Transactions on the Built Environment vol 8, © 1994 WIT Press, www.witpress.com, ISSN 1743-3509

The response of civil engineering structures to impulsive loads

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ABSTRACT

The paper considers the accidental damage to buildings from explosive blast loading which has been back analysed to estimate the overpressure regime produced by the explosion. Such analyses in the past have led to the introduction of design recommendations in current codes of practice for the common structural materials but there are not yet enough of these results to provide characteristic values of pressures likely to arise from different forms of impulsive loading.

INTRODUCTION

Impulsive loading is applied very rapidly and maintained for a very short duration. If that duration is less than about 10% of the fundamental natural period of the structure, then the specific impulse, the time integral of pressure, is the dominant characteristic of the load, and the loaded area of the structure acquires a velocity in an extremely small displacement. The impulse and effective mass then determine the work put into the structure and an energy balance can be used to analyse the distortion that is produced[1]. If the duration is greater than the period then peak pressure is dominant.

Structures must be designed to provide safe and serviceable paths for loads, including accidental loads which are often impulsive. Codes of Practice for structural materials [2], give recommendations to avoid disproportionate effects from accidental loading. For example, peripheral and horizontal ties should be provided and buildings over four storeys should have key elements designed either to resist exceptional loads, or if they fail, to avoid the collapse of more than a limited portion of the whole structure.

Impulsive loads caused by explosion or impact may be totally different in magnitude or direction from static design loads and produce local damage such as cratering of concrete elements or local buckling of steel elements, that will reduce the moment of resistance locally. Initial deformation may be similar for distributed static or dynamic loads but not for concentrated loads, Watson, Ang. [3].

Many industrial processes or transport environments have the potential for accidentally imposing high impulses on buildings and engineering a safe response might seem uneconomic. Some of the more notorious accidents on buildings, however, show that the impulsive load was not exceptionally severe, but had exposed a weakness in the load path.

For instance, Griffith's inquiry into the collapse of Ronan Point, a 22 storey block of flats in Canning Town, London, [4] revealed that a gas explosion in a corner flat on floor 18, although described as being "within the normal limits of a gas explosion in a residential property", had failed the joints between the large precast concrete panels of this "system" building. It was estimated that the flank walls had a peak pressure of about 42kN/m^2 for a few milliseconds and an average of 21kN/m^2 for 100 milliseconds. The ultimate strength of the wall panel was 48kN/m^2 but a pressure of 39kN/m^2 would displace the bottom of the wall on floor 18 and 20kN/m^2, aided by the upward explosive pressure on the slab above, would displace the top of the wall and the explosion removed all support from the floor slab of the flat above. There was no alternative load path and collapse progressed upwards from the 18th floor. Impact from the collapsing floor slabs then caused collapse as far as the 2nd floor and the whole corner of the building was demolished. A subsequent risk assessment showed that Ronan Point, with 110 flats and a design life of 60 years, had a 2% risk of one of the flats having a structurally damaging explosion in 60 years.

Interconnected slabs joined along their common edge have six degrees of freedom for movement of two slabs relative to each other. A weakness in the design at Ronan Point was in the poor restraint against the rotational and two of the directional displacements and the direction and magnitude of the blast loading exposed this weakness.

In 1968, many large concrete panel system buildings in the UK, were particularly vulnerable to progressive collapse if a key loadbearing member were to collapse. The Building Regulations were amended in April 1970 to include checks on the stability of all buildings over 4 storeys; to design key elements for 35kN/m^2 loading, or provide structural continuity to limit the area of collapse if a key element failed.

The 35kN/m^2 loading was derived from a gas explosion but it has no statistical significance as an impulsive load. Characteristic blast pressures

Transactions on the Built Environment vol 8, © 1994 WIT Press, www.witpress.com, ISSN 1743-3509

depend upon the type of explosion, air/gas mixtures deflagrate and have a longer duration, slower rise time, lower peak pressure and a more dispersed centre of explosion than high explosives which detonate.

BLAST PRESSURE EFFECTS ON BUILDINGS

Figure 1 shows a blast wave in air from a high explosive detonation.

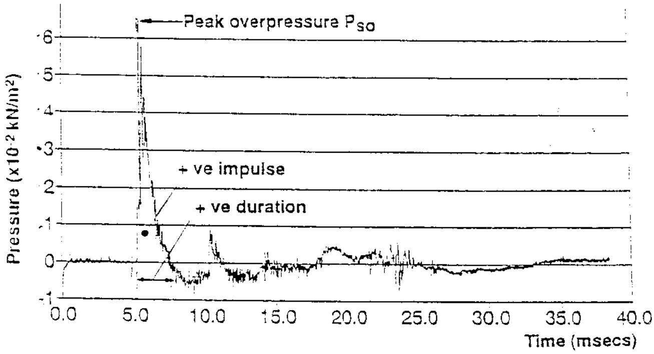

Figure 1: Measured blast wave in air (1.6kg TNT at 4m)

When a plane shock wave approaches normal to a wall of a rectangular building, then there are three components of blast loading applied to the building by the +ve phase, which is usually regarded as the most damaging. These are:

1. Initial diffraction when the blast wave reaches the front surface and is reflected. The resultant pressure p_r is greater than the initial peak overpressure p_{so} for a duration t_c determined by the height h and width b of the front surface. The peak reflected overpressure $(p_r)_{max}$ and the duration t_c are approximated by

$$(p_r)_{max} = 2p_{so}\left(\frac{7p_o + 4p_{so}}{7p_o + p_{so}}\right), \qquad t_c = \frac{3s_c}{u}$$

where p_o - atmospheric pressure, S_c - the smaller of h and $b/2$

$$u = u_s\left(1 + \frac{6p_{so}}{7p_o}\right)^{\frac{1}{2}}$$ = shock wave velocity, u_s - sound wave velocity

2. General overpressure when the front and back faces of the building are at different overpressures.

3. Drag loading which is a wind effect when the particle velocity of air, v, behind the shock front, produces a dynamic pressure p_d and drag pressure $C_d p_d$ where:

$$p_d = \tfrac{1}{2}\rho v^2$$

where ρ is the density of air, C_d is an appropriate drag coefficient.

An explosion usually imposes a very complex pattern of loading on exposed structural elements because of reflections. Externally, reflections are from the ground and adjacent buildings, internally they are from internal surfaces.

DIAGNOSIS OF EXPLOSIONS

To obtain a statistical base for characteristic blast pressures the damage to structural elements from an explosion can be back-analysed. The back-analysis of the Ronan Point accident produced a requirement to analyse key elements for 35kN/m^2 equivalent static loading. An explosion at Flixborough in 1974 damaged many structures and from an analysis of damaged lamp posts Roberts and Pritchard [5] estimated the dynamic pressure produced by the explosion. Sadee et al [6] estimated the overpressure-distance curve from observations of the damage to brickwork and concrete structures. The case study below describes some of the damage that occurred from an explosion and how this was back analysed.

CASE STUDY

A gas explosion totally destroyed a building of light construction and the survey of the surrounding damage included windows, traffic signs and lamp posts, and the distance travelled by debris found after the explosion, were used to determine the characteristics of the explosion.

<u>Analysis of broken windows</u>
Windows which had an unobstructed sight of the exploded building were used to analyse the blast, Watson et al [7]. The survey obtained the frame dimensions and probable glass thickness for all the windows exposed to the direct blast wave, and noted whether the glass had been broken or not. Eye witness accounts indicated that window panes may have broken either inwards or outwards.

The resistance of a pane of glass to blast pressure depends upon the edge condition, dimensions, thickness and ultimate tensile strength of the

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glass. Dragosavic's analysis [8] for a rectangular pane of glass, assuming simple supports on all four sides and uniform pressure on the pane, gives the ultimate resistance q(kN/m^2) as:

$$q = f_{kb}(10^3)d^2 / \beta^2 b^2$$

where f_{kb} = ultimate tensile strength of glass, assumed to be 84N/mm^2
d, b = thickness (mm) and short side length (mm) respectively
β = a function of the side lengths L, b

Because of the variability in the strength of glass, and in the degree of fixity to the frame, the calculated results probably do not predict the actual ultimate resistance by better than ± 50%, Mainstone[9].

The calculated resistance q (kN/m^2) for each window, is plotted against r, the distance from the explosion, Figure 2, indicating whether or not the glass was broken. The resistance of broken and unbroken panes gives an estimate for the blast overpressure at various distances assuming normal incidence. Upper and lower limits for this blast overpressure are indicated in Figure 2 as (UL) and (LL). Windows possibly broken by effects other than overpressure are identified in Figure 2 but have less significance in estimating the blast limits. For example, those possibly broken by flying debris.

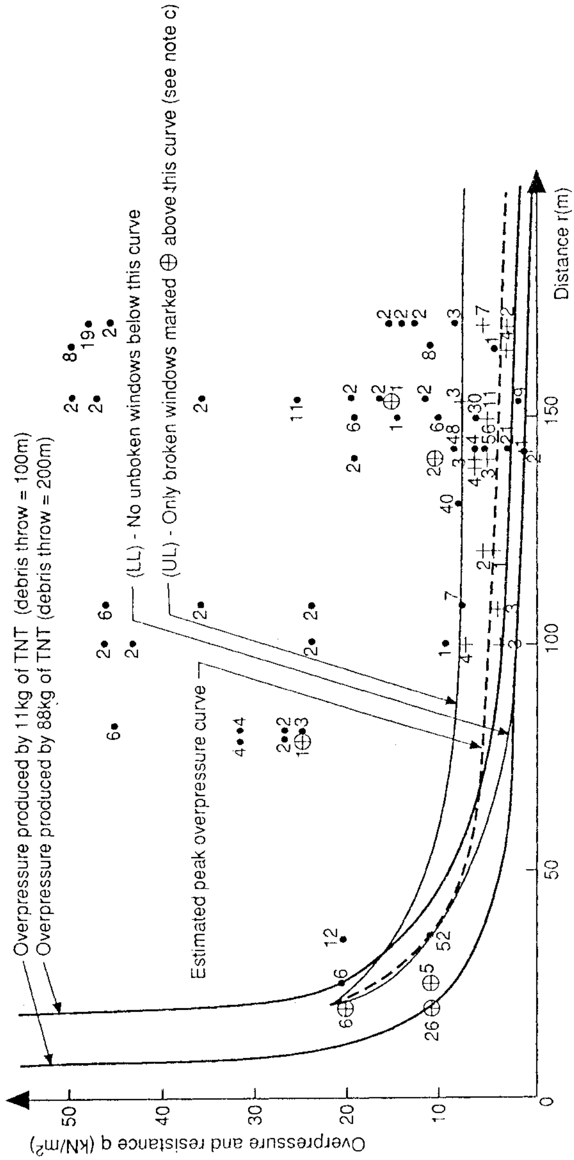
By considering the weightings of the data points, shown in Figure 2, a lower bound estimate of peak overpressure is plotted. This smoothed curve has no broken windows above it if a 50% reduction is made on the theoretical resistance of the broken windows and other more doubtful breakages are neglected. It has only 10 unbroken windows below it if a 50% increase is made on the resistance of the unbroken windows in the survey.

Analysis of metal posts

Some metal posts closer to the explosion than any of the buildings, provided simple elements for analysis. A site inspection showed none with any damage that could be attributed to the explosion and the analysis would therefore be an upper bound estimate of the pressure.

The response to blast pressure depends upon the duration of the blast t_d relative to the fundamental natural period of vibration of the post, and by simple measurement, T = 0.4secs. If $t_d << T$ it responds to impulse and to peak pressure if t_d > T. Between these limits it responds to both.

The duration t_d was estimated by assuming a triangular pressure-time curve with peak pressure p_m. The post had no visible damage, indicating that it had not exceeded the elastic limit. Using Bigg's analysis [10] and assuming a linear resistance-deflection curve:



Notes:

a) • - Unbroken
b) + - Broken
c) Points marked ⊕ are windows that could have been broken by effects of the explosion other than overpressure
d) The number against each point is the number of windows represented by that point

Fig. 2. Estimated Peak Overpressure From A Window Survey

$$t_d = \frac{R_m T}{A p_m \pi}$$

where R_m, T = maximum elastic resistance (kN) and natural period (secs) respectively
A = area subjected to blast pressure (m^2), p_m = peak blast pressure (kN/m^2)

Analysing a post at 60m from the explosion for first mode deformation, and using p_m = 7.5 kN/m^2 from Figure 2, gives t_d = 0.18secs.

A post at 16m from the corner of the exploded building was also undamaged by the blast and the peak pressure on the post was estimated assuming a triangular pressure-time pulse. The peak pressure predicted is extremely sensitive to the assumed shape of the pressure pulse. If the pulse had a rise time of 16% of the decay time then p_m is calculated to be 150kN/m^2 which fits reasonably well with the extrapolated peak overpressure line from the window survey in Figure 2.

When Bigg's analysis is applied to the post at 16m using a peak pressure of 30kN/m^2 extrapolated from Figure 2, the duration of the blast pulse t_d is 0.093secs. As expected it is less than at 60m.

Analysis of debris

Eye witness accounts and press photographs indicated that debris from the exploded building was thrown up to 200m from the centre of the building. The debris throw distance was compared to that of TNT using an analysis by Kinney and Graham [11]. This showed that 11kg of TNT would have thrown the debris 100m and 88kg TNT would have thrown it 200m. The overpressures produced by these quantities of TNT at different ranges are plotted on Figure 2.

CONCLUSIONS

Back analysis from the damage caused to structural elements by accidental explosions can estimate the overpressure produced on structural elements. Although the methods cannot yet be precisely validated, different analyses do compare reasonably well and the results obtained can provide a statistical and rational base for the safe design of vulnerable facilities in the future.

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