Computational Simulation of Shock Wave Propagation in Blast and Shock Tube

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Objectives

In this study, detonation of TNT was simulated using an FE code and the resulting mechanical behavior of air, in which the explosion took place, was studied as a function of distance. Incident and reflected pressure and impulse profiles were compared with published data. In addition, an FE model of a shock tube setup at Temple University was developed using equations of state for Helium and air as the driver and driven fluids. The characteristics of the shock wave developed from explosive blast and shock tube were compared. It was shown that merely the two variables commonly used in the literature to compare the results from a shock tube to that of blast, i.e., peak incident pressure and positive duration, could not thoroughly include all the characteristics of the shock wave. Other parameters such as reflected pressure and impulse, which includes the velocity of the particles in addition to the pressure, are also needed to describe the shock wave.

Blast Wave Characteristics

The blast wave initiated by detonation of a high explosive material, such as TNT, is marked by extremely high overpressures (in the order of 1 GPa) in short time periods (in the order of 10 ms) [1]. Upon detonation, the gaseous products are forced outwards, compressing the surrounding air, at velocities much higher than the sound velocity in the air (initially in the order of 7 km/s) [1, 2, 3]. This process creates shock waves that are essentially discontinuities in pressure, density and other mechanical properties. Below the numerical methods used to model this phenomenon as well as its validation are reported [4].

$$p(t) = A\left(1-\frac{\omega}{R_1 V}\right)e^{R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{R_2 V} + \frac{\omega E}{V}$$

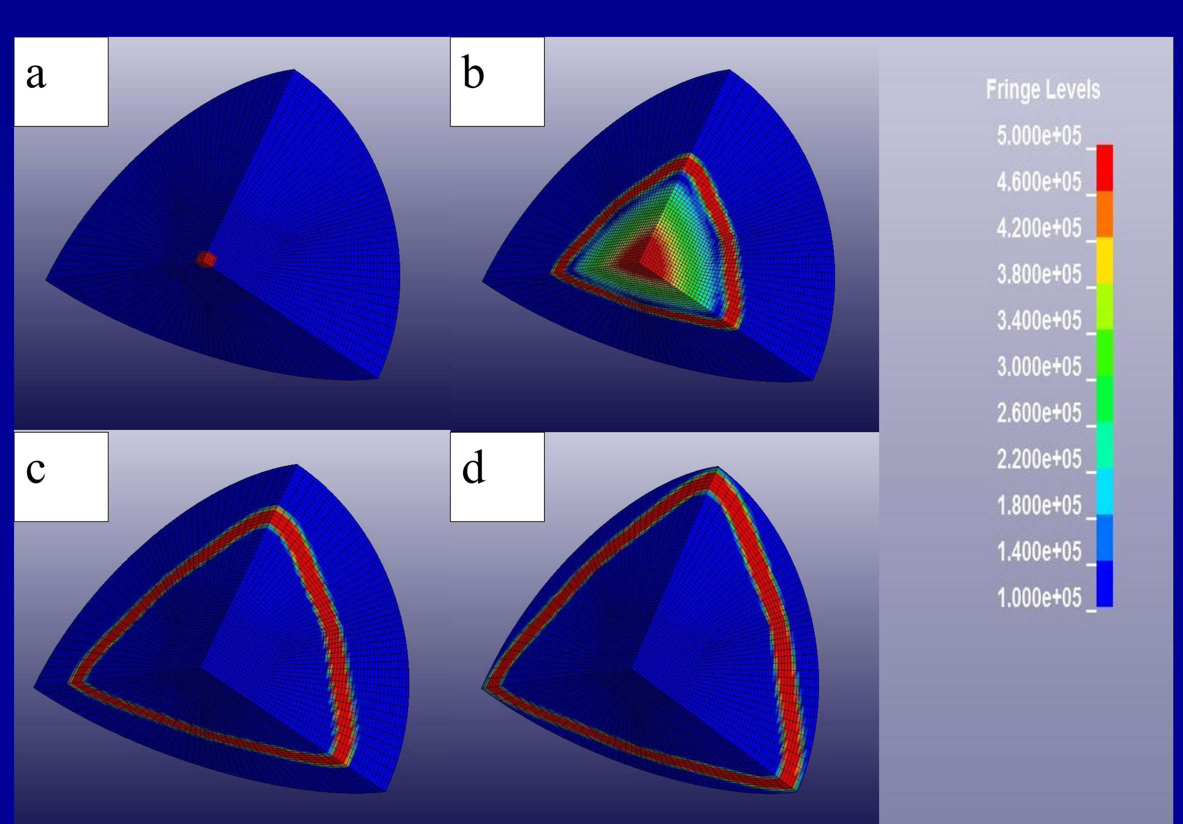

Figure 1 - Finite element model of blast in a smaller scale for viewing purposes. (a) to (d) represent the pressure profiles at times t=[0, 0.2, 0.5, 0.7] ms.

Table 1 – Material parameters used in the FE model

High Explosive (TNT) Material Parameters	
$A\ (GPa)$	371.2
$B\ (GPa)$	3.231
R_1	4.15
R_2	0.95
$E\ (GPa)$	7.0
ω	0.3
$\rho (kg/m^3)$	1590

Gaseous Material Parameters	Air	Helium
$\rho (kg/m^3)$	1.293	0.1786
γ	1.4	1.667
$C_{p0} (J/kg.K)$	1005	5191
$C_{v0} (J/kg.K)$	1.4	3114
$R (J/kg.K)$	287	2077
$p_0 (kPa)$	100	100

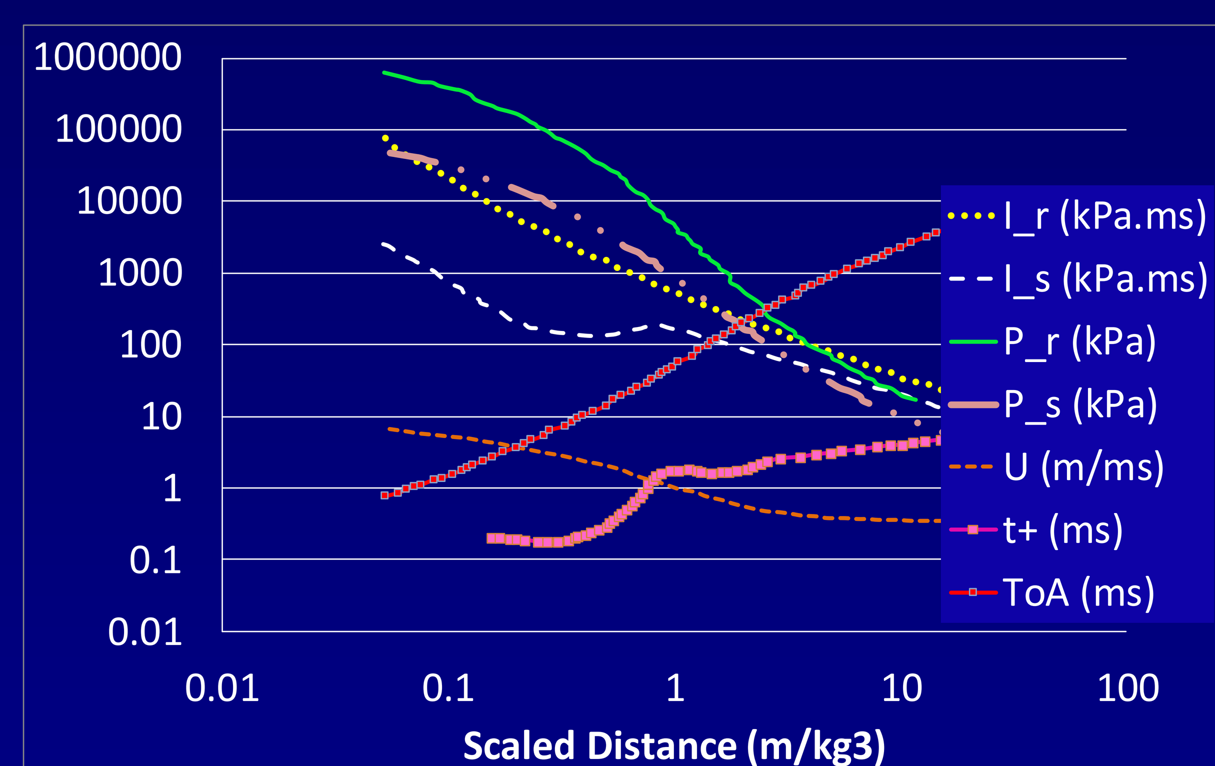

Figure 2 - Convergence of blast wave overpressure rise time and shock front thickness as a function of element size. Experimental values are shown by the dashed line.

Shock Tube Characteristics

Figure 3 shows the shock tube system at Temple Biomechanics Laboratory. The shock tube has a diameter of 50mm with a 645-mm-long driver and a 625-mm-long driven, separated by a membrane of varying thickness to produce shocks with different strengths. The pressure in the driver section is gradually increased by an inflow of Helium (He) until the membrane ruptures and initiates a shock wave, the peak pressure of which is linearly dependent on the membrane thickness.

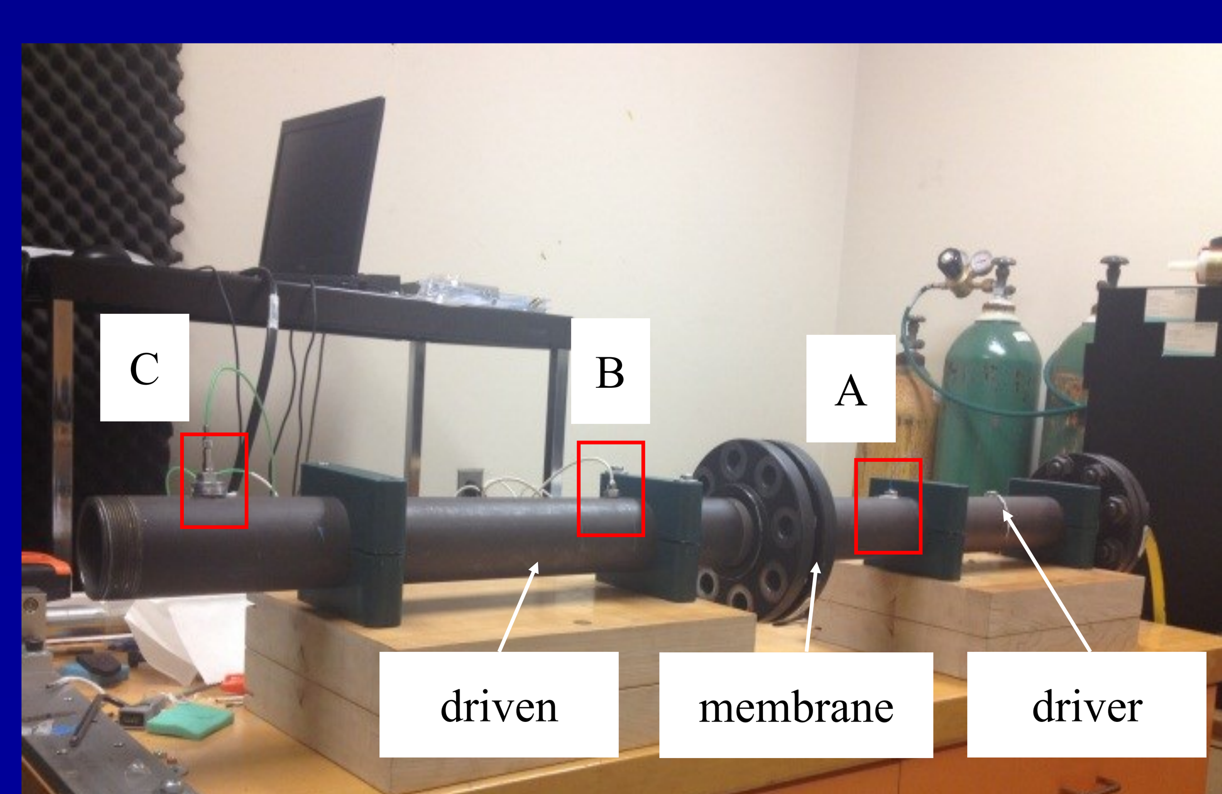

Figure 3 - Shock tube with open end on the left and output locations (A, B, and C) marked.

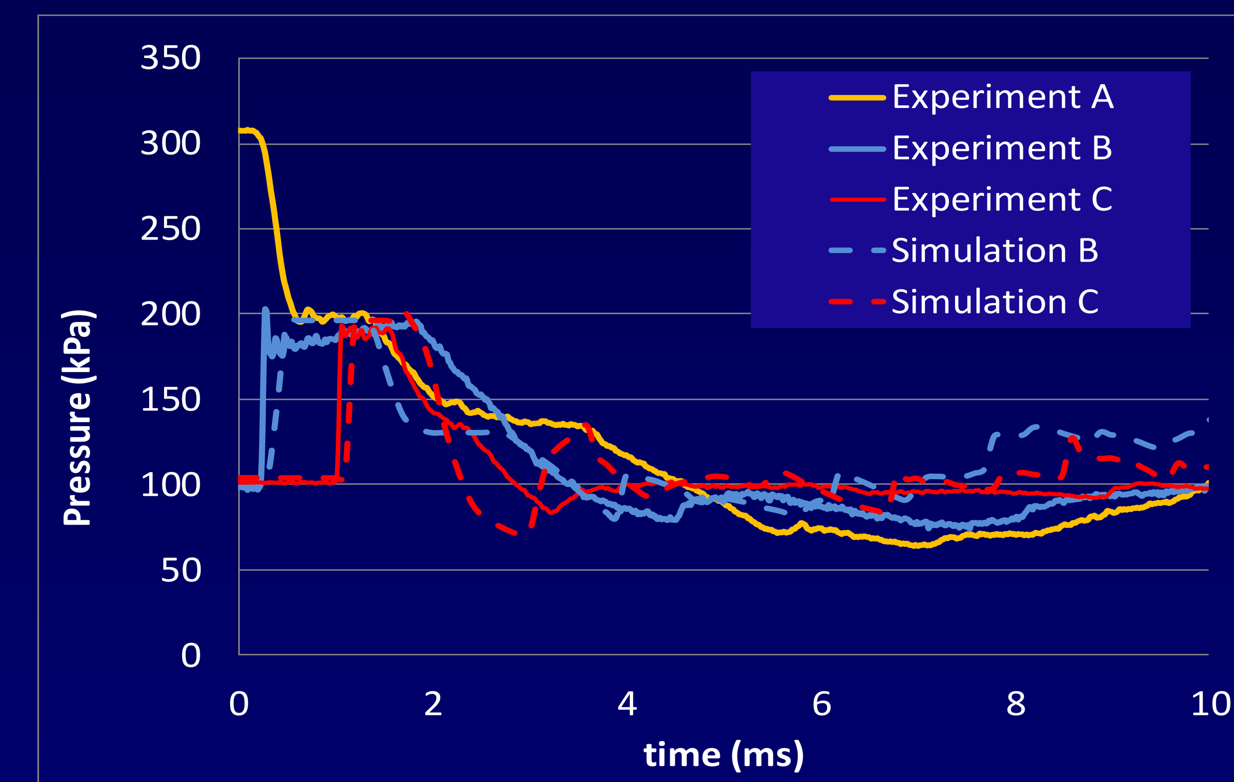

Figure 4 - Validation of the computational results with the measured pressure values at three locations A, B and C.

Results and Conclusion

It is common practice in the literature to use the idealized Friedlander pressure profile in shock tubes:

$$p(t) = p_a + p_s e^{-\frac{t}{t^+}\left(1-\frac{t}{t^+}\right)}$$

Here, p_a is the atmospheric pressure, p_s and t^+ are the peak incident pressure and the positive duration of the shock wave. In Figure 5, a typical explosive blast pressure profile at a distance of 3.5 m is plotted and compared against with the well-known Friedlander profile (shock tube). The peak pressure and positive duration of this simulation was then used to create a similar situation in a given shock tube, the results of which are also shown in the same Figure. However, as seen in Table 3, other reported mechanical properties show that the peak incident pressure and positive duration are not conclusive parameters to simulate blast wave propagation using a shock tube. Reflected pressure, shock velocity and gas particle velocity should also be taken into account.

Table 1 - Comparison between the experimental results and the computational model

		Sensor Location		
		A	B	C
Arrival Time (ms)	Experiment	0	0.2	1
	Simulation	0	0.29	1.09
Peak Pressure (kPa)	Experiment	308	202	193
	Simulation	260	196	196

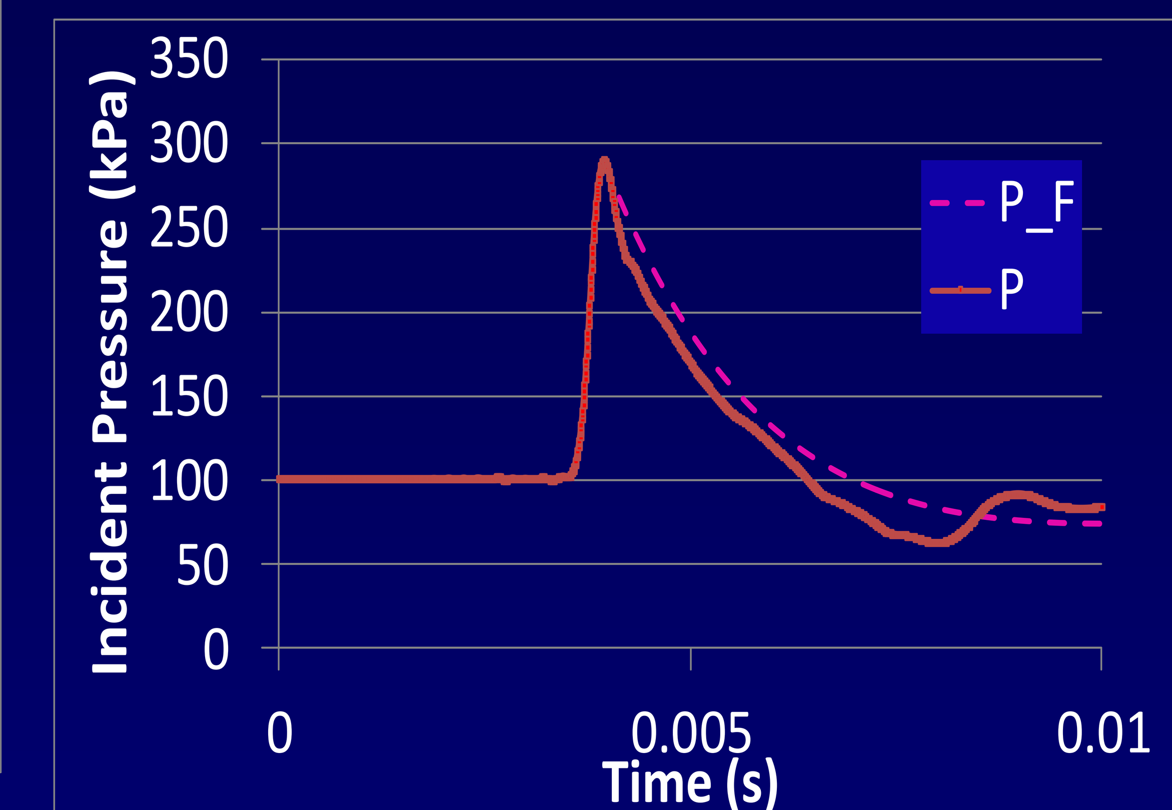

Figure 5 - Friedlander profile for shock tube incident pressure (P_F) and pressure profile from blast (P) at 3.5 m.

Table 2 - Mechanical parameters for explosive blast and shock tube for similar peak incident pressure and positive duration.

	Blast	Shock Tube	Difference (%)
Positive Duration (ms)	3.0	3.0	0.0
Peak Incident Pressure (kPa)	290.5	287	1
Peak Reflected Pressure (kPa)	1165	980	15
Shock Speed (m/s)	582	343	41
Gas Particle Velocity (m/s)	553	337	39

References

[1]Bulson, Taylor & Francis, 2002.

[2]Zhu, Wagner, Leonardi, Jin, Vandevord, Chou, Yang, and King, Biomechanics and modeling in Mechanobiology, 2011.

[3]Hemmasizadeh, Autieri, and Darvish, J of the Mechanical Behavior of Biomedical Materials, 2012.

[4]J. Hallquist, "LS-DYNA keyword user's manual." 2007.