Dispelling Misconceptions about Bast Waves (Irvine Israel Glass Lecture)

Charles Needham

Introduction

There are a number of misconceptions about air blast waves interacting with structures that I would like to dispense with. There is a persistent notion that a structure is "blown away" when it is hit by a nuclear blast wave. This image probably comes from the many movies from nuclear tests that show a structure such as a house or an industrial building being torn apart and "flattened" by the air blast. There is no argument that this does not happen; however, the timing of the structure response is what I would like to examine.

Consideration of the timing of the response of structures to air blast loading becomes a dominant factor when predicting the air blast propagation in urban environments. A number of questions have been asked about the absorption of energy and reduction of air blast as the blast wave interacts with structures in the urban environment. How much energy goes in to breaking the structure? How much energy is converted to the kinetic energy of the debris? How much energy is dissipated on the interior of structures? How much debris will be entrained in the blast wave? How far does the debris get thrown? What is the "protection factor" of nearby buildings? How different are the blast waves traveling down streets and the blast waves going over and around buildings?

There have been many high-explosive and shock-tube experiments conducted with urban structures of various scales. A few were done at full scale with houses; others were done at small scale with a few pounds of explosive. Not all of these experiments had a primary purpose of looking at the effects of blast on structures or, more directly, the importance of structures on blast wave propagation. Let me review a few experimental results to demonstrate the fallacy of some of the misconceptions. (I held these views prior to seeing experimental data with corresponding calculational results.)

Some assumptions that I have heard expressed include: (1) At pressures of 2 bars or more, windows will be blown away so rapidly that you can ignore their presence. (2) Once the window is broken, gas will flow through the opening. (3) Debris will be translated to large distances by blast waves.

Let us look at some basic properties of blast waves. Table 1 contains a list of overpressures and their associated dynamic pressures and wind velocities. Remember that the ambient speed of sound is about 750 miles per hour. A blast wave with an overpressure of more than about 36 PSI will have a material velocity at the shock front that is supersonic. For comparison: Sustained winds >155 mph define a Category 5 hurricane, and 3 s gusts >200 mph define an enhanced Fujita scale (EF5) tornado.

The velocities behind a 6 PSI shock are equivalent to the winds in an EF5 tornado, and the winds in a Category 5 hurricane are present at the shock front of a 4 PSI shock. At half a PSI, the dynamic pressure is only 0.006 PSI, but a sudden wind gust of 18 miles per hour will certainly blow the hat off your head.

This is a true story.

I was at a NATO blast effects on animal symposium in Halifax a few years ago when one of the researchers made the statement in his presentation that he had exposed mice to 40 PSI dynamic pressure and they had survived. I found this very hard to believe. At the break I asked him about his experiment which he described as follows: I had the mice walk across a beam in front of a nozzle. When they were in front of the nozzle, I opened the valve to the nozzle and all it did was knock the mice off the beam. The nozzle was connected to a hose which was connected to a tank which was pressurized to 40 PSI. Isn't that 40 PSI dynamic pressure?

From the table below, we see that a blast wave with 40 PSI dynamic pressure has a wind velocity of about 900 miles an hour (Mach 1.3+) material velocity with a corresponding overpressure of 50 PSI.

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Example 1

In 1999 an experiment was conducted at White Sands Missile Range in which a full-sized four-story concrete building, Fig. 1, was subjected to the blast wave from a 300 lb charge detonated on the center line of the building, 50 ft in front of the structure. The front face of the structure had concrete walls with glazed windows. The structure was 80 ft wide and 48 ft deep by four stories tall. The walls on the sides of the building were only wing walls and extended just 6 ft from the front of the structure. Extensive air blast instrumentation was located throughout the building. For this example we need only the gauges on the front wall and on the floor of the fourth story. The fourth floor gauges were located ten feet behind the windows and centered on the windows on either side of the center line (Fig. 2). The windows on either side of the center line were 6 mm thick (~.25 in.). With the charge located 50 ft in front of the structure, the shock radius was greater than the height or the half width of the building when the front face was struck. The reflected overpressure on the entire front face of the building exceeded 35 PSI, while on the center line, the overpressure exceeded 40 PSI. Without going into all the details, we examined two gauges on the front of the structure and two gauges that were 10 ft inside the building, about 10 ft on either side of the center line, in line with the windows. All expectations were that such a high-pressure blast wave would blow out the windows and hit the interior blast gauges with an incident pressure in excess of 5 PSI, which is just a little less than the unobstructed incident pressure at that range.

A comparison of two blast gauges on the front of the building showed that the measured overpressure waveforms were essentially overlays throughout the positive duration of the blast wave, even though one gauge was on the concrete surface and the other was in the middle of a window. This was a good indication that no gas penetrated the window and

Table 1 Some properties of shock waves

Peak overpressure (PSI)	Peak dynamic (PSI)	Maximum wind velocity (mph)
200	330	2078
150	222	1777
100	123	1415
50	41	934
30	17	669
20	8.1	502
10	2.2	294
5	0.6	163
0.5	0.006	18

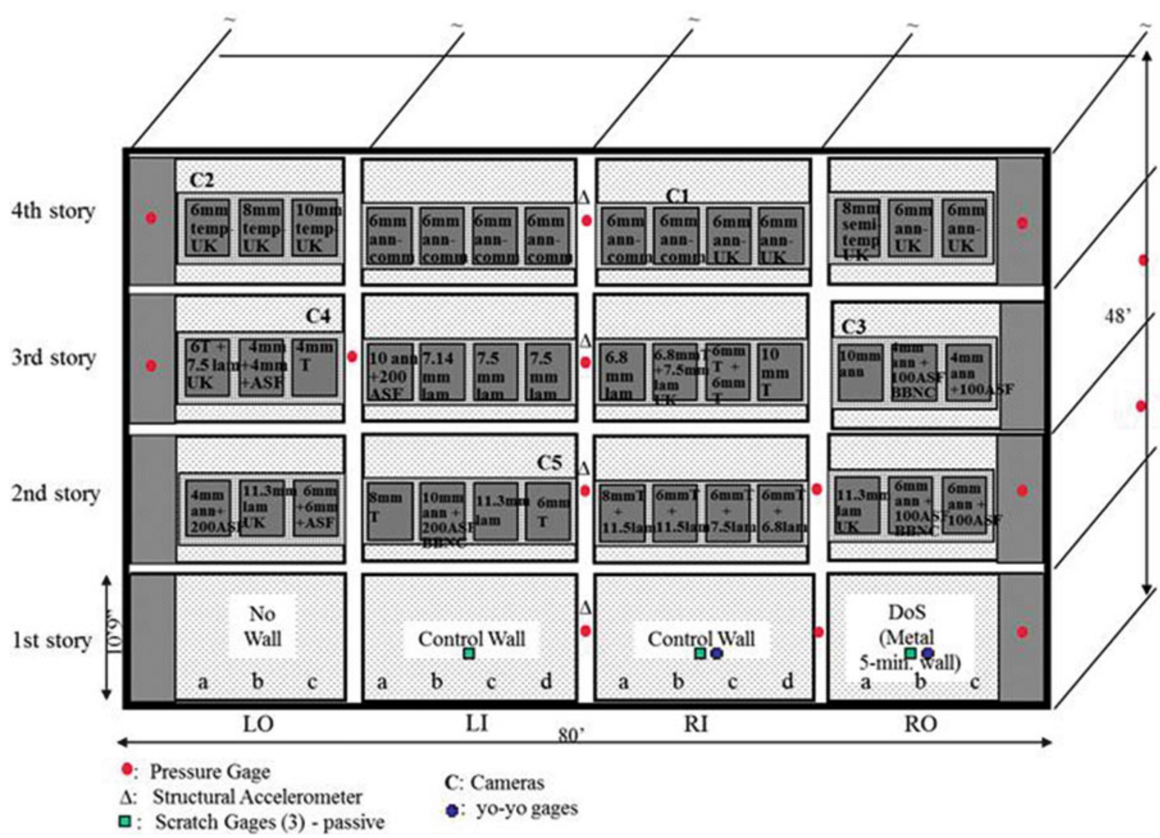


Fig. 1 The four-story full-scale test structure

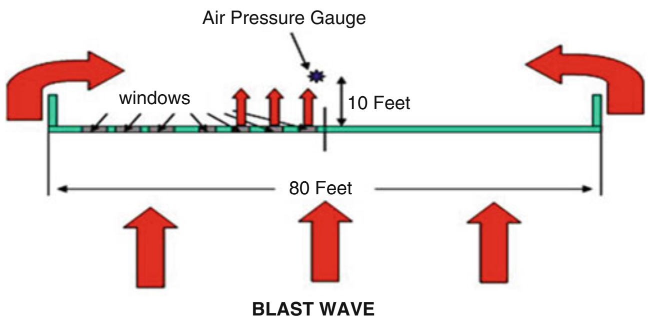


Fig. 2 Plan view of the fourth floor of the building

that the window glass did not move significantly over the entire positive duration of the blast wave.

We then examined the waveforms on the two gauges on the floor, ten feet behind the windows. By looking at the relative arrival of signals at these gauges, we found that the arrival of the first significant signal did not arrive until about 25 ms after the arrival at the window center. The expected arrival, assuming the blast wave came through the window, would be 7 ms later. The 25 ms delay corresponds exactly with the arrival of a blast wave coming around the sidewalls and traveling 30 ft to the gauges on either side of the center line. Further evidence that the shock came from the side was the arrival of a second shock just 20 ms later on both gauges. The 20 ms corresponds to the travel time for a weak shock over the 20 ft separating the gauges. It was not clear whether *any* signal came through the windows.

One additional note from this experiment is the windows were shattered into small pieces and the majority of the glass was found outside in front of the building. This was caused by a combination of the negative phase on the exterior of the building and the arrival of the blast wave from the sides in the interior of the building, pushing the broken glass outward.

An easy way to think of this response is that the density of the glass is more than 1000 times the density of the air in the shock. Because overpressure is a scalar, the air and the glass receive the same impulse, and the air is accelerated 1000 times faster than the glass. The air blast will move 1000 times further than the glass in the same amount of time. The air shock will move at least 20 ft in the time the glass will move 0.25 in.

Another consequence of this timing is that there was very little blast wave wind on the interior. Papers and office furniture would not be blown out the windows as some might envision. The argument against this might be that the positive duration is too short for such a small charge and that, for a nuclear event, the duration would be a large fraction of a second, thus allowing acceleration of interior debris.

Example 2

In 2002, the British conducted a series of scaled experiments using 250 kg of high explosive detonated at a height of burst of ~25 ft near a 1/50th scaled model of downtown San Francisco. The buildings were constructed of concrete and were instrumented for air blast on the back, front, top, and sides. Measurements of air blast and its propagation through the model city were carefully recorded. Calculations using the SHAMRC hydrodynamic code were made and showed excellent agreement with the measured air blast waveforms. Significant criticism was expressed because the structures in the calculation and in the experiment were rigid and non-responding. In the following year, the experiment was repeated except that the structures were constructed of 3 mm-thick mirror glass. The instrumentation was placed in the same locations.

Posttest comparison of the waveforms showed no significant difference of the peak pressures, waveform shapes, or impulses between the concrete structures and the mirror glass structures. This was true throughout the test bed, whether closer to ground zero or after transiting the entire city. In addition there was no measurable difference in arrival time between the two experiments. The mirror glass experiment showed that the debris was concentrated within about four building heights of the original location. Debris was not "blown to long distances" (Fig. 3).

As a side note, the 3 mm glass at 1/50th scale corresponds closely to a 15 cm-thick concrete wall, not too bad an approximation to actual construction thickness.

Again the explanation is that the density of the responding structural material was more than 1000 times the density of the air in the blast wave. The air moves about 1000 times as far as the glass in the same amount of time.

Example 3

The Ernst Mach Institute (EMI) in Freiburg, Germany, did some shock-tube experiments using a small-scale, three-dimensional model of a house. The house was machined from steel and included a pitched roof, a door, and several windows. The house was placed in the test section and loaded with about 1 bar overpressure shock. Some excellent shadowgraphs were made using a multiple spark back-lighting technique to provide a time sequence of the shock reflection, diffraction, and transmission. Someone decided to repeat the experiment with a balsa wood house to see how the responding structure would change the reflected shock wave patterns. A balsa wood house was constructed to the same dimensions as the steel house and carefully placed in

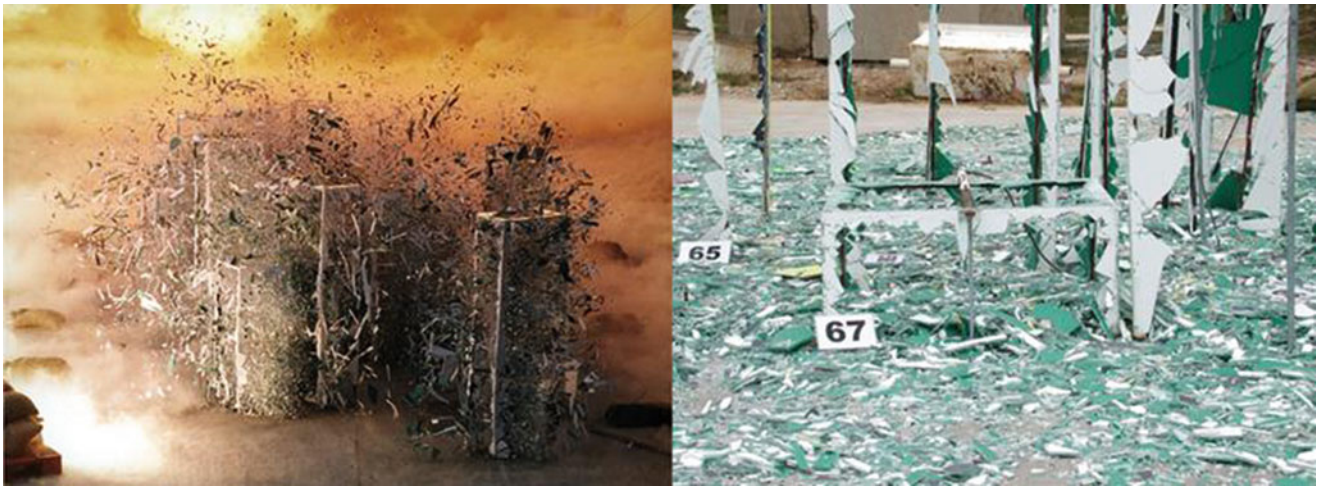


Fig. 3 Blast wave interaction with a scaled glass city and the aftermath

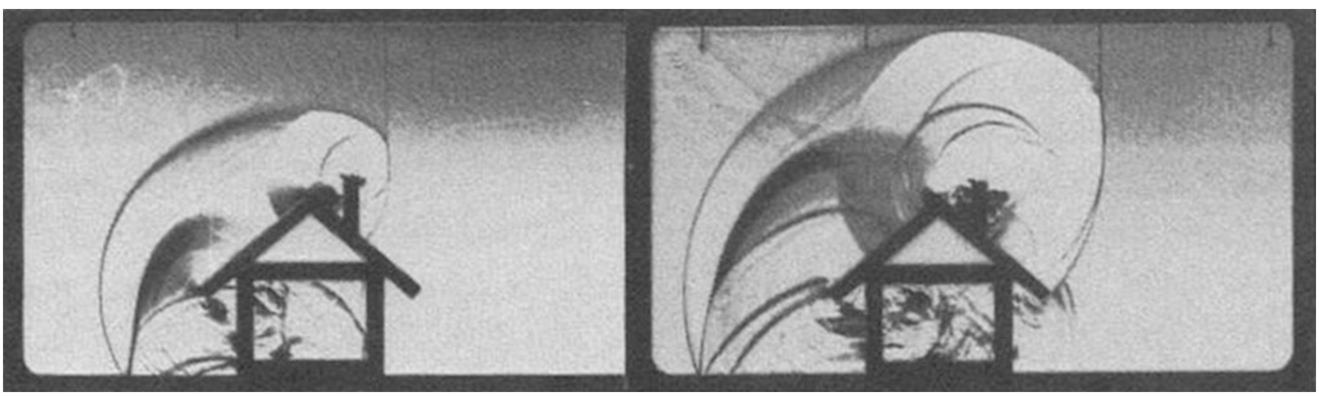


Fig. 4 Shock interaction with a scaled house

the shock tube. The house was exposed to the same shock loading as the steel house, and the same series of shadowgraphs were taken (Fig. 4).

Upon examination of the comparisons from the two experiments, there was no measurable difference between the two shock patterns. In addition, there was no measurable motion of the balsa wood house over the entire duration of the blast passage. The balsa wood house was found in small pieces in the dump tank at the end of the shock tube when the experiment was over.

The factor of ~1000 in density between the balsa wood and the air explains the observed phenomena.

Example 4

Under a contract to Sandia Laboratories, ARA made calculations of building damage and response to nuclear air blast in urban settings. The initial calculations indicated that the debris field from individual structures was translated over a very limited region near the original location of the structure. This was not the anticipated result. It was thought that the debris would be widely spread and translated to large distances. A detailed investigation of the assumptions, drag coefficients, and effects of shape of debris was undertaken. After several months of study and detailed analysis, including examination of photos from nuclear tests and scaled high-explosive tests, it was concluded that the calculated debris distributions were correct.

The general rule of thumb from this study was that debris is translated by the shock wave to distances no more than four times the building height.

Vortices on Sides (Blow Out)

The general consensus of what happens when a blast wave strikes a structure is that the loads are compressive and the structure is collapsed by the external pressure. Let us look at the flow field around a rectangular block (Fig. 5). In the

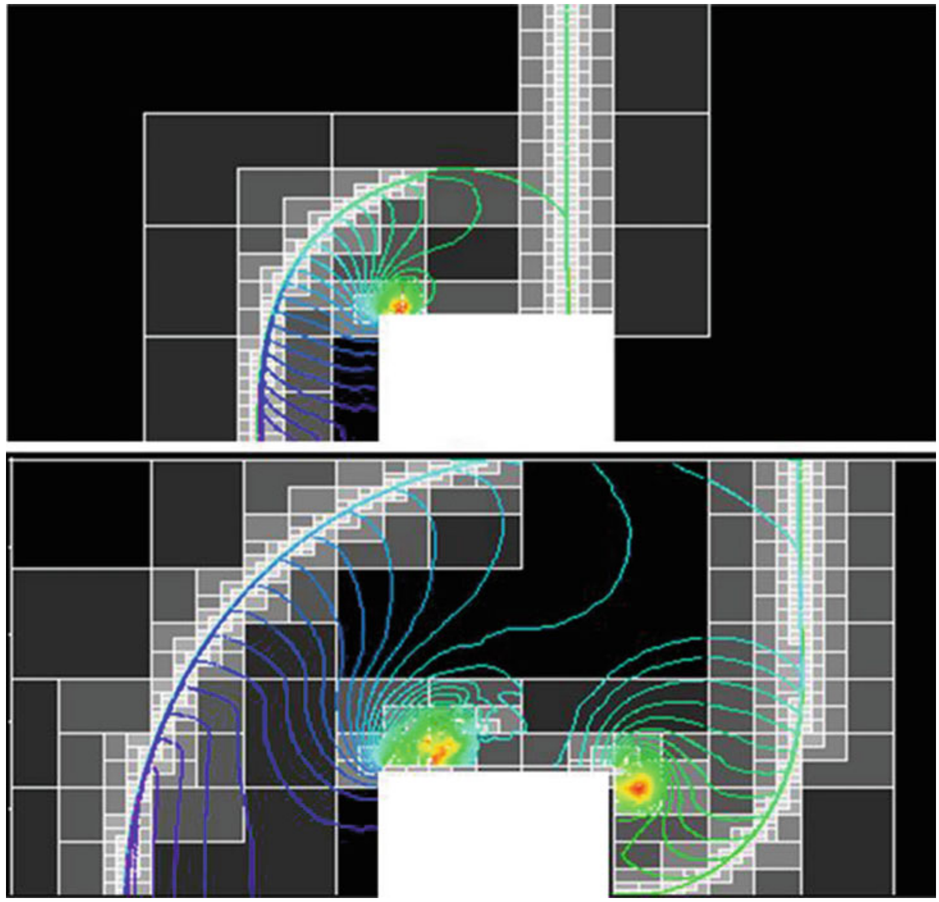


Fig. 5 Shock interaction with a rectangular box

upper figure, the shock wave has reflected from the front of the block and has progressed over the top of the block toward the rear of the structure. A vortex has formed just beyond the leading face of the block. The pressure in the vortex is well below ambient. As the shock progresses over the rear of the structure, a second vortex forms near the top of the rear face and moves down the backside of the structure. The vortex on the roof of the structure has grown and somewhat weakened, but maintains a lower than ambient pressure on the roof of the structure.

The commonly observed resulting damage is that the front wall is blown in, but the top (and sides and back wall) are blown out. This is a direct result of the under pressure on the exterior, caused by the formation of the vortices causing a net outward force because the interior pressure remained at ambient. Thus it appears that the structure "explodes".

Shock Reflection Factors

The behavior of the reflected shock pressure as a function of the incident angle to a surface is well known and has been measured by many experimenters. The peak reflected pressure does not necessarily occur when the incident shock velocity is perpendicular to the reflecting surface. Yet as recently as last year, I heard people saying that they did not "believe" the observed phenomena because either they had never measured it or it must be such a short spike in pressure that it is not important. The accompanying Fig. 6 shows that for incident overpressures below a few hundred PSI, the maximum reflection factor occurs when the impinging shock is oriented about 41° or more from the reflecting plane rather than perpendicular to it.

This phenomenon is associated with the onset of Mach reflection when the reflected shock catches the incident shock. The next two figures are measured (solid) and calculated (dashed) waveforms from replicated detonations of 1080 lb HMX charges at a height of burst of 13.7 ft. Figure 7 is the waveform at a ground range of 12.5 ft. The incident pressure was 2.3 MPa (~330 PSI). The experimental data clearly show a peak reflected pressure very near 14 MPA or a reflection factor of 6. This point is displayed on the reflection factor curve on the right. Note that the reflected peak is not at the shock front; in fact, it is not a shock but is compressive wave caused by the converging flow at ground level just prior to Mach formation.

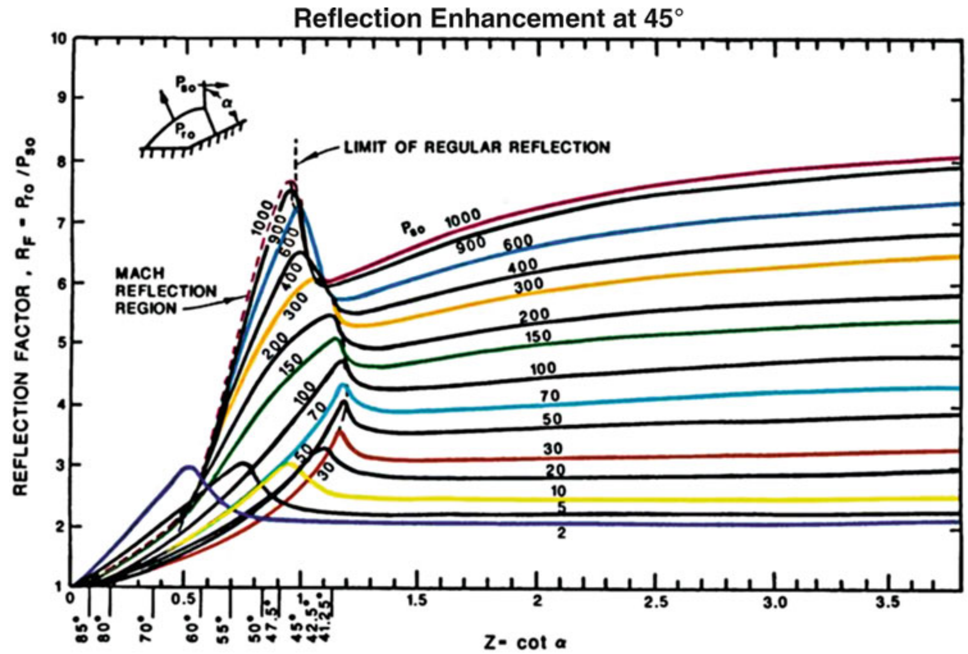


Fig. 6 Reflection factors for selected incident overpressures as a function of incident angle

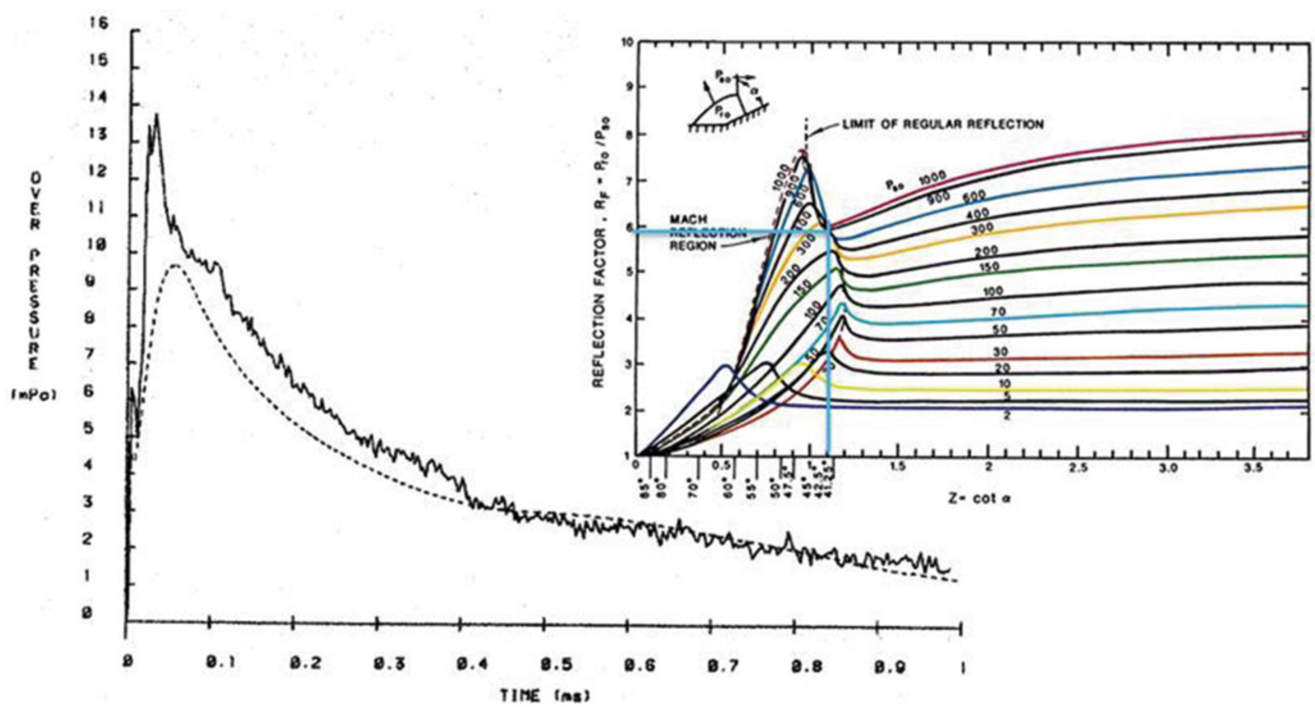


Fig. 7 High explosive reflected waveform. GR = 12.5, HOB = 13.7, incident OP = 2.3 MPa

At a ground range of 16 ft (Fig. 8), the Mach stem has formed and is growing. Note that the distance between the shock front and the peak pressure has increased significantly. This peak pressure corresponds to the range at which the slip line from the triple point reaches the ground. Again the point on the reflection factor curve is displayed in the plot on the right.

Figure 9 demonstrates the high resolution that is needed to resolve this double-peak phenomenon in numerical calculations. The waveforms were calculated, using the US government code SHAMRC, for a 1 kt detonation at a height of burst of 100 m. The three sets of waveforms were taken at 80, 90, and 100 m from ground zero. With 10 cm zoning, the double peak is not resolved and results in an extended rise

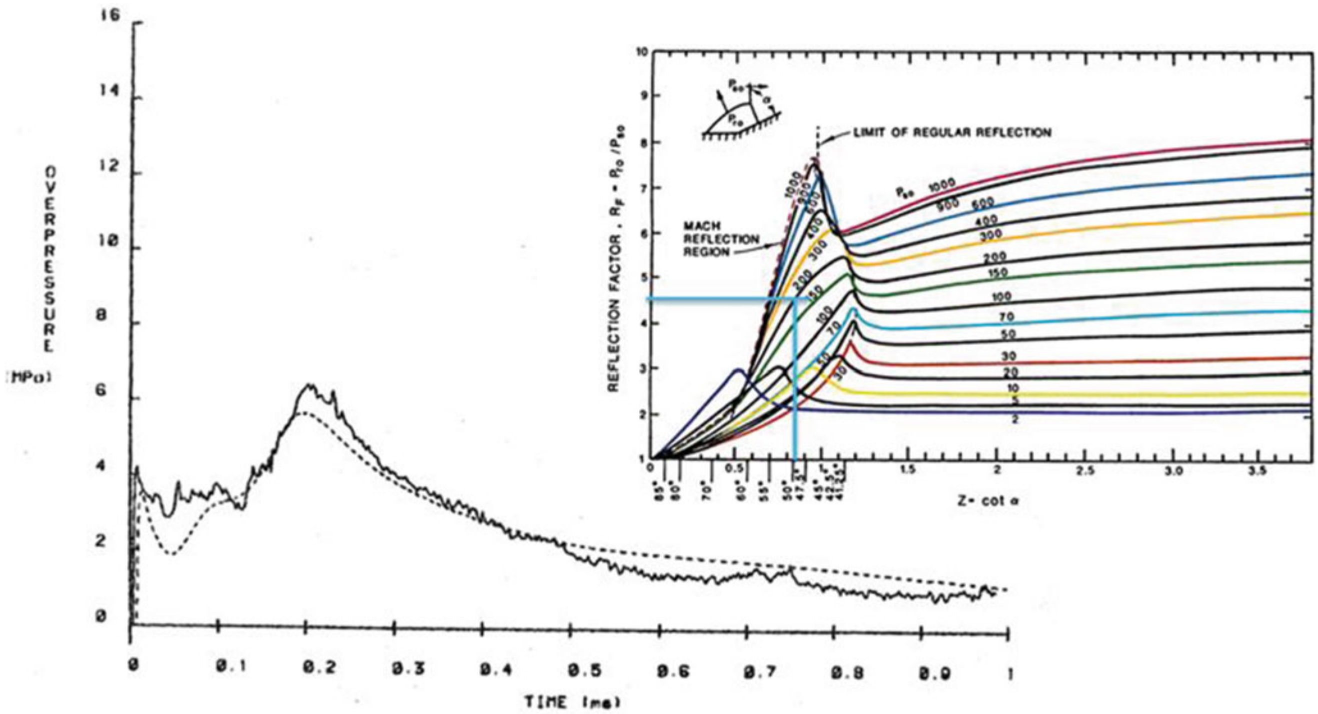


Fig. 8 High explosive reflected waveform. GR = 16, HOB = 13.7, incident OP = 1.5 MPa

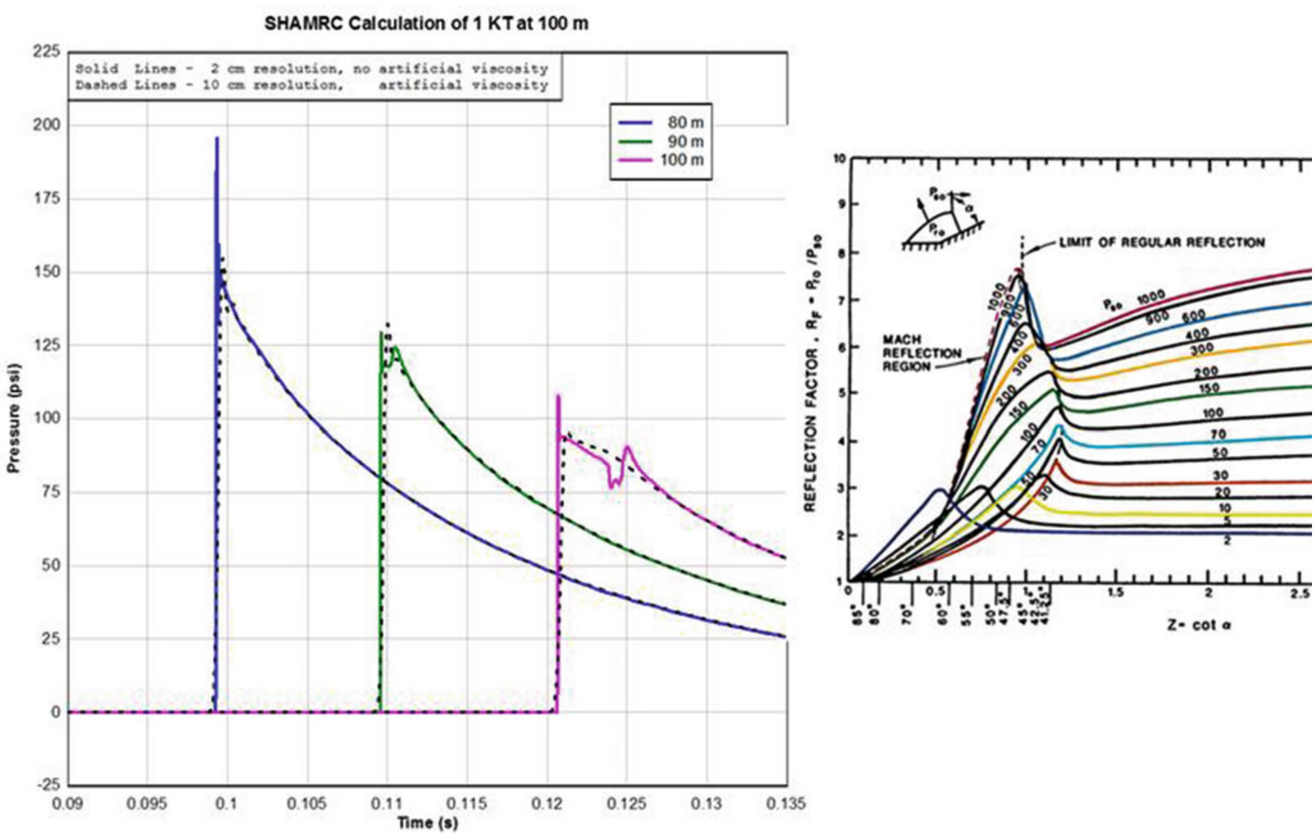


Fig. 9 Nuclear calculation reflection factor resolution example

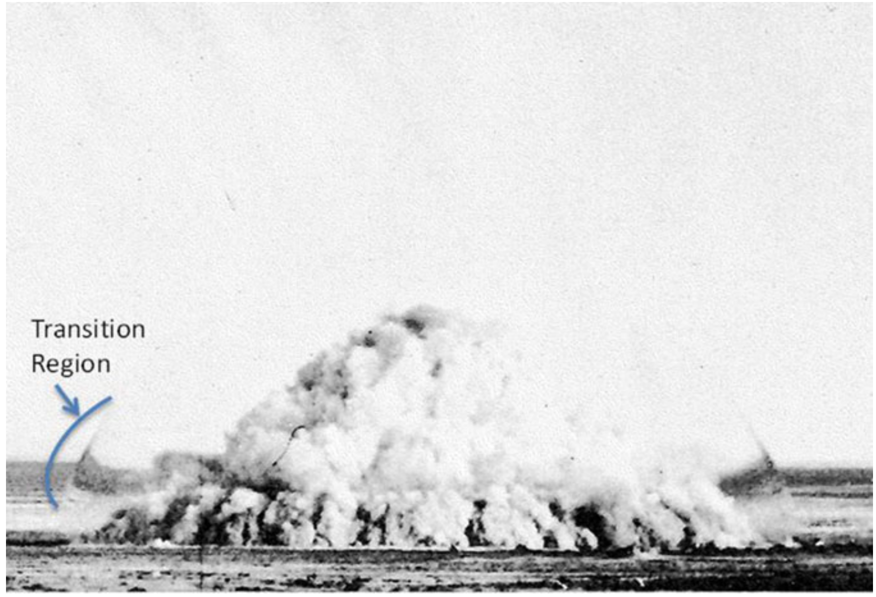


Fig. 10 628 ton event showing shock geometry

time to a peak. With 2 cm resolution (25 times the number of zones in 2-D), the second peak is resolved and can be distinguished from the shock front. Keep in mind that the second peak is not a shock, but a sharp compressive wave resulting from the two-dimensional character of the flow behind the shock reflection. Because the peak pressure is the result of a compressive wave, the Rankine-Hugoniot relations may not apply.

Note that the waveform at 90 m, calculated with 10 cm zoning, is higher than either peak in the resolved 2 cm calculation. Because the 10 cm zoning cannot separate the two signals, they are combined into a single peak with a slightly higher pressure.

A Shock from Cylindrical Source Will Become Spherical at a "Few" L/D

A large-scale experiment included the detonation of 628 tons of AN/FO in the shape of a cylinder with a 4.55 m radius with a hemispherical cap. The cylindrical part of the charge had a height to diameter ratio of 0.75. The charge was detonated at seven equally spaced points on the axis of the cylindrical part of the charge, the highest detonator at the top of the cylinder corresponding to the center of the base of the hemisphere. The assumption was made that at a distance of over 1 km, where the overpressure would be ~1 PSI, the shock would be hemispherical and uniform. The Army wanted to test a helicopter in flight at about this distance and pressure level.

The air blast from the hemispherical part of the charge expands in three dimensions. The air blast from the cylindrical portion expands in only two dimensions, but the shock front must remain continuous. This results in an inflection point in the curvature of the shock front which is induced by the geometrically different flow fields above and below the inflection point. At early times, the difference is dominated by the geometry (spherical vs. cylindrical), Fig. 10. As the shock expands and decays, the pressure gradients parallel to the shock front become small, and energy cannot be moved fast enough to change the shape of the shock front. Thus, even at distances of over 1 km, the shock front is not hemispherical and the pressure at the shock front is not uniform. There are also slip lines that form between the spherically and cylindrically expanding waves. The flow behind the shock in the transition region is complex.

A Shock Will "Clean Up" Within ~4 Diameters of an Obstacle

A widely used rule of thumb for shocks encountering obstacles is that the interrupted shock will heal within about four obstacle diameters. This rule may apply for many applications but is certainly not universally true. Figure 11 is taken from a three-dimensional calculation of a nonideal blast wave interacting with two parallel buildings. The dynamic pressure was higher than for an ideal wave of the same overpressure. The shock front does not "clean up" for over 700 m beyond the buildings. In that distance, the shock pressure has dropped by nearly a factor of 3. We have observed such large shock-healing distances in many experiments. In most cases the shock is prevented from healing because the dynamic pressure exceeds the overpressure, and the overpressure driving forces are insufficient to overcome the momentum of the redirected flow.

Exit Jet Environment

Exit jets from shock tubes cannot be used to generate blast waves simulating those from free field detonations. The shock emanating from the end of a shock tube is nonuniform. The planar shock in the tube suddenly expands in three dimensions. The shock expanding radially has a significantly lower pressure than the portion of the shock near the axis. A strong dynamic pressure jet extends from the end of the tube with little expansion. A strong vortex forms at the edge of the tube.

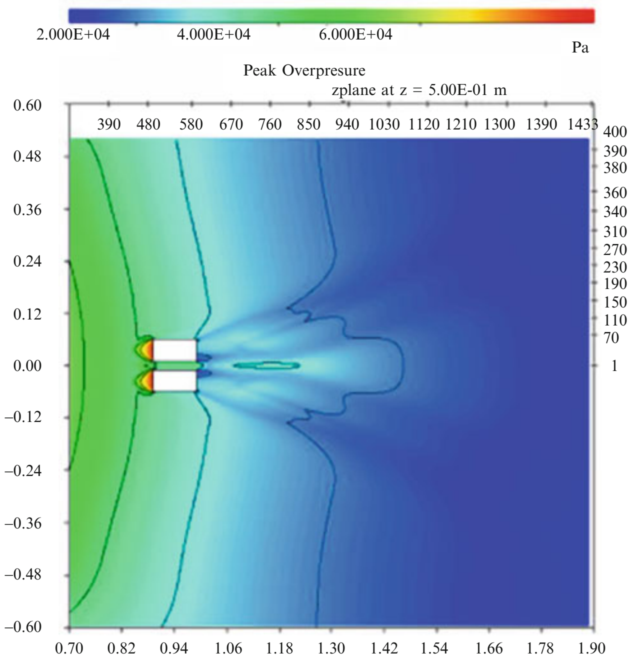


Fig. 11 0.5 bar nonideal blast wave interaction with two parallel structures

Figure 12 is a time sequence showing development of a shock-tube end-jet (efflux gas artificially colored). (A) The muzzle-blast shock front rapidly diffracts, weakens, and separates from the plume. (B) Ring vortex develops and separates from the lip of the tube end and is swept along with the venting column of shock-tube gases. (C) The venting jet of high-speed shock-tube gases has extreme dynamic pressure and long duration having an entirely different time waveform than the static pressure condition.

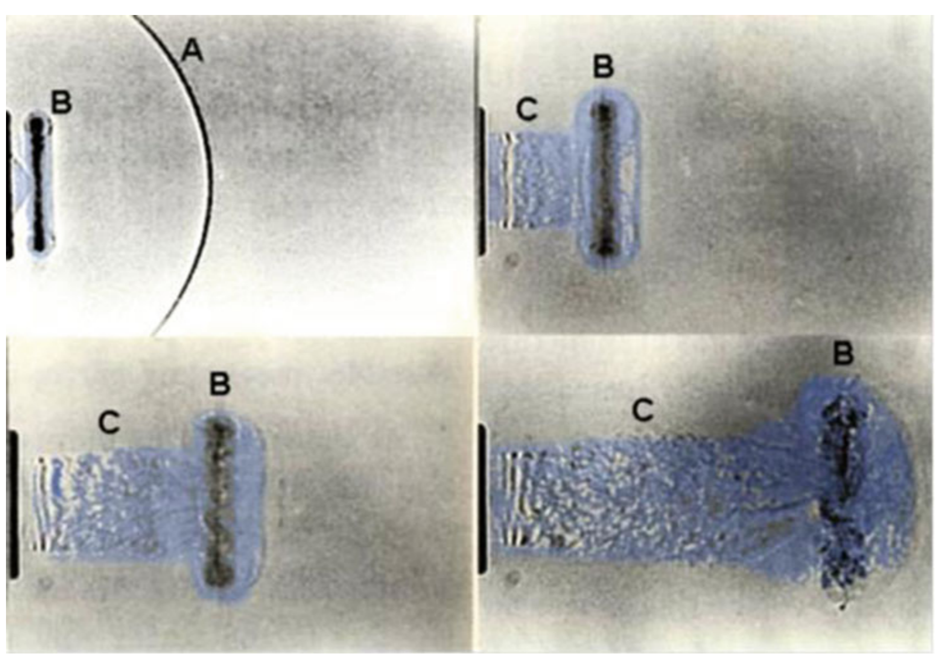
Because there is a sudden expansion of the shock at the end of the shock tube, rarefaction waves move into the flow from the edge of the tube. This introduces significant nonuniformities to the flow and reduces the useful area in which experiments can be made. To show the variation of the dynamic pressure impulse as a function of position in the exit jet, we include Fig. 13. This figure shows the dynamic pressure impulse in the exit jet in only the inner ½ of the diameter of the tube. The upper figure has the lateral dimension exaggerated by a factor of 5. The lower figure shows the true geometric relation of the dynamic impulse in the core of the jet. The large nonuniformities in the jet make it very difficult to use as a blast simulator.

Shock-Tube Blockage

Similarly, studies of blast-induced drag give the following equation:

$$Q_b = Q_0\left(\exp\left(2.64{*}R^{1.038}\right)\right)$$

Fig. 12 Time sequence of exit jet formation. Pictures courtesy of Dr. K Kontis, C. Eng., Lecturer in Aerodynamics, University of Manchester



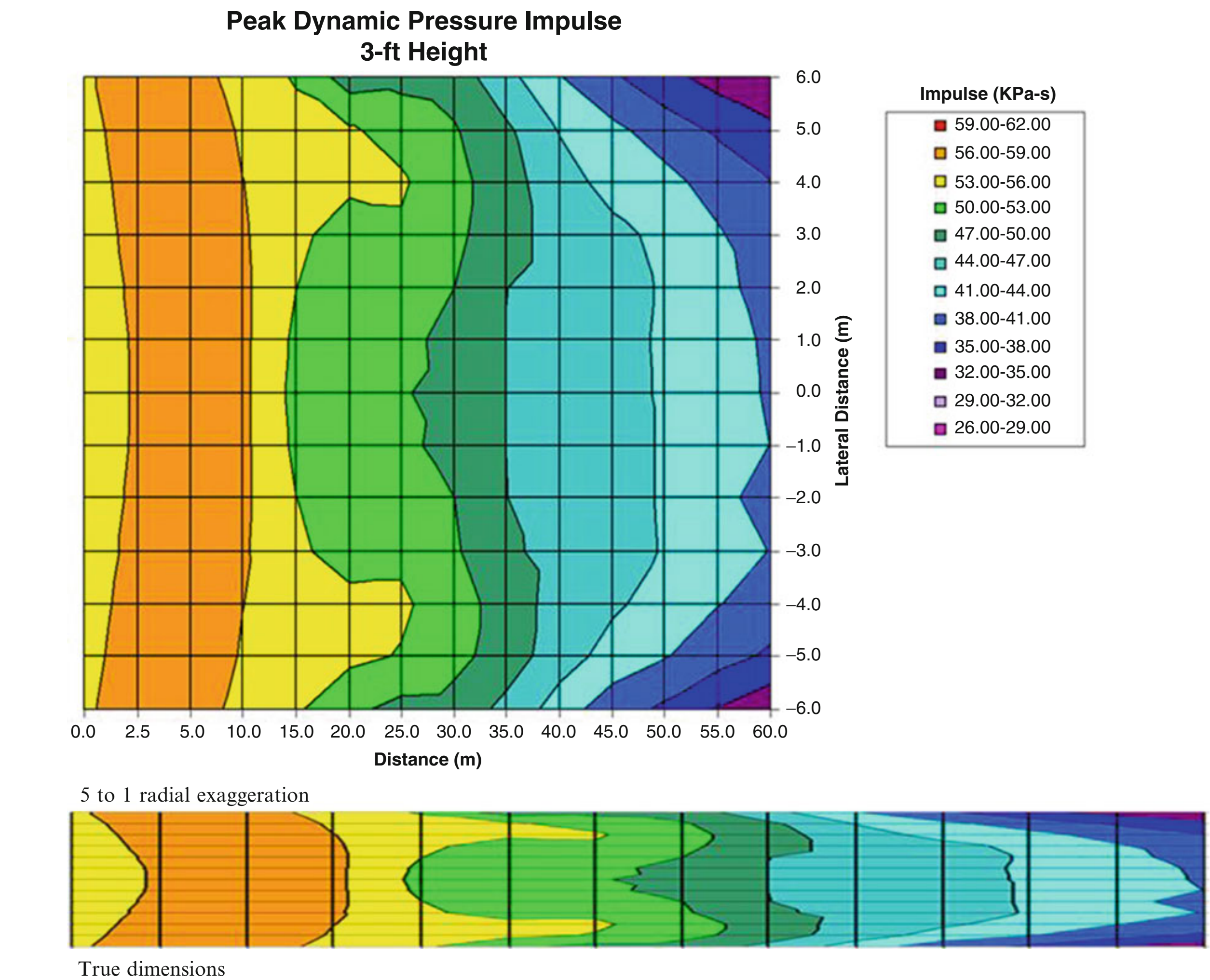


Fig. 13 Dynamic pressure impulse calculated over the center 50 % of the tube diameter at a height of 5 % of the tube diameter; measured from the open end of the tube

where Q_b is the dynamic pressure in the partially blocked tube, Q_0 is the dynamic pressure with no blockage, and R is the blockage ratio (the cross-sectional area of the target divided by the cross-sectional area of the shock-tube test section).

Evaluating this equation at 10 % blockage, the dynamic pressure (and the drag load) is increased by 27 % over the empty tube value. At 20 % blockage, the dynamic pressure is increased by 64 % and at 30 % it is increased by 113 %. This has been known and published for over 30 years, yet experiments continue to be conducted in shock tubes that are much too small for the test subjects.

Upward Force

When we think of air blast effects on buildings, we usually think about crushing and collapse. Buildings are constructed to withstand vertical gravitational loads. Construction techniques provide for large static loads and, to a lesser extent, for dynamic loads. In one test a detonation took place at ground level a few meters in front of a four-story building. The building was constructed of reinforced concrete and a static load was placed on the floors. The load was representative of an occupied office building.

The calculations of the air blast loads indicated that the initial loads on all upper floors were initially upward (Fig. 14). The blast wave came through the windows on the floor below and generated an upward force. The construction was not designed to resist upward motion and the floors were displaced upward. The shock wave then came through the windows on the floor above and drove the floor downward. This downward acceleration generated much higher dynamic loads than the structure was designed for, and the front wall connections failed.

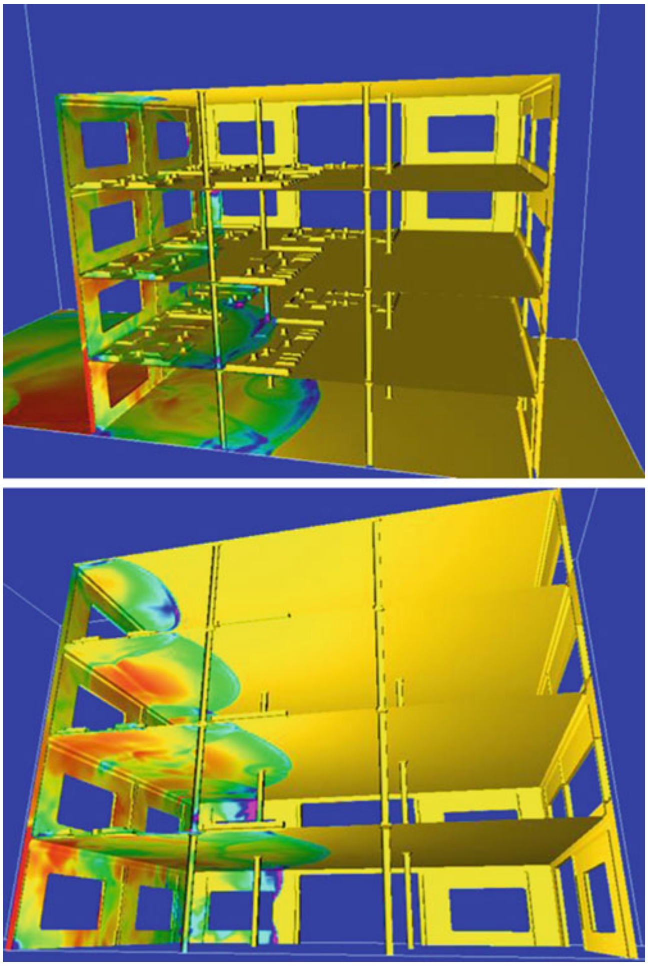


Fig. 14 Internal pressure loads on a four-story office building

Pacific vs. NTS

While validating the nuclear blast standard, I encountered arguments that data from some test or series of tests showed that the standard was high or low depending on the specific test cited. Nearly all of the discrepancies were found below an overpressure level of 1 bar or 100 kPa. Further investigation showed that much of the Nevada Test Site data fell above the standard curve. Reluctantly I adjusted the curve upward to agree with the NTS data. I then started comparing the revised curve with the Pacific Proving Ground test data and found that the standard was consistently higher than the PPG data (Fig. 15). After a few years of discussions, we decided that "standard" should represent all of the data. All of the data shows large scatter for overpressures below about 0.1 bar (10 kPa), and because the standard was well above the Pacific data, we decided that the original standard was a better representation of all the data.

The question remained: Why was the PPG data well below the NTS data? While most of the shots in the PPG were in the megaton range, I found that the data from PPG shots with yields below 100 kt agreed well with the NTS

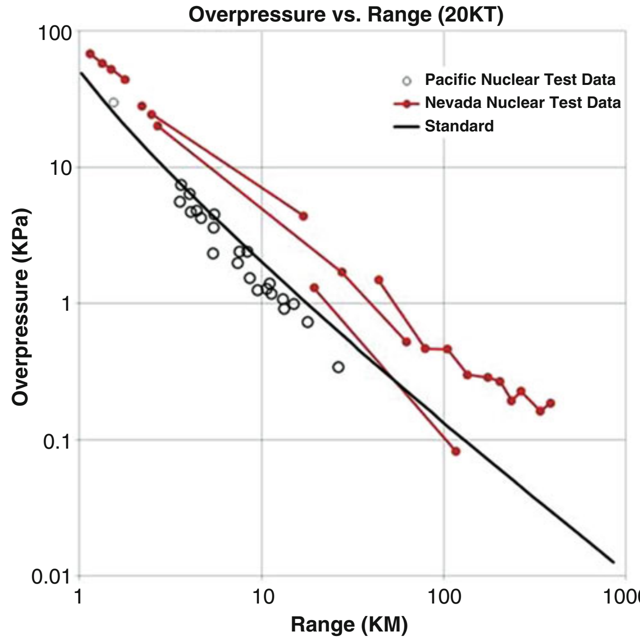


Fig. 15 Overpressure as a function of scaled range for pressures below 1 bar

data. A few high-resolution calculations were made to investigate this dramatic difference in low overpressure propagation. The calculations revealed that when the radius of the shock front at an overpressure of 0.1 bar is approximately the scale height of the atmosphere (~9 km) or greater, more energy is directed upward, thus reducing the energy and pressure propagating in the horizontal direction.

Perhaps the discussion about the scatter in the data at low overpressures is illustrated by the comparisons shown in Fig. 16. Below a tenth of a bar, the air blast data has a scatter of more than an order of magnitude. Much of the scatter is explained by tracing the path of the shocks through the atmosphere. The effects of the troposphere, ozonosphere, and ionosphere are plotted separately.

Note that at the pressure level associated with threshold window damage, there is about an order of magnitude scatter in the range at which it may be measured. This scatter is caused by differences in the structure of the atmosphere at the time of the shot. Remember that the NTS shots were all conducted with fair weather and relatively calm winds. Departures from "good" weather will cause even greater scatter.

The 1 Kt standard was criticized for "not matching the data." It is difficult to match the data when there is an order of magnitude scatter. This scatter is real and is caused by variations in the real atmosphere.

Jeep Translation

During the NTS nuclear tests, a number of vehicles were exposed to nuclear air blast at different levels to determine the correlation of damage with pressure level. In compiling the data, it was noted that vehicle displacement correlated well with dynamic pressure impulse. Many more jeeps were tested than any other type of vehicle, and jeep displacement was plotted as a function of dynamic pressure impulse. The correlation was so good that during some later tests, the dynamic impulse was quoted in jeep feet. Figure 17 is a plot of the jeep displacement in feet as a function of dynamic pressure impulse.

Similar curves can be plotted for other types of vehicles, and the damage thresholds for these vehicles are shown at the top of the plot.

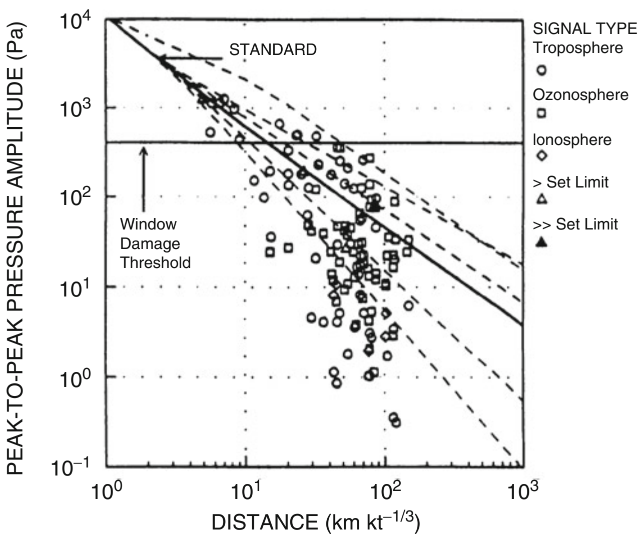


Fig. 16 Peak-to-peak pressure plot from the first six shots of Operation Teapot

Summary

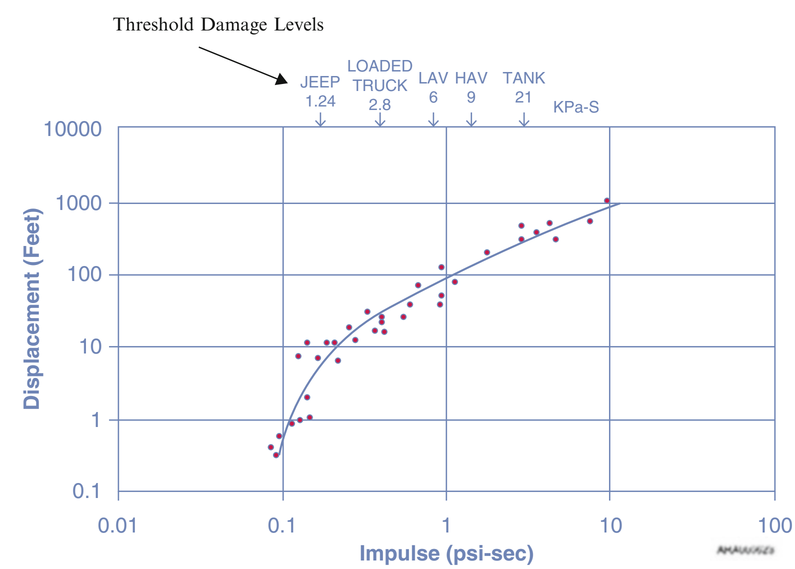
In all the above examples, the shock wave was reflected, and the "responding" material effect on the blast wave was insignificantly different from that of a non-responding material. In all cases the shock wave reflected as if the structure was non-responding. This justifies and simplifies calculations of shock interactions with structures with the assumption that the structures are rigid and non-responding.

The debris velocity of the structures reached a maximum of less than half of the material velocity behind the shock. The debris remains well behind the shock front because the shock velocity is greater than the material velocity at the shock front by the speed of sound. As the velocity of the air behind the shock slows and reverses, the debris falls to the ground or reverses direction and may fall closer to the detonation point than its original location.

With the possible exception of a few buildings that may be in or very near the fireball, urban structures absorb little energy from the blast wave. The debris is almost always at least 1000 times denser than the air in the blast wave. The air responds 1000 times faster than the solid material. The kinetic energy of the debris is therefore much less than 1 % of the air blast energy. The debris from these structures generally falls within about four times the building height.

Many years ago Hal Brode advised me to "not do hydro in your head." The above are several examples of why this is good advice for everyone. Most of the misconceptions about air blast waves and their interactions with structures are caused by a lack of understanding of the differences between overpressure and dynamic pressure. Further we must keep in mind that most solid materials, whether wood or steel, are at least 1000 times more dense than air and will therefore move one thousandth as fast as the air blast that loads them.

Fig. 17 Jeep displacement as a function of dynamic pressure impulse



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