1. INTRODUCTION

A comprehensive assessment of the consequences of blast on a structure is a complex undertaking. This is partly so because it involves actions which are so far outside our normal experience. In most cases a blast is over and done with in a fraction of the time required for the blink of an eye and yet may involve loads that are orders of magnitude greater than the strength of most materials. Moreover, to comprehensively assess the ramifications of an explosive blast requires an appreciation of a variety of discipline areas that most of us are only vaguely aware of. For example,

- Blast Loading
    - Thermodynamics
    - Compressible gas dynamics
    - Equations of state
    - Blast loads on buildings
- Non-linear structural dynamics
    - Stress wave theory
    - High strain rate material behaviour
    - Fracture mechanics
    - Ballistic effects
- Structural Design Issues
    - Design philosophy for blast resistant structures
    - Detailing of structures
    - Blast mitigation
- Ground Shock
- Blast effects on humans

Only some of these will be addressed here – specifically,

- Blast Loading
    - High explosive blast (as distinct from gas explosions)
    - Blast loads on buildings
- Structural Design Issues
    - Blast mitigation
    - Design philosophy for blast resistant structures
- Ground Shock

Clearly a comprehensive assessment of the consequences of blast on a structure can be a complex undertaking.

2. BLAST CHARACTERISTICS

When a high explosive such as TNT is detonated a rapid decomposition of the condensed phase material occurs to release a gas at extremely high temperature and pressure behind the interface. Typically the pressure in the detonation wave is of the order of 20 GPa with the shock wave proceeding outwards at 7000 m/s (Zukas at al). The sudden release of a gas at high pressure results in an outward directed pressure wave in the air with an extremely steep pressure rise – so steep that an almost instantaneous rise in pressure to the peak can be assumed. Whilst this peak pressure decays rapidly with distance from the source and with time – it is not at all uncommon for a structure in the path of this pressure wave to be subjected to blasts with peak pressures of the order of hundreds if not thousands of kilopascal (kPa). Where the explosive is in intimate contact with the member then pressures of the order of 20 GPa are experienced by the element.

Whilst high explosive blast is invariably defined with respect to an idealised spherical charge (or hemispherical charge), in fact the precise details of the blast close in to the source also depends on such factors as the,

- explosive shape
- degree of confinement afforded the explosive.

In addition it is as well to recognise that although our standard engineering analyses are based on available charts and tables – such data is usually only readily available for one explosive i.e. TNT (US Dept. of Army, 1985; US Dept. of Army,1990). There are many other explosive compositions and the precise details of the decomposition process appropriate to the composition will affect the pressures and also the rate of decay of those pressures with time.

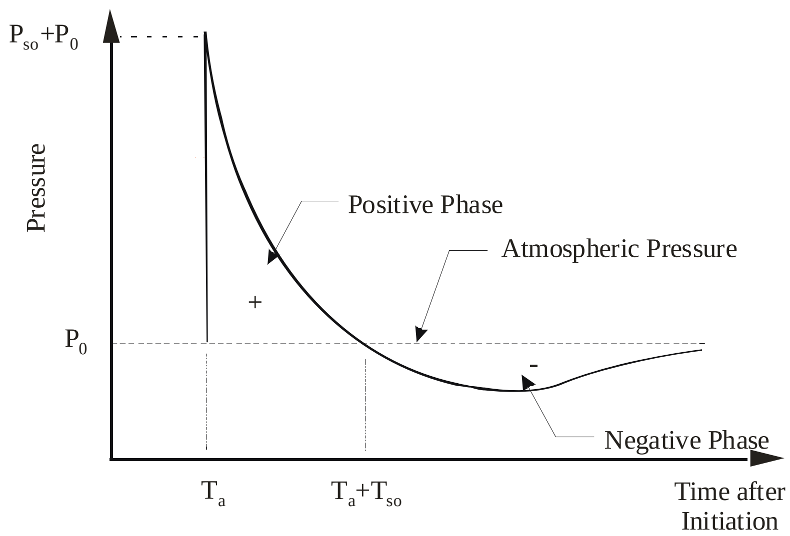

Figure 1: Blast Pressure Trace at a Point

A typical pressure trace at some point distant from a detonation appears in Figure 1. The sudden rise to a peak pressure is evident, as is the “exponential” decay to zero.

Given that the outward directed pulse has mobilised a substantial amount of fluid to generate a substantial outward directed wind, the inertial effects of this outwards directed wind results in a drop in pressure below atmospheric behind the initial pressure pulse. Whilst this negative phase can have a substantial duration - as it is limited to a maximum negative pressure of 1 atmosphere (100 kPa) – only a small fraction of the initial positive pulse - it is rarely of significance.

If an explosion occurs well away from any surfaces then we can consider the explosion to set up a radially propagating shock wave – with the leading edge defining a spherical shell. Whilst the peak pressure reduces rapidly with distance – typically a function of $1/R^3$ - the duration of the positive phase tends to lengthen and so the impulse (the area under the pressure time curve) tends to reduce much more slowly. As it propagates, the shock front velocity and peak pressure reduces with distance and ultimately decays into a sound wave as illustrated in Figure 2.

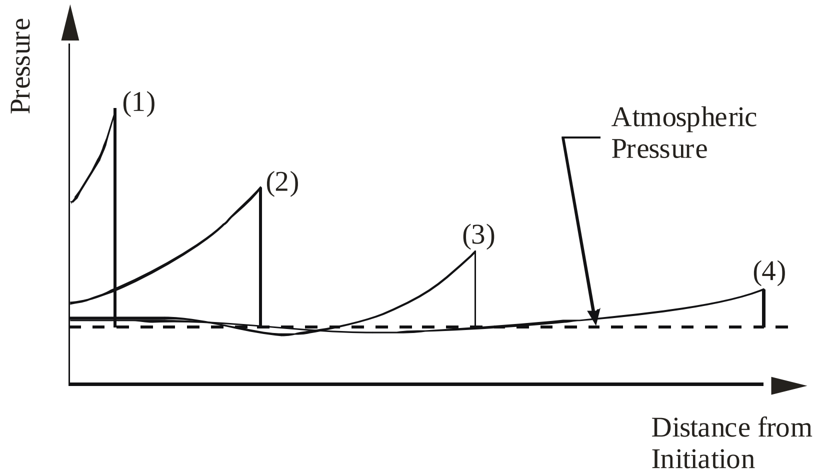

Figure 2: Blast Pressure Traces for at Different Times

For conventional engineering activities, the most commonly used route to the determination of the blast loads generated by an explosion is via the use of standard charts such as shown in Figure 3 (only two of many relevant parameters are presented here). Such charts are simply curve fits to an extensive series of experimentally derived data points. The charts are usually presented with distances and impulses scaled by the cube-root of the explosive mass. So although the peak pressure generated by 1 kg explosive at 1m separation is the same as that for 1,000,000 kg at 100 m, the impulse is 100 times greater and thus the damaging potential is much greater for the latter case.

The charts are usually only available for one explosive – TNT – so where predictions for other explosives are required it is required to adjust the effective mass of explosive by a scaling factor appropriate to the explosive. It is as well to recognise that the scaling factor is often different for pressure and impulse and so it is necessary to select a suitable value for the problem at hand.

Where an explosion occurs in contact with the ground then, in the absence of any energy losses due to cratering etc, all of the energy can be assumed to be released into the hemisphere above the ground. In effect the blast environment is the same as for a spherical explosion with double the quantity of explosive.

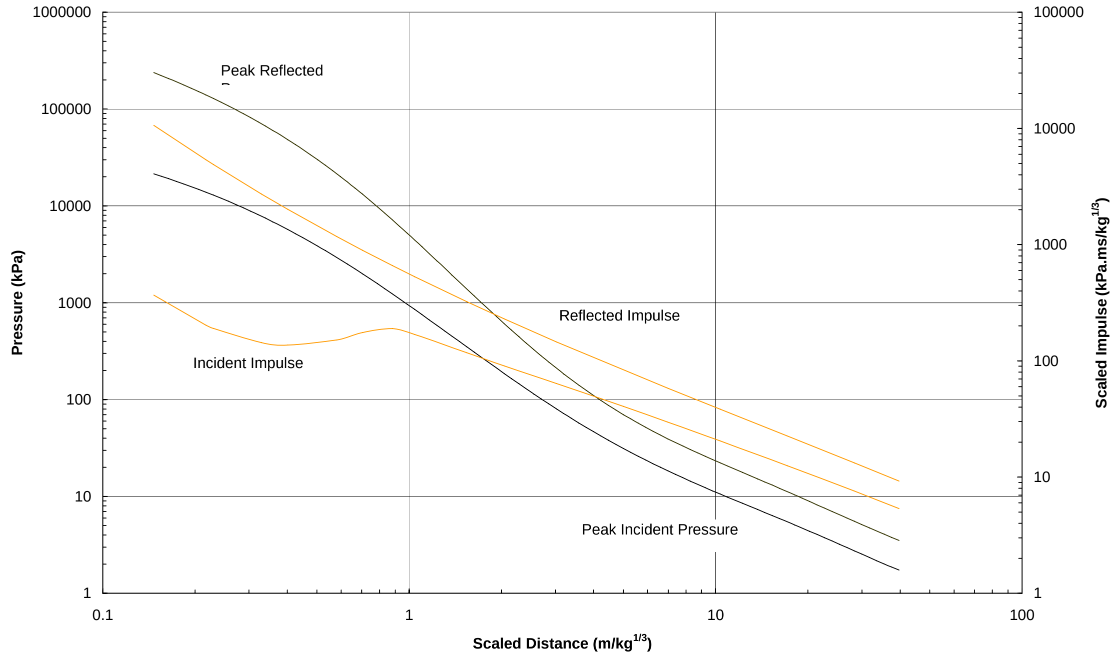

Figure 3: **Spherical Explosion Parameters (Data extracted from TM5-855-1)**

To account for the energy losses due to cratering it is common to reduce this factor from 2 to approximately 1.8. In this manner charts for spherical explosions can also be used for hemispherical explosions.

For the simple cases discussed here a plot of the pressure trace with time indicates an exponentially decaying curve. The positive phase of this trace is generally simplified to an equivalent triangular pulse for engineering calculations – only two parameters are thus used to define the load,

- peak pressure, and
- effective duration

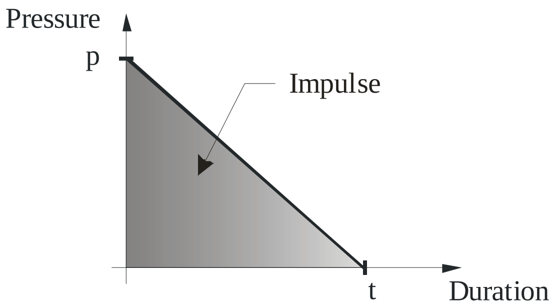

Figure 4: **Equivalent Triangular Pulse**

With this information standard dynamic response charts can be used to determine the deflection response of a member.

3. BLAST LOADING

Whilst the charts for a spherical detonation can be used for an isolated building well removed from other obstructions, the charts are unfortunately of limited applicability to real civil engineering structures.

The presence of a surface in the flow field will reflect the shock wave and it is this reflected pressure that is applied to the surface. For a planar surface the strength of the reflected wave depends on the magnitude and angle of incidence of the incoming shock wave and this can be as large as 8-10+ times the magnitude of the incoming wave. In fact, as shown by Slater et al (1994), the reflection factor at the corner for a pressure wave entering a re-entrant corner may be substantially larger than these values because of the double or even triple reflection that may occur in this region. Note that the reflected pressure magnitude is only a local surface effect and as the wave leaves the surface the pressure reverts to a value similar to that of the incoming or incident wave.

Hand calculation estimates of the blast loads on buildings are generally limited to isolated buildings. The blast load on building groups is generally too complex for hand calculations – although it is sometimes possible to proceed with conservative assumptions. In undertaking such calculations – two loading regimes typically occur.

- explosions remote from the building – in such cases the blast front may be regarded as essentially planar
- explosions relatively close in to building – in such cases the front attacking the building is still essentially spherical and loading is thus non-uniform – both temporally and spatially.

A highly idealised view of the loading process on a tall rectangular shaped building appears in Figure 5 after Norris et al (1959). It assumes normal incidence of the shock wave on a solid façade – i.e. no openings or breakable windows and that the explosion is remote from the building so that the shock front is effectively planar.

The four stages of the loading process are identified in this figure,

- planar blast wave arriving at a the building
- reflected pressure at front face , collapse of reflected pressure in from edges, incident wave passing by side walls and roof
- incident wave reforming at rear wall – with pressure infill – coalescence of shock wave at rear
- incident wave leaving building

As the shock progresses from front face to rear face the strength of the shock reduces. In addition, as it is the front face that ‘sees’ a full reflection – this is the face at greatest risk from the blast. The side walls and roof essentially ‘see’ only an incident wave and as the rear wall loads take some time to build to a peak they thus have less of a dynamic effect than the suddenly applied loads on the front face.

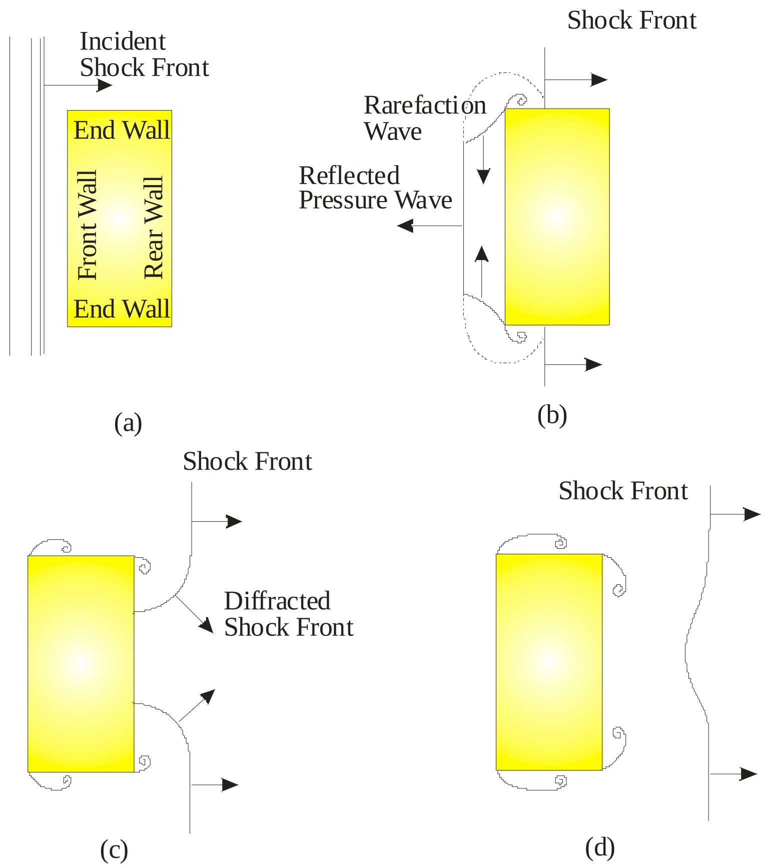

Figure 5: **Blast Loading on Rectangular Building (After Norris et al, 1959)**

Where the shock wave incidence is not normal, the building geometry is irregular and re-entrant corners occur in the face exposed to the blast or where other buildings occur in close proximity to the target structure then additional complications arise in the estimation of the blast loads on a structure.

It will be apparent from these notes that the blast loading for cases other than the extremely idealised cases discussed above is spatially and temporally complex. The loading for such cases cannot be estimated using manual methods - nor can manual methods be easily used to assess the response of structures to these loadings.

For more complex geometrical configurations it necessary to resort to numerical analysis techniques commonly referred to as computational fluid dynamics (CFD) approaches. Although such methods appear to present an attractive alternative – it should be noted that the necessary codes are expensive to acquire, generally require a specialist to drive and are extremely demanding computationally. As it is rarely sensible to perform a single analysis, there is the risk of descending into a massive parametric study taking weeks. Finally, the results obtained are not necessarily correct – depending in part on the details of the code, the explosive modelling and in part on the coarseness of the model. Ultimately a CFD analysis only presents a set of results for the pressures acting on surfaces etc. Such traces are invariably complex and cannot easily be converted to a simplified triangular pulse. Hence in principle it is necessary to couple the CFD analyses (which produce the structural loading) directly to the structural dynamic analysis. Clearly such an approach although attractive to the analyst – is an extremely dangerous approach in that it reduces the analysis to one massive "black box".

In undertaking such analyses it is as well to recognise that in most cases the design event cannot be specified with any certainty – such details as the explosive quantity, explosive composition, explosive standoff from a surface, explosive shape and degree of confinement all have an effect on the loads experienced by a structure. And so the outcome of such studies must still be qualified.

4. STRUCTURAL DESIGN

The design of military facilities to resist blast is often straightforward – because a relatively simple geometry can be imposed on the designers, there is limited provision of openings in the walls for windows and doors, coupled with the potential for the extensive use of reinforced concrete. With such features a relatively robust structure can be readily designed to withstand a substantial range of blast events.

For civilian structures, the issues are more complex. Few architects would be happy to design bunkers for civilian structures. Typically such structures are geometrically complex, often with many re-entrant corners. In addition the facades are extensively glazed – which under blast will generate large numbers of extremely hazardous shards. Whilst a very substantial effort is underway around the world to improve the capacity of glazing systems (for example Beauchamp et al (1998), US Department of State (2002), Security Facilities Executive (1998)) such solutions at present are often extremely costly – with all up costs of 5 to 10 times that of normal glazing.

Typically for modest blast loads with peak pressures limited to a few hundred kPa thick laminated glass units with a substantial PVB interlayer is often feasible. Whilst polycarbonate glazing elements can be used for more substantial blast events, such products tend to be scratched easily and 'yellow' under UV light and thus do not have the same trouble free performance under normal operating conditions. Critical in the design of such windows is the provision of framing that can sustain the substantial loads developed by the blast resistant glazing. In addition the framing must be detailed such that the glazing element (which will experience large deflections) is not pulled out of the supporting frame.

A variety of issues must be addressed in the structural design of buildings to resist blast. The design must recognise,

- the uncertainty in the design load
- the influence of fragmentation – both that generated by the weapon and that generated by the failure of structural elements
- that whilst the design of structural elements most commonly addresses the flexural response of such elements to blast, it is as well to recognise that other failure modes may occur - that have nothing to do with flexural response and so a standard design for flexural behaviour may in some cases be totally erroneous
- the potential effect of blast on personnel – direct pressure effects, indirect effects such – impact injuries caused by blast mobilised bodies, fireball effects

In designing a civilian building it is necessary to consider,

- façade failure (glazing, masonry infill also can be particularly hazardous)
- attack on building columns located on building face
- uplift on slabs – slabs are not normally reinforced to sustain significant uplift loads – such members will crack readily and lift up – perhaps relying on the bottom steel to develop some catenary action. Such catenary action ultimately results in “pull-in” of columns.
- debris attack from destroyed perimeter wall.

A critical design objective thus is to prevent the blast from entering the building - not only to protect personnel in the building from the direct effects of blast but to minimise the opportunity of the blast to disrupt the structure.

Two approaches are commonly used in the analysis of structures for blast,

- simplified hand calculations
  - with this technique the structural member is converted to an equivalent elastic-plastic single degree of freedom (SDOF) system. The dynamic analysis is undertaken for a simplified load – most commonly triangular
  - transformations to an equivalent system is feasible only for relatively simple planar geometries
  - such a technique permits a reasonable solution by moderately skilled personnel within a reasonable time.- nevertheless although the results are believed to be conservative the degree of conservatism is difficult to establish
  - some issues such as shear failure are not addressed

- nonlinear dynamic analysis using finite elements
  - although such approaches provide a sense of precision it is as well to appreciate the limitations of such an approach
  - must be aware that even here the nature of the model adopted may prevent the manifestation of various failure mechanisms.
  - strain rate effects need to be included – such effects can often only be approximately allowed for

The choice of the method adopted depends in part on the complexity of the structure to be designed.

6. DESIGN PHILOSOPHY:

In undertaking the design of elements to resist blast it is essential to recognise that,

- blast load of interest typically exhibit pressures of the order of tens to thousands kPa. In contrast the typical design load for (say) a car park or office floor is only 3-5 kPa.

- typical duration of a blast load is extremely short – typically 1- 10 ms and as a consequence many structural elements only see a fraction of the applied load.

Notwithstanding the fact that the full magnitude of the load is not felt by the element because of its short duration, the effective load experienced by the element is still likely to be orders of magnitude greater than the static capacity of conventionally sized elements. The options available to us are,

- to massively increase the strength (size) of the member. An approach that is likely to be extremely expensive and result in a substantial loss of amenity.

- to accept some damage in the member – provided that the structure does not collapse or deform sufficiently that secondary hazards are induced. Such an approach requires a ductile material or a member detailed to develop ductile behaviour.

The design basis for such structures therefore needs to be modified. For conventional (statically loaded) structures the conventional acceptance test for structures is that the load capacity of a member is always greater than the design actions applied to it as shown in Figure 6(a). Such a test ensures no inelastic response (or damage) under normal conditions. For blast loads such a test is inappropriate and instead we resort to an acceptance test based on the comparing the maximum predicted deformation of a structure against some (arbitrarily) assigned deflection limit as shown in Figure 6 (b).

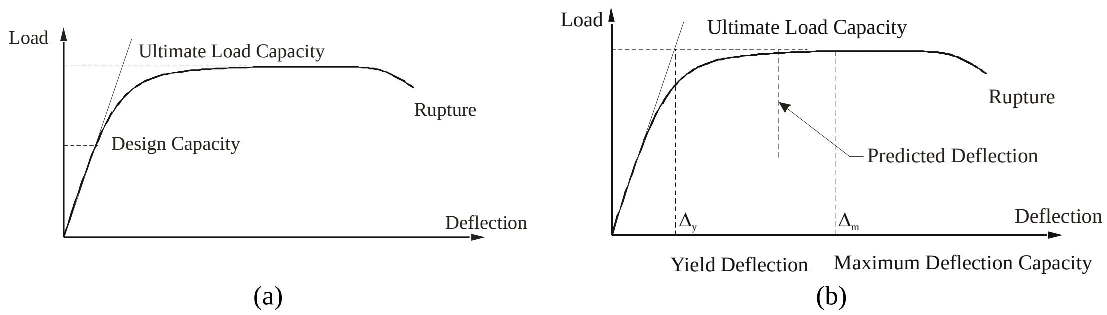

Figure 6: Comparison of Design Bases

For design based on hand calculations - common deflection limits are a ductility ratio or a maximum hinge rotation as depicted in Figure 7.

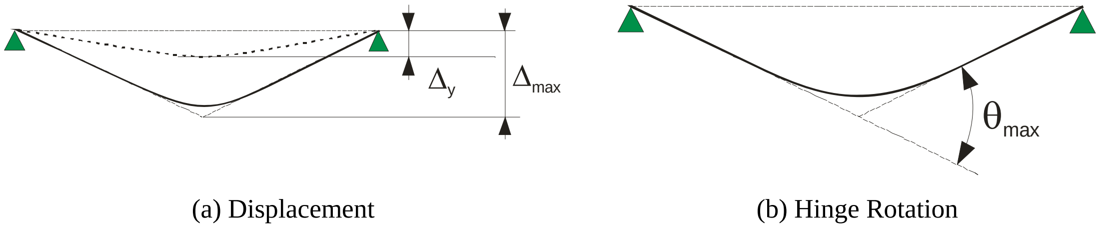

Figure 7: Common Deflection Measures

The deflection limit adopted is determined by reference to the performance level required of a facility. As the deformation limit adopted increases – there is an increased risk of collapse/rupture – and even in the absence of such failure modes there is an enhanced risk of secondary effects jeopardizing the personnel or facilities behind the structure. Thus unoccupied facilities or facilities remote from personnel may be designed to accept a higher deformation limit than those located in close proximity to an occupied area.

At the same time – where the likelihood of an explosion is substantial – such as in a test facility – lower deflection levels are set than where the likelihood of an explosion is remote. Baker et al (1984) set out typical deflection limits for various facilities in the following table.

Facility Type	Performance Requirement	Deflection Criteria
Test Facility	Repeated blasts to be sustained without damage	$\Delta_{\max}/\Delta_y < 1.0$
Explosives Processing – Personnel in close proximity to structure	Personnel protection required from fragment impact, blast	$\theta_{\max} \le 2^\circ$
Explosives Processing – Personnel remote from structure	Severe damage permitted providing catastrophic damage does not occur	$\theta_{\max} \le 12^\circ$

Table 1: Typical Design Deflection Limits

It is as well to be aware that conventional analysis tools do not necessarily identify all of the possible failure modes likely to be experienced in a blast. This is certainly true of conventional hand calculations but can also be true of non linear FE codes. Our conventional analyses – that implicitly focus on flexural actions - tell us nothing about spalling of the structure, scabbing of the structure about breaching of the wall or about sudden shear failure.

7. MATERIALS OF CONSTRUCTION:

The important properties of materials designed to resist blast are

- Strength
- Ductility
- Mass – particularly where the load is impulsive (i.e. the load duration is short compared to the natural period of vibration of the element)

It is as well to note that for an impulsive load the maximum deflection response of a rigid-plastic element is related to the applied impulse in the following manner.

$$\Delta_m \propto \frac{I^2}{2 m_u r_u} \tag{1}$$

Where,

$$\begin{aligned} \Delta_m &= \text{maximum displacement} \\ I &= \text{applied impulse} \\ m_u &= \text{effective mass of element} \\ r_u &= \text{ultimate load capacity of element} \end{aligned}$$

Hence for an impulsive load the effective mass of the element is equally as important as its strength (load capacity). It is for this reason that reinforced concrete is an ideal material to resist blast – a standard wall panel can be detailed to economically achieve a high strength and effective mass. Moreover monolithic joints can be readily constructed to further improve their capacity. Such elements also provide excellent protection against fire and flying debris.

Whilst steel plate, as it is stronger and has a higher density, is potentially better than reinforced concrete – economics dictate the use of relatively thin sections. Hence the effective mass of a steel panel is substantially less than that of a concrete wall and so the load capacity of the wall is thus required to be correspondingly greater simply to compensate for the loss of mass.

Given that economic realities militate against the use of steel in substantial thicknesses (both basic material costs, and fabrication and connection difficulties) the principal use for this material is where mass is a concern – eg in the design of blast doors, offshore oil /gas structures etc. Steel structures are better suited to situations where the peak pressure defining the impulse is more important than the impulse.

Other materials such as timber and unreinforced masonry are generally unsuitable to resist any more than very low blast levels and thus have a very limited domain of application.

8. BLAST MITIGATION:

As noted earlier the magnitude of the peak pressure and impulse reduces rapidly with distance from the source (or standoff). For this reason a vital approach to reducing the risks of blast on a facility is to increase standoff to the greatest extent possible. Many new embassies are now constructed with substantial set backs from the property boundary. Typically a perimeter wall is constructed at the property boundary to restrict access to the site and the building is constructed that no face of the building is closer than (say) 30 m from this boundary (Smith et al).

Whilst blast resistant perimeter walls are often suggested as a means of mitigating the severity of a blast experienced at the building face it should be noted that the details of the wall and its relationship to the building affect the extent of the benefit obtained. The actual blast loading experienced on the building face is complex because of the blast wave diffraction that occurs. Whilst a point low down and immediately behind the wall will see a significant reduction – higher points on the building façade (particularly for points with line of sight to the source) typically experience only a modest reduction. Some test results obtained by Dove et al (1989) illustrate this behaviour in Figure 9 for the test layout defined in Figure 8. Note that Figure 9 only applies for a point on the building face with a scaled height of 0.72 ft/lb$^{1/3}$ (0.29 m/kg$^{1/3}$) and for a wall with a scaled height of 1.0 ft/lb$^{1/3}$ (0.40 m/kg$^{1/3}$).

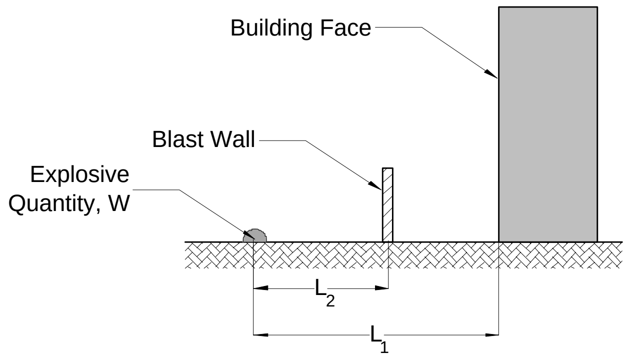

Figure 8: Blast Wall Test Layout (After Dove et al)

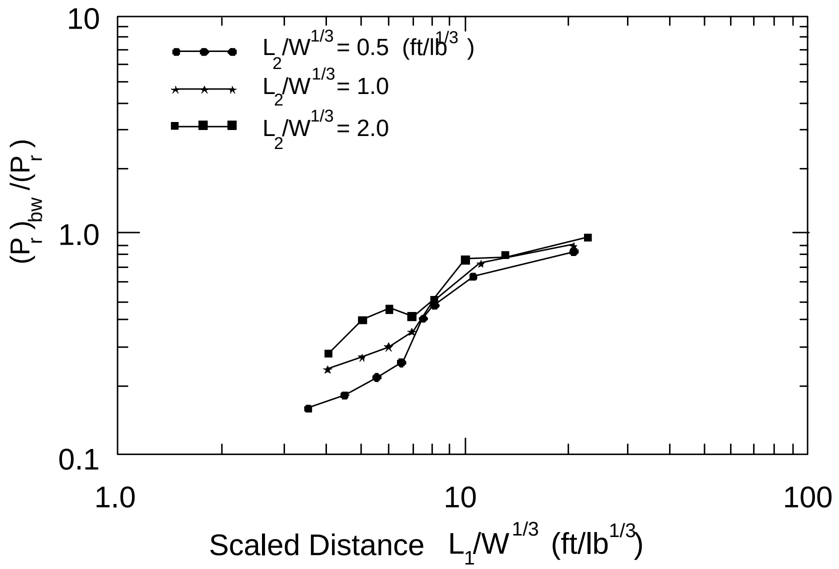

Figure 9: Peak Reflected Pressure Ratio (After Dove et al)

Numerical studies by Rice et al (2000) that examine the shock wave diffraction over a blast wall provide further confirmation of the complex processes involved.

The provision of blast walls in itself is not without concern. As a major explosive device can in principle be brought up hard against such a wall there is a substantial risk that the explosive blast will breach the wall thereby generating a large number of massive high velocity fragments to attack the building.

Unfortunately the option to increase standoff distances in the normal city environment is rarely available. This coupled with the architectural desire for openness and access to natural light severely restricts the opportunity to provide a building any more than a modest blast resistance. In such cases it is inevitable that a more modest design objective will be required. Nevertheless even here by ensuring that the minimal standoff distances available are maintained, that the structure is redundant, that robust and ductile elements are used and that the structure is designed to resist progressive collapse the severity of the terrorist attack can be limited.

9. GROUND SHOCK:

Although often not considered in the assessment or design of structures to resist blast – it is worthwhile appreciating some of the features associated with explosive induced ground motions – particularly near field motions.

The severity of the ground motions induced by the detonation of an explosive depends on the coupling of the explosive to the ground. Clearly an explosive buried sufficiently deeply that the blast does not break the surface is well coupled to the ground – and all of the energy of the blast is transmitted into the ground. On the other hand a surface burst (generated by an explosive resting on the ground) is much less well coupled – and consequently substantially less severe ground motions will occur. In a terrorist attack – such as a vehicle bomb – the centre of gravity of the explosive is well separated from the ground and the coupling is even weaker.

In principle a spherical explosion in an elastic space – will generate a relatively simple ground motion - a pulse of motion associated with the pressure pulse. In reality the ground is not an ideal elastic space – but a half space and at depth throughout this space are layers of material of different density – the various reflections emanating from these interfaces soon generate a complex motion akin to an earthquake. Nevertheless the characteristics of induced ground shaking are well beyond those experienced in an earthquake. For example, a numerical simulation by Dhakal and Pan (2003) reports peak horizontal accelerations at a point 50 m from a 250 tonne in-ground blast of 1220 m/s^2. Whilst the duration of strong shaking is only of the order of 50 ms - significant frequency components approaching 1000 Hz were identified with a dominant Fourier amplitude peak occurring at 185 Hz. Whilst the peak motions decrease rapidly with distance so that at 150 m the peak acceleration is only 340 m/s^2 these values are still substantially beyond those experienced in an earthquake. Full scale field trials by Horoschun (1991) at Woomera confirm the general validity of these simulations with recorded peak accelerations in excess of 100g at 30 m from a 75 tonne detonation.

It is as well to recognise that the severity of the motions coupled with their frequency content suggests that a conventional earthquake analysis of a building subjected to such motions is unlikely to be reliable. Conventional flexural element models are unlikely to reliably capture the propagation of stress waves up into the structure from the foundation.

Whilst the dominant role air blast plays in the design of structures to nearby explosions suggests that ground shock can often be ignored. This is not always the case - even where a structure has been designed to resist blast – the ground shock can enter the building to compromise critical facilities.

CONCLUSIONS:

Some of the issues associated with the effect of blast on structures and the analysis and design of structures to resist these effects have been briefly introduced. The nature of blast loading and the complications associated with the reflection of the blast wave from surfaces has been noted. Whilst simplified tools are available to estimate the blast load for an isolated building more sophisticated tools such as CFD are required for more complex geometries.

Some of the principles associated with the design of structures have been discussed and the importance of mass, ductility and strength highlighted. The importance of minimising the severity of the blast applied to a structure by the provision of an adequate standoff distance is highlighted. Although blast pressures dominate the design of most structures subject to a terrorist event very severe ground motions can on occasion be induced. Even if such motions do not directly control the design of the building envelope they may significantly affect its internal fitments/equipment.

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