, and the loose threaded joint. DC-4 grease was used between the bars and the insert to mitigate high frequency content that caused the accelerometers to resonate. An example of the acceleration response at the threaded joint interface is shown in Figure 9. An averaged Fourier transform for five measurements of the incident force at 40,000 lbs. is in Figures 10 and demonstrates the high degree of consistency in the applied force for the different tests. The averaged Fourier transforms for five measurements of the response at the insert for applied force of 40,000 lbs. is in Figure 11; results for a 70,000 lbs. applied force is essentially the same. Averaged Fourier transforms for the response accelerometer on the end of the transmitted bar are nôt shown because the measurements were essentially the same for all inserts and the two applied force magnitudes. The response accelerometer results were confirmed by analytical calculations that showed that the effect of threaded joint is limited to a length equal to three or four diameters down the transmission bar. Beyond this length, the wave returns to a one-dimensional wave undistorted by the effects of the inserts. The tight thread and the loose thread inserts appear to attenuate the high frequency content in the applied force because of impedance mismatch. The solid insert does not have the hollow cavity as in previous portions of the evaluation so the impedance mismatch is minimized for this insert. The loose thread insert rattles more than the tight thread insert, so it has a higher Fourier transform magnitude for frequencies between 10,000 and 30,000 Hz.

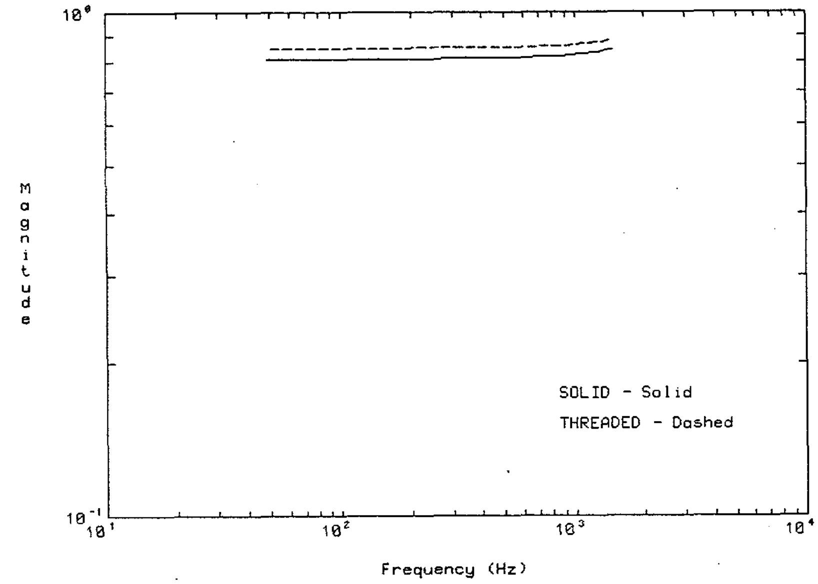

Figure 8: Shock Transmission Efficiency at 40,000 lbs.

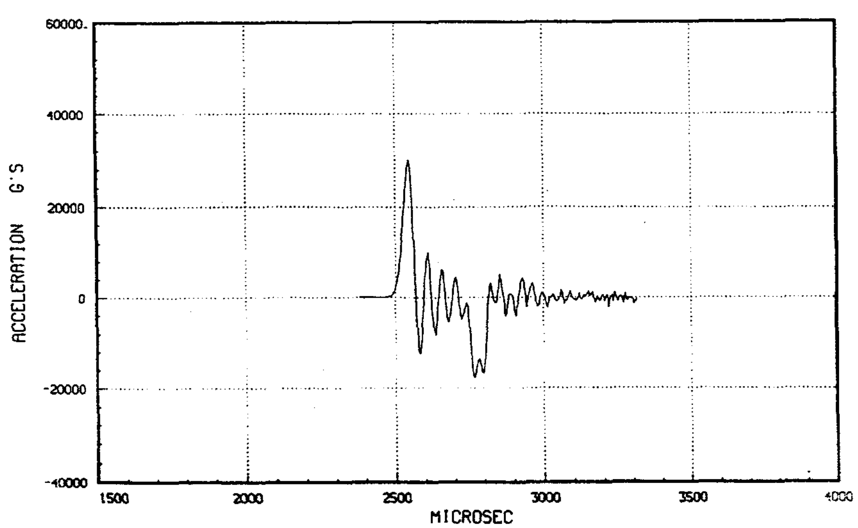

Figure 9: Acceleration Response at the Threaded Joint Insert for Part 3 of the SNL Experiments.

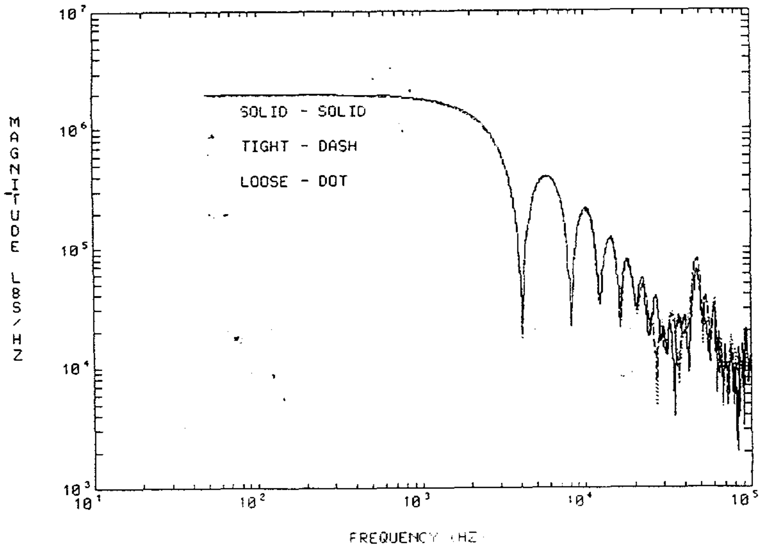

Figure 10: Averaged Fourier Transforms of the Incident Wave at 40,000 lbs.

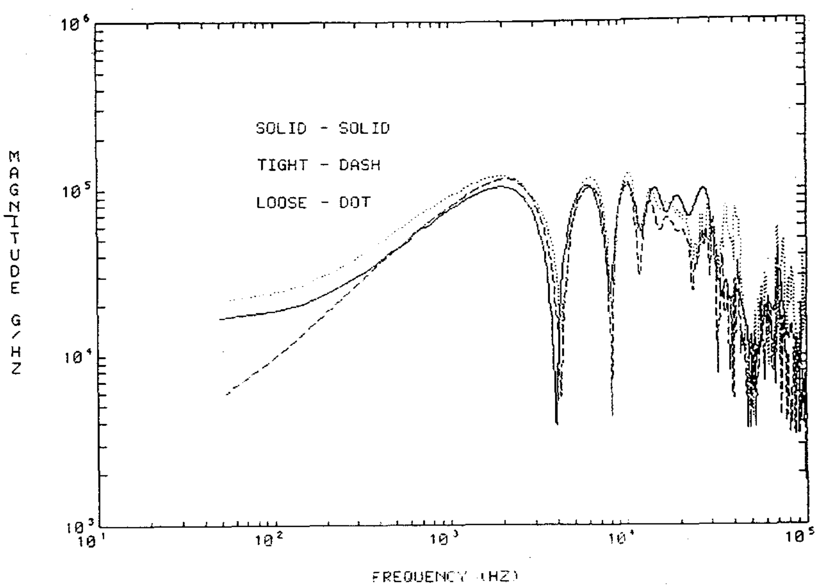

Figure 11: Averaged Fourier Transforms of the Insert Acceleration for 40,000 lbs. Applied Force.

The fourth and last part of the evaluation looked at the force input created by the two projectile lengths of 12 in. and 24 in. The results are shown in the form of averaged Fourier transform magnitudes in Figure 12 for force values of 40,000 lbs; the results for 70,000 lbs are essentially the same. The Fourier transforms are similar up to 30,000 Hz that is the valid frequency bandwidth for this 3 in. diameter Hopkinson bar configuration. There are no anomalies in this DC-30,000 Hz. bandwidth. For the 40,000 lbs incident force, there is resonant behavior at 50,000 Hz for the 12 in. projectile but not for the 24 in. projectile. The resonant behavior at 50,000 Hz for the 12 in. projectile is absent for the 70,000 lbs. incident force. However, these differences are not considered a significant factor in the results because they are so high in frequency.

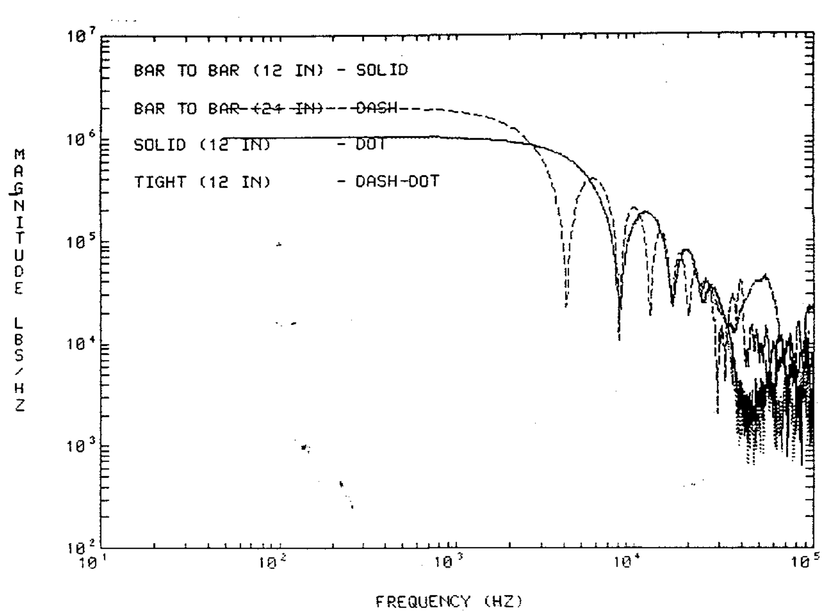

Figure 12: Averaged Fourier Transform for the Incident Force at 40,000 lbs.

FINITE ELEMENT ANALYSIS OF THE SPLIT HOPKINSON BAR CONFIGURATION

As discussed in the previous section, an analytical study accompanied the experimental evaluation to verify the dispersive behavior of the force waves and to verify various other experimental results. The P3 capability in the PATRAN finite element analysis code was used to model both the incident and the transmitted Hopkinson bars and the various joint inserts. The model is two-dimensional and axi-symmetric with a 1.5 in. radius. Four square elements spanned the radius with dimensions of 0.375 by 0.375 in. The model was used to evaluate the effects of rise time, pulse shape, and bar anomalies for a 400 μs duration simulation. Time history stress comparisons and Fourier transform magnitude comparisons at various locations are shown for a 5 μs rise time in Figures 13-14. Rise time values of 15 μs, 30 μs, and 60 μs was also evaluated; the results were essentially the same as those shown for 5 μs. The Fourier transform comparisons have differences above 30,000 Hz and confirm the attenuation of the frequencies above 30,000 Hz in all stress pulses. This attenuation is a limitation due to the 3 in. diameter [6]. Any changes in the high frequency response are localized as shown by the time history results at various locations down the Hopkinson bar. In a large structure, these high frequency responses would disperse in the structure and would not be transmitted through the structure. However, high frequency response could couple into local substructures. Additionally, a convergence study was performed for this PATRAN model. The parameters of bar width, stress magnitude, rise time, and time step were varied. In general, the convergence of the model was insensitive to variation of these four parameters, and differences due to changes in the parameters are minor.

CONCLUSIONS

The evaluation of the shock transmissibility of threaded joints in a split Hopkinson bar configuration has been completed. A four part experimental evaluation was completed in the SNL Mechanical Shock Laboratory. The results show that variations in the transmitted force through a solid joint insert and a threaded joint insert differ at frequencies above 10,000 Hz and the differences are relatively minor. This result is sensitive to incident force rise time, incident force magnitude, length of projectile, and tightness of the threads. An analytical study, performed with a PATRAN finite element analysis, confirms the experimental evaluation results that in this split Hopkinson bar configuration, the change in the one-dimensional shock wave by the threaded joint is localized to a length equal to a few diameters' length beyond the threaded joint.

REFERENCES

1. Bateman, V. I., R. L. Mayes, and G. H. James, "Structural Response Measurements to Insure Penetrator Data Integrity," *Proceedings of the 64th Shock and Vibration Symposium,* Vol. I, Fort Walton Beach, FL, October 1993,

pp. 145-154.

2. Lindholm, U. S., and L. M. Yeakley, "High Strain-Rate Testing: Tension and Compression," *Experimental Mechanics*, Vol. 8, 1968, pp. 1-9.
3. Davies, R. M., "A Critical Study of the Hopkinson Pressure Bar," *Philosophical Transactions of the Royal Society of London,* Vol. 240, 1948, pp. 375-457.
4. Leung, R. C. N. and R. J. Pinnington, "Wave Propagation Through Right-Angled Joints with Compliance-Flexural Incident Wave," *Journal of Sound and Vibration*, Vol. 142, Issue 1, 1990, pp. 31-46.
5. Leung, R. C. N. and R. J. Pinnington, "Wave Propagation Through Right-Angled Joints with Compliance: Longitudinal Incident Wave," *Journal of Sound and Vibration*, Vol. 153, Issue 2, 1992, pp. 223-237.
6. Bancroft, Dennison, "The Velocity of Longitudinal Waves in Cylindrical Bars," *Physical Review*, Vol. 59, Paper 71, April 1, 1941, pp. 588-593.
7. Gorham, D. A., "A Numerical Method for the correction of Dispersion in Pressure Bar Signals," *Journal of Physics E: Scientific Instrumentation*, Vol. 16, 1983, pp.477-479.

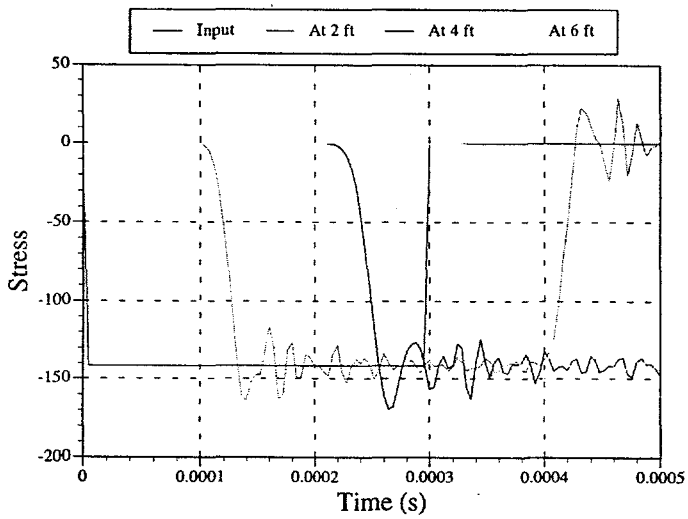

Figure 13: PATRAN Stress Time History Results for a 5 μs Rise Time.

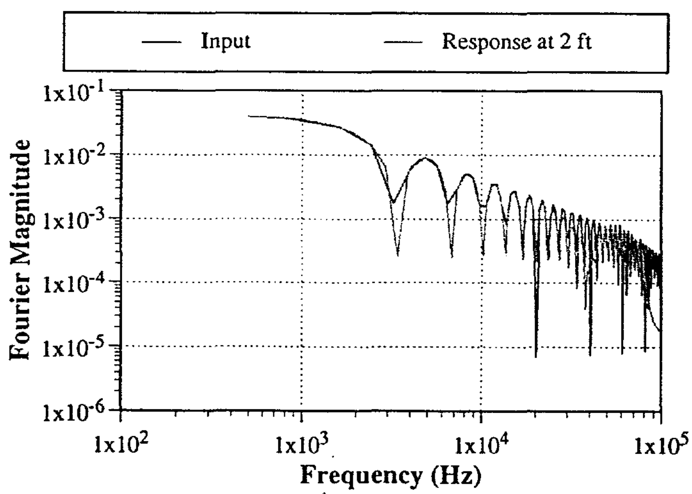

Figure 14: Fourier Transform Magnitude Comparison for a 5 μs Rise Time.