A REVIEW OF BLAST PHENOMENON

An explosion is the result of a very rapid release of large amount of energy within a limited space and time. The sources of such an action can be different and based on this, the blast event is categorized. With respect to the location of the blast, it is classified as internal or external blast. When it occurs below the ground, it is termed as underground blast and the one above the ground is called air blast. The process by which the blast is created is used to identify whether the explosion is nuclear, chemical or gaseous. The different types of blast are discussed below.

2.1 EXTERNAL BLAST

When the source is outside the structure, the phenomenon is called an external blast. The outer components of the structure gets loaded initially and transmit the shock to the internal elements. External blast is further classified as underground blast and air blast.

2.1.1 Underground blast

Quarry and mining blast wherein the explosive charge is located in a bore hole below ground belong to this category of loading. The explosion is confined inside a small area of a shallow bore hole, thus producing very high pressures resulting in:

1. the propagation of stress waves fracturing the medium of confinement, and

2. the generation of gases at high temperature and pressure.
These gases expand to fill any interstices that may pre-exist or that may be produced by the stress waves, and in so doing they breakup the confining medium. Continuing expansion of the gases serves to dislodge and move the broken fragments away from the seat of explosion. The major obstacle in the study of the process of fracture during actual expansion is the lack of ability to monitor the effects of reactions which changes quite rapidly. Complete understanding of the process of fracture and fragmentation is still a debatable one as there is no accepted theory of blast for solids that fully explains all the observed phenomena. However, the experience and intuition of the engineers have achieved a certain degree of confidence which serves as a basis for design calculations.

2.1.1.1 Stress waves

The detonation of an explosive generates forces that impact upon any confining medium that surrounds the blast. This impact produces stress waves which propagate outwards in all directions through the confining medium. If the explosion pressure exceeds the strength of the confining solid, a zone immediately surrounding the explosive charge may be pulverized. In conventional blasting using industrial explosives, the pulverized zone is likely to be small. Surrounding it, there is a transition zone in which nonlinear phenomenon of passage of shock waves, occurrence of plastic flow and generation of radial cracks occur. At very high pressures, shock waves are produced affecting the compressibility of the medium and making it behave hydrodynamically. Large strains are produced which lead to the nonlinear material behaviour of the medium. Immediately surrounding the crushed and transition zones of the subsurface blast, tangential stresses are produced as the dilatational stress wave expands outwards in the confining medium. The expanding stress wave is compressional in the radial direction and its amplitude is generally less than the compressive strength of the medium. But the tensile strength of the medium being much smaller than the compressive strength, the circumferential or hoop stresses cause radial cracks. The tangential stresses attenuate with distance until they reach a value below the tensile strength of the medium. Beyond this zone, they will pass through the medium without causing further fracture if they do not
interact with the reflected stress waves in the elastic zone.

2.1.1.2 Ground particle velocity

It is observed that the peak ground particle velocity produced by an underground blast in the medium at the site of the structure, represents a good general index of damage. This parameter is independent of the frequency of wave propagation and it can be adopted for specifying the safety criteria against threshold damage. The ground particle velocity at any point mainly depend on the amount of charge exploded, distance between the shock front and the station of observation and the local geological characteristics of the medium. The other less important factors are the nature of explosive used, its coupling state with the surrounding medium and structural properties of the medium.

The value of ground particle velocity is computed using the following expression given in Indian Standard Specification, IS:6922-1973.[7]

\[ v = K \left( \frac{Q}{R} \right) \]  

\[ \text{where} \quad v = \text{ground particle velocity in mm/sec.}, \]

\[ K = \text{constant,} \]

\[ = 800 \quad \text{for soils, whethered or soft rock and} \]

\[ = 1400 \quad \text{for hard rock,} \]

\[ Q = \text{charge per delay in kg} \]

\[ R = \text{distance from blast point in metres.} \]

Taking into account the threshold of human perception and the vibrations intolerable to human beings, the safe values for ground particle velocity are stipulated in the code as shown in Table 2.1.
Table 2.1 SAFE VALUES FOR GROUND PARTICLE VELOCITY [7]

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Ground particle velocity (mm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>By equation (2.1)</td>
</tr>
<tr>
<td>For soils, whethered</td>
<td>50</td>
</tr>
<tr>
<td>or soft rock</td>
<td></td>
</tr>
<tr>
<td>For hard rock</td>
<td>70</td>
</tr>
</tbody>
</table>

When it is desired to design structures for seismic effects of the blast, the following equation is recommended for finding the design acceleration in the horizontal direction.

\[
a / g = K Q / R \tag{2.2}
\]

where

- \(a\) = design acceleration in cm/sec
- \(g\) = gravitational acceleration in cm/sec,
- \(K\) = constant,
- \(K = 4\) for soils, whethered or soft rock
- \(K = 6\) for hard rock,
- \(Q\) = charge per delay in kg.
- \(R\) = distance of structure from blast point in metres.

2.1.2 Air blast

Any explosion which occurs above ground drives an air blast wave into the surrounding atmosphere. This wave can interact with and load the nearby structures or other mobile targets such as vehicles, humans etc. The blast wave is often the primary source of damage and it is all pervasive interacting with everything in its path. The wave causes a 'boom' which can be heard at far away places. It is necessary to have the
complete information for this type of blast wave to satisfactorily understand its effects.

2.1.2.1 Blast wave propagation

During the explosion, a chemical reaction takes place which leads to a sudden rise of temperature and pressure within the surrounding air thus creating an outward moving pressure pulse as shown in Figure 2.1. Parts of this outspreading pressure field which are close to the explosion centre, move faster due to higher temperature and pressure than parts farther away. This causes the pressure wave to become steeper and steeper resulting finally with a fast travelling shock front, called explosion if subsonic and detonation if supersonic. The shock front which presents a rapidly expanding spherical surface, moves outwardly from the point of explosion. This is called as initial shock front. As the shock front moves forward, the peak side-on pressure decreases (Figure 2.2). The pressure behind the front does not remain constant but instead falls off in a regular manner. After a short time, at a certain distance from the centre of explosion, the pressure behind the shock front becomes smaller than that of the surrounding atmosphere and a negative phase or 'suction' develops. The front of the blast wave weakens as it progresses outward and its velocity drops to that of the velocity of sound in the undisturbed atmosphere.

As the initial shock front reaches the ground surface, a reflected shock front develops as shown in Figure 2.3. The geometric relationship between centre of explosion, shock front and the structure are also shown in this diagram. The reflected shock front adds to the intensity of the initial shock front, as the two wave fronts move further and get fused together near the ground as one shock front as shown in Figure 2.4. This merged shock front is approximately vertical and sweeps over the surrounding area with an intensity corresponding to a bomb of twice the yield of the actual one. This intensity of pressure depends on the ground zero distance, height of burst and bomb yield.
FIG. 2.1 DEVELOPMENT OF A SHOCK FRONT

FIG. 2.2 PRESSURE PHASES OF SHOCK FRONT
FIG. 2.3. GEOMETRIC RELATIONSHIP BETWEEN CENTRE OF EXPLOSION, SHOCK FRONT & STRUCTURE
FIG. 2.4. FORMATION OF A FUSED SHOCK FRONT

TOWARDS CENTRE OF EXPLOSION

INITIAL SHOCK FRONT

FUSED SHOCK FRONT

BLAST MOVEMENT
2.1.2.2 Pressure field

At any location in the vicinity of blast, the variation of pressure with respect to time is shown in Figure 2.5. Prior to a shock front arrival, the pressure is ambient pressure $p_a$. At arrival time $t_a$, the pressure rises quite abruptly to a peak value $p_a + p_s^+$. The pressure then decays to ambient condition in time $t_d^+ + t_d^-$, drops to a potential vacuum of amplitude $p_s^-$ and eventually returns to ambient pressure $p_a$ in a total time of $t_a + t_d^+ + t_d^-$. Dynamic pressure is the pressure developed by the strong blast wind created by the explosion. This is proportional to the square of the wind velocity and the density of air behind the shock front.

$$p_d = \frac{1}{2} \rho v^2 \quad \ldots (2.3)$$

where
- $p_d$ = dynamic pressure,
- $\rho$ = density of air,
- $v$ = velocity of blast wind.

Variation of overpressure with time $t$ is given by

$$p_s = p_s^+ (1 - t / t^+) e^{-t/t^+} \quad \ldots (2.4)$$

where
- $p_s$ = overpressure at any time $t$,
- $p_s^+$ = peak overpressure,
- $t^+$ = time at the end of positive phase,
- $e = 2.7182$

Similarly the variation of dynamic pressure with time is given by

$$p_d = p_d^+ (1 - t / t^+) e^{-2t/t^+} \quad \ldots (2.5)$$

where
- $p_d$ = dynamic pressure at any time $t$. 
FIG. 2.5. VARIATION OF BLAST PRESSURE WITH TIME
The velocity of the shock front depends on the peak overpressure and its relationship is given by

$$u_o = u_s \left(1 + \frac{6 p_{\text{so}}}{7 p_o}\right)^{1/2}$$ \hspace{1cm} \ldots (2.6)

where

- $u_o$ = velocity of shock front,
- $u_s$ = velocity of sound
- $p_{\text{so}}$ = peak overpressure and
- $p_o$ = atmospheric pressure.

### 2.1.2.3 Blast wave scaling

Scaling of the properties of blast waves from explosive sources is a common practice and it is utilized to predict the properties of blast waves from large scale explosions based on small scale tests. Similarly, the results of tests conducted at sea level and ambient atmospheric conditions are normally used to predict the properties of blast waves due to explosions occurring at high altitude conditions.

The most common form of blast wave scaling is 'Hopkinson-Cranz' or 'Cube root' scaling. This law states that similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive, but of different sizes are detonated in the same atmosphere. A dimensional parameter $Z$ is defined as the scaled distance and is calculated as

$$Z = \frac{R}{E^{1/3}}$$ \hspace{1cm} \ldots (2.7)

or

$$Z = \frac{R}{W^{1/3}}$$ \hspace{1cm} \ldots (2.8)

where $R$ is the distance from the centre of explosive source, $E$ is the
total heat of detonation of the explosive and \( W \) is the total weight of a standard explosive such as TNT. Figure 2.6 shows schematically the implications of Hopkinson-Cranz blast wave scaling. An observer located at a distance \( R \) from the centre of an explosive source of characteristic dimension \( d \), will be subjected to a blast wave with amplitude \( p \), duration \( t \) and a characteristic time history. The integral of the pressure-time history is the impulse \( i \). The Hopkinson-Cranz scaling law then states that an observer stationed at a distance \( \lambda R \) from the centre of a similar explosive source of characteristic dimension \( \lambda d \), detonated in the same atmosphere will feel a blast wave of similar form with amplitude \( p \), duration \( \lambda t \) and impulse \( \lambda i \). All characteristic times are scaled by the same factor as the length scale factor \( \lambda \). In Hopkinson-Cranz scaling, pressures, temperatures, densities and velocities are unchanged at homologous times. Hopkinson's scaling law has been verified by many experiments conducted over a large range of explosive charge energies [5].

The blast scaling law which is universally used to predict characteristics of blast waves from explosions at high altitudes is that due to Sachs. Sachs' law states that dimensionless overpressure and dimensionless impulse can be expressed as unique functions of a dimensionless scaled distance, where the dimensionless parameters include quantities which define the ambient atmospheric conditions prior to the explosion. Sachs' scaled pressure is given by

\[
\tilde{p} = \frac{p}{p_0}
\]

Sachs' scaled impulse is defined as

\[
\tilde{i} = \frac{i}{u_o} \left( \frac{p_0}{E} \right)^{1/3}
\]

where \( u_o = \) ambient sound velocity.

These quantities are functions of a scaled distance defined as

\[
\tilde{R} = R \left( \frac{p_0}{E} \right)^{1/3}
\]

Both the above scaling laws apply to reflected wave parameters...
FIG. 2.6. HOPKINSON-CRANZ BLAST WAVE SCALING
2.1.2.4 Blast wave loading

When the advancing shock front due to a blast strikes a structure, there is a diffraction effect producing forces which result from higher overpressures due to the reflection of the wave on the front face of the object and also from the time lag before the overpressure acts on the rear face. At the same time, the air behind the shock front is moving outward with a high velocity and this blast wind produces drag forces on any object encountered. Thus the total loading on any structure due to blast consists of three parts:

1. Initial diffraction effect
2. Effects of general overpressure
3. The drag loading due to dynamic pressure

Structures below the ground are subjected to the effects of the overpressure and to ground transmitted shock but obviously not to the diffraction and drag effects. From the point of view of predominant type of blast loading, structures can be classified into two distinct categories.

a. Diffraction structures: These are closed structures without any openings. These structures are subjected to both the shock wave overpressure and the dynamic pressure due to blast wind.

b. Drag structures: These are open structures composed of elements like beams, columns, trusses etc. which will have small projected area opposing the shock wave. These are mainly subjected to dynamic pressures.

Closed rectangular structures:

When the shock front strikes the solid front face of the structure, there is an instantaneous increase in pressure above that of the shock front itself. This is in part due to the formation of a reflected wave which has the effect of doubling the overpressure in addition to the sudden onslaught of dynamic pressures. This value of the
Instantaneous pressure is given by

\[ P = P_o \left( 2 + \frac{6 p_{so}}{p_{so} + 7 p_o} \right) \]  \hspace{1cm} \text{(2.12)}

where

- \( P_o \) = peak reflected overpressure,
- \( p_{so} \) = peak side-on overpressure,
- \( p_o \) = ambient atmospheric pressure.

Within a short time called clearance time, the reflected shock wave disintegrates and reduces the overpressure existing on the front face to a value which is in equilibrium with the high velocity air stream associated with the incident shock wave. The complete pressure time variation for the front face is as shown in Figure 2.7(a) and Figure 2.7(b). The clearance time \( t_c \) is given by the relation

\[ t_c = \frac{3 S}{U} \]  \hspace{1cm} \text{(2.13)}

where

- \( S \) = clearance height, taken as either half the width or the full height of front face whichever is smaller and
- \( U \) = velocity of blast wind.

After the clearance time, the pressure on the surface is the overpressure plus the drag pressure both of which decay subsequently. During this decay period the maximum pressure on the front face is given by

\[ p = p_{so} + C_d q_o \]  \hspace{1cm} \text{(2.14)}

where \( C_d \) is the drag coefficient.

The overpressure on the front face of a structure is not uniformly distributed. The maximum value occurs at the midpoint of the base and the minimum value occurs at the edges. Those portions of the front face nearest to the edges are cleared or relieved of the reflection.
FIG. 2.7 BLAST LOADING ON FRONT FACE

\[ P_{so} + C_d q_0 \]

\[ t_c < t_d \]

\[ P_{ro} \]

\[ t_c > t_d \]

\[ C_d = -0.2 \text{ to } 0.4 \]

\[ q_0 = 0 \text{ to } 9.0 \]

FIG. 2.8 BLAST LOADING ON REAR FACE
effects in a shorter time than the remainder of the front face. The overpressure existing at points nearer to edges is lower following the clearing stage. However, the net effect of this vertical and horizontal variation has no value for design purposes as it is smaller than the uniform pressure. Hence the front wall loading is assumed to be distributed uniformly over the front wall surface.

The average overpressure curve for the rear face is as shown in Figure 2.8. For the rear face, the time displacement factor, i.e. transit time $t_t$ is given by

$$t_t = \frac{L}{U} \quad \ldots(2.15)$$

where $L$ is the length of the building in the direction of the propagation of the shock and $U$, the velocity as defined earlier.

When the shock front crosses the rear edge of the structure, the foot of the shock spills down the back wall. The overpressures on the back wall behind this differential wave are considerably less than those due to incident blast wave because of the vortex which develops at the top and travels down the wall. A period of time larger than that required for the passage of this diffracted wave to the bottom of the wall, must pass before the back wall average overpressure reaches its peak value. This time, called pressure rise time, $t_p$, measured from the instant at which the shock wave reaches the back wall, is given by

$$t_p = \frac{4S}{U} \quad \ldots(2.16)$$

The variation of the pressure on the roof and sides of a closed rectangular structure is complicated due to vortex formation along the edges. The local overpressure on the roof and side walls varies in the direction parallel to the shock front. Although this lateral variation is a smooth one, the roof has been divided into three zones of different pressure time histories. However for design purposes, the average pressure time curve for this case is shown in Figure 2.9(a), for the
FIG. 2.9. BLAST LOADING ON ROOF AND SIDE WALLS
transit time \( t_t = \frac{L}{U} \) being less than \( t_d \). When \( t_t \) is greater than \( t_d \), the load on the roof and the side walls are considered as a moving triangular pulse as shown in Figure 2.9(b).

2.2 INTERNAL BLAST

The Ronan Point incident in 1968 which resulted in an extensive damage in a 22 storey block of flats in East London following an internal gas explosion, drew attention to a new possible hazard to the safety of structures. This led to detailed analytical and experimental investigations in the field of internal blast in buildings and subsequent development in design procedures.

2.2.1 Sources of internal blast

The main sources of internal blast are as follows:

1. The detonation of high explosives, which may enter the building as the result of aerial bombing or shelling or planted by saboteurs.

2. The accidental ignition of mixtures of flammable gases and air produced by industrial process.

3. The accidental ignition of mixtures of flammable gases and air produced by leakages from pipelines.

4. Accidental explosion in a containment structure.

2.2.2 Characteristics of internal blast

The internal blast is characterized mainly by the source of blast, high explosive or gaseous, and by the effect of venting in the structure. The detonation of high explosives, being independent of atmospheric oxygen, is a very rapid process that leads to a very large and instantaneous rise in pressure at the point of detonation and a shock front moving outward rapidly. The loading from detonation within a vented or unvented structure consists of two distinct phases. The first phase is the reflected blast loading and a second one is a quasi-static pressure pulse.
2.2.2.1 Reflected blast loading

The reflected blast loading phase of initial and reflected shock consists of the effects of initial high pressure short duration reflection wave and perhaps several later reflected pulses arriving at times closely approximated by twice the average time of arrival at the chamber walls. These later pulses are usually attenuated in amplitude because of an irreversible thermodynamic process and they are irregular in waveform because of the complexities of the reflection process within the structure whether vented or unvented. The simplest case of blast wave reflection is that of normal reflection of a plane shock wave from a rigid plane surface. In this case the incident wave moves at a velocity $U$ through still air at ambient conditions. The conditions immediately behind the shock front are similar to those for the free air shock wave. When the incident shock wave strikes the plane rigid surface, it is reflected by it. The reflected wave now moves away from the surface with a velocity $U_r$ into the flow field and the compressed region associated with the incident wave. In the reflection process, the incident particle velocity $U_s$ is arrested and the pressure, density and temperature of the reflected wave are all increased above the values in the incident wave. The overpressure at the wall surface is termed as the normally reflected overpressure and is designated as $p_r$.

Following initial shock wave reflections from the walls, the internal blast pressure loading can become quite complex in nature. Figure 2.10 shows a stage in the loading for a cylindrical vented structure [5]. At the instant shown, portions of the cap, base and cylindrical surface are loaded by the reflected shock and the incident shock is reflecting from all three internal surfaces. Following the initial internal blast loading, the shock waves reflected inward will usually strengthen as they implode toward the centre of the structure and rereflect to load the structure again. The second shocks will usually be attenuated and after several such reflections, the shock wave phase of the loading will be over.
FIG. 2.10 SCHEMATIC REPRESENTATION OF SHOCK REFLECTIONS FROM INTERIOR WALLS OF CYLINDRICAL CONTAINMENT STRUCTURE
Simplified load predictions can be made rather easily from scaled blast data for reflected waves and based on several approximate equations. The first approximation is to assume that the incident and reflected blast pulses are triangular with abrupt rises. i.e.

\[ p_s(t) = p_s(1-t/T_s), \quad 0 \leq t \leq T_s, \quad \ldots(2.17) \]

\[ p_s(t) = 0, \quad t > T_s, \quad \ldots(2.18) \]

\[ p_r(t) = p_r(1-t/T_r), \quad 0 \leq t \leq T_r, \quad \ldots(2.19) \]

\[ p_r(t) = 0, \quad t > T_r. \quad \ldots(2.20) \]

The duration of these pulses are not the same as the actual blast wave duration \( T \), but instead are adjusted to preserve the proper impulses.

\[ T_s = 2 I_s / p_s \quad \ldots(2.21) \]

\[ T_r = 2 I_r / p_r \quad \ldots(2.22) \]

These two equations constitute the second approximation. The third approximation is that the initial internal blast loading parameters are the normally reflected parameters even for the oblique reflections from the walls of the structure, provided the slant range is used as the distance \( R \) from the charge centre to the location on the wall. This is almost true up to the angle of regular reflection of 39 degrees for strong shock and up to 70 degrees for weak waves.

In enclosed structures, shock waves reflect and rereflect several times. Generally they are attenuated considerably before again striking the walls, floor or ceiling (Figure 2.11). For a centrally located detonation, it can be assumed that the second shock has half the amplitude and impulse of the initial reflected shock, the third shock has half the amplitude of the second shock and that all later reflections are insignificant. The later two reflected pulses are often ignored in estimating the internal blast loading because the pressures and impulses are much lower than the initial pulse. Because of the combined loads from all three pulses are only 1.75 times those from the initial pulse, a
FIG. 2.11. REJECTED PRESSURES IN INTERNAL BLAST
design simplification can be employed for structures with response time much longer than the longest time of the three pulses in Figure 2.11. This simplification is to combine all three pulses and multiply the amplitudes by 1.75. For vented or unvented structures with response times much shorter than the initial shock wave duration, a simplification can be made by considering only the initial pulse and ignoring the other two reflected pulses.

2.2.2.2 Quasi-static pressures

During an internal explosion, the amplitude of the reflected waves usually decay with each reflection and eventually the pressure settles to a slowly decaying level which is a function of the volume and vent area of the structure and the nature and the energy release of the explosion. A typical time history of pressure at the wall of a vented structure is shown in Figure 2.12. From the figure it can be seen that the maximum quasi-static pressure is quite difficult to define because it is obscured by the initial shock and first few reflected shocks. Obviously several reflections should occur before irreversible processes attenuate the shocks and convert their energy to quasi-static pressure. Hence it is appropriate to designate point B as the peak quasi-static pressure rather than point A because some time has been allowed for establishing the maximum pressure at point B. Another inherent problem is the accurate determination of the pressure loss due to venting. When the pressure traces approach ambient, the shock reflections would have largely decayed. But they approach the base line nearly asymptotically so that it is quite difficult to determine the time accurately.

Some actual recorded pressure pulses in experimental gas explosions in rooms are shown in Figure 2.13. A gaseous explosion is nearly always slow as compared with the one resulting from the detonation of a high explosive. This is because the inflammable mixture of gas and air is widely dispersed. To burn it all, the flame must travel a considerable distance from the point of ignition and it rarely does so at speeds exceeding 10 metres/sec. The slower rate of combustion results in a slower and uniform pressure rise over the entire surface exposed to
FIG. 2.12. TYPICAL TIME HISTORY OF INTERNAL PRESSURE AT INNER SURFACE OF A SUPPRESSIVE STRUCTURE
FIG. 2.13. PRESSURE PULSES RECORDED IN INTERNAL GAS EXPLOSIONS
blast. A further important consequence of the slow gaseous deflagration is that it leaves time for much of the flammable mixture to be expelled through the available vents before the flame reaches it. Such vents are usually provided by windows and similar light weight elements which are themselves expelled by initial pressure rise. This has the effect of greatly reducing the maximum pressure generated. In such a case the pressure may be assumed to rise to an initial peak in 0.1 sec. Before the peak is reached, the main vents would have been blown out and the expulsion of much of the unburnt gas would have reduced the rate of pressure rise considerably below that which otherwise would have occurred. Further expulsion of both burnt and unburnt gases will then lead to a slightly less rapid fall in pressure from the peak. If the combustion is still proceeding in the room and the area of venting is small, the pressure will probably rise again and may reach a second peak higher than the first. The whole pressure history will be over in about 0.3 sec. as indicated in Figure 2.13. Variations from these norms may result from differences in the size and shape of the room and differences in the speed of flame travel due to turbulence.