# Structural Performances of Buildings against Blast Loading

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***Abstract***

*In recent years, the explosive devices have become major weapons of choice of the most of the terrorist attacks. Such factors, as easy accessibility if information on the construction of the bomb devices, relative ease of manufacturing, mobility and portability, coupled with significant property damages and injuries, are responsible for significant increase of bomb attacks in all over the world. In of most cases, structural damage and the glass hazard have been major contributors to death and injury of the targeted buildings. While the issue of blast-hardening of structure has been an active topic with the military services, the relevant design documents are restricted to official use only. A very limited body of design documentation currently exists which can provide engineers with the technical data necessary to design civil structures for enhanced physical security. The professional skills required to provide blast resistant consulting services include structural dynamics, knowledge of physical properties of explosive detonations and knowledge of physical security practices.*

*In this study, damaging ways from a bomb explosion, mitigation of blast effects and protective design for a bomb blast was investigated. A blast modelling software (AT Blast) was used for the evaluation of blasting effects and SAP 2000 software was used for the evaluation of loading effects.*

**Keywords—** *blast effects, blast-hardening, blast-resistant, structural damage, structural dynamics*

## I. INTRODUCTION

The history of the use of explosives goes back some hundred years and it was originated in ancient China. However, major leap of explosive technology began in the latter part of 19th century when Alfred Nobel invented "Dynamite".

Following the incidents in 11th September 2001, the so-called "icon buildings" are perceived to be attractive target for possible terrorist attacks. Hence detailed research studies on methods for protecting buildings occupants against such bomb attacks essential under present situations in most countries in the world.

The bombing of the world trade centre in New York City in February 1993, devastating attack against the Alfred P. Murrah Building in Oklahoma City in April 1995 and the recent collapse of the both WTC towers have underscored the attractiveness and vulnerability of civilian buildings as terrorist targets. The bomb attack on Colombo Central Bank on 17 October 1997 and Kandy Dalada Maligawa in year 1998 in Sri Lanka are another two examples. These attacks have also demonstrated that modern terrorism should not be regarded as something that could happen elsewhere. Guidance should be given to structural engineers for the designing of structures to withstand this type of terrorist acts.

The blast protection objective of any commercial or public building must be similar to those of embassy structures that is to prevent structural collapse, to save lives and to evacuate victims. Embassies and military structures occupy secured sites with substantial keep-out distances surrounding the assets, unfortunately that is not possible for most civilian structures.

The keep-out distance is vital in the design of blast resistance structures since it is the key parameter that determines for a given charge weight, the blast over pressures that load the building and its structural elements. The degree of fenestration is another key parameter as it determines the pressures that enter the structure. Following these key parameters, architectural and structural parameters play a significant role in determining how the building will respond to blast loading.

## II. MATERIALS AND METHODS

In this research, studies related to blast effect on building carried out by different research institutes were studied. AT Blast, blasting modelling software was used for estimating maximum reflected pressure and total reflected impulse for a given combination of standoff distance and explosive charge size using and scaled distance parameter published curves. AT Blast is a computer programme which can perform these calculations and provide much greater accuracy. TNT equivalent size, the charge weight, TNT equivalence factor and standoff distance has to be entered in to this software and the pressure loading and impulse loading published curves were drawn.

A four storied building model, which was already designed for static loading was analysed against blast. This design was mainly depending on this computer programme. Since it was a already existing building, the length and the width were known. Explosive type, radius, TNT equivalent charge size and angle were the unknown factors for the programme.

Those factors were calculated by studying the analysed model, which was described under the blast modelling visualization for vulnerability assessment published by National Technology Alliance. In this study, several analytical methods available to predict the loads from a high explosive blast on buildings were examined. Analytical and numerical techniques were presented and the results obtained by different methods were compared.
The aim was to analyse the buildings under blast loading and find out blast force released. Hence, an analysis for a four-storied building model against blasts, which was already designed for static loading was done.

### *A. Idealisation of Blast Loading*

The simple way to a blast load for structural analysis and design purposes, is with a triangular distribution of pressure with respect to time, which has a start peak pressure p, and decreases with linearly with time to zero within the time period $t_d$ as illustrated in the following figure and those figures were described by this equation.

$$P(t)= \begin{cases} Ps(I - I/\ td)\ , & t < td \\ 0, & t > td \end{cases}$$

$$P(t)=P_{S0}(I-(t-t_a)t_d)e^{-a(t-ta)td}$$

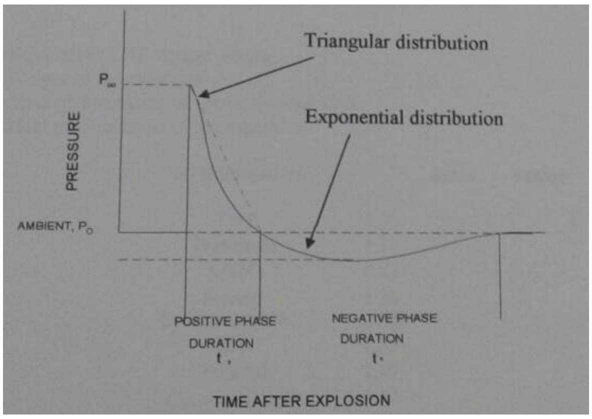


**Fig. 1 Exponential and Triangular Distribution of Pressure due to Blast Load**

### *B. Hemispherical Surface Blasts*

Normally free air bursts remote from any reflecting surface and is usually categorised as a spherical air bursts. When attempting to quantify overpressure generated by the detonation of high explosive sources in contact with the ground, modifications must be made to charge weight before using the graph presented earlier. Therefore, it is more suitable to choose hemispherical surface bursts other than spherical bursts.

### *C. TNT Equivalency*

The majority of data on blast effects in practice relates to the blast pressures output of a spherical charge of TNT (Tri Nitro Toluene) explosive. These data can be extended to include other mass, detonating materials, even nuclear weapons by relating the explosive energy of the effective charge weight of those materials to that of an equivalent weight of TNT. The equivalency of materials compared to TNT may be affected by other factors such as the material shape (flat, square), the number of explosive items, explosive confinement, nature of source and the pressure range being considered. The effect of the energy output of explosive material, relative to that of TNT, can be expressed as a function of the heat of detonation as follows.

$W_{TNT}=(H_{exp}/H_{TNT})W_{exp}$
$W_{TNT}$ – Equivalent TNT charge weight
$W_{exp}$ – Weight of the explosive
$H_{TNT}$ – Heat of detonation of the equivalent TNT
$H_{exp}$ - Heat of detonation of the explosive

| **TNT Equivalence** | | **Index** | **Factor** |
|---|---|---|---|
| TNT | 1.00 | 1 | 1 |
| Dynamite | 1.30 | | |
| ANFO | 0.83 | | |
| Semtex | 1.25 | | |
| Cyclonyte (RDX) | 1.19 | | |
| H-6 | 1.35 | | |
| Tritonal | 1.07 | | |
| Composition B | 1.11 | | |
| Composition A-3 | 1.07 | | |
| Composition C-4 | 1.30 | | |
| Explosive D | 0.92 | | |
| HBX-1 | 1.17 | | |
| HBX-3 | 1.14 | | |
| Minol II | 1.20 | | |

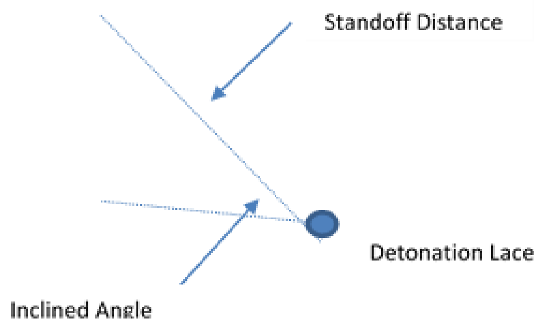


**Fig 2: Building Model**

Where Z is standoff distance and α is the inclined angle.
In this study, four storey building model was analysed against explosions by using SAP 2000 software.

### D. *Pressure Forces Calculation*

For pressure forces calculation, special software was used. This software can be used only for the hemispherical blast. However, it was sufficient for the analysis. Some initial data required to analyse the model was mentioned below.

- Explosive Type TNT
- Standoff Distance/(m) 10
- Inclined Angle/(deg) 45
- Factored Weight/(kg) 220
- Length/(m) 12
- Width/(m) 22.5
- Height/(m) 14

The building was analysed for factor of safety 1. By giving those data to the software, required pressure forces were received. Output data are shown below.

**Table 1: Hemispherical Blast Calculations**

| R/(m) | W/9kg) | R/(ft) | W/(lb) |
|---|---|---|---|
| 10 | 220 | 32.8084 | 485.0174 |
| | | | |
| Y | Pso/(psi) | Pso/(kPa) | A |
| 1.803083 | 63.5452102 | 438.1288 | 0.058842 |
| | | | |
| I | Is/W1/3 | Is/(psi-ms) | Is/(kPa-ms) |
| 1.254266 | 17.95832 | 141.0971 | 972.830346 |
| | | | |
| qo/(psi-ms) | qo/(kpa-ms) | G | H |
| 59.31847418 | 408.9864651 | 0.09959 | 0.382259 |

| Z/(ftlb1/3) | Z/(m/kg^1/3) | ta/(ms) | T | U |
|---|---|---|---|---|
| 4.175732 | 1.65703646 | 7.19477358 | 0.620733 | 0.081622 |
| | | | | |
| C | Pr/(psi) | Pr/(kPa) | t+/(ms) | V |
| 2.433682 | 271.1448 | 1871.546 | 12.59398 | -1.4195 |
| | | | | |
| E | F | Ir/W1/3 | Ir/(psi-ms) | Ir/ (kpa-ms) |
| 0.046242 | 1.709246 | 51.19719 | 402.2523 | 2773.432 |
| | | | | |

| U/(ft/ms) | U/(m/ms) | S | tc/(ms) | tof/(ms) |
|---|---|---|---|---|
| 2.411345 | 0.734978 | 14 | 57.14458 | 4.440842 |

**Loading on a Building from a Hemispherical Blast**

| | | | |
|---|---|---|---|
| | | **Assume a rectangular Building** | |
| **Explosive Type** | **TNT** | | |
| **Radius/(m)** | **10** | **Width** | **22.5m** |
| **Weight/(kg)** | **220** | **Height** | **12m** |
| **In. Angle** | **44** | | |
| **Factored Weight/(kg)** | **220** | | |

| | |
|---|---|
| Scaled distance/(m/kg$^{1/3}$) | 1.66 |
| Time of arrival at range/(ms) | 7.19 |
| Over-pressure at range/(kPa) | 438.13 |
| Reflected Press at Range (kPa) | 1871.55 |
| Positive Phase duration at range/(ms) | 12.59 |
| Positive Phase duration at range/(kPa-ms) | 972.83 |
| Reflected Impulse at Range (kPa-ms) | 2773.43 |
| Shock Front Velocity/(m-ms) | 0.73 |
| Clearing Time/(ms) | 48.98 |
| Idealised Positive Phase/(ms) | 4.44 |
| Dynamic Overpressure at Range/(kPa) | 408.99 |
| Stagnation Overpressure/(kPa) | 487.11 |
| Ir Alfa | 2101.54 |

### E. *Calculation of the above Outputs*

Those results were obtained based on an empirical equations. Those equations can be given as follows.
Empirical equations for Hemispherical surface blast
Several blast wave front parameters produced in a hemispherical surface burst can be calculated by the following empirical formulae, Imperial units are used in these formulae, which are valid for 0.067m/kg$^{1/3}$ $\leq Z \leq 40$ m/kg$^{1/3}$
Formulae used to determinate peak incidence overpressure, $P_{so}$
T=log (Z)

U=-0.7564579301809+1.35034249993(T)

Y=1.9422502013-1.6958988741(U)-0.1541593768146(U$^2$)+0.514060730593(U$^3$)+0.0988

534365274($U^4$)-0.293912623038($U^5$)-0.0268112345019($U^6$)+0.109097496421($U^7$)+0.0016284676311($U^8$)-0.0214631030242($U^9$)+0.001456723382($U^{10}$)+0.00167847752266($U^{11}$)

$P_{so}=10^{(Y)}$

(Note: The symbol Z is scaled distance. T,U & Y used in above are dummy variables.

Formulae used to determine the peak normal reflected overpressure, $P_r$

A=0.789312405513+1.36637719229(T)

C=2.56431321138-2.21030870597(A)-0.218536586295($A^2$)+0.895319589372($A^3$)+0.24989009775($A^4$)-0.569249436807($A^5$)-0.11791682383($A^6$)+0.224131161411($A^7$)+0.0245620259375($A^8$)-0.045511600269($A^9$)-0.00190930738887($A^{10}$)+0.00361471193389($A^{11}$)

$P_r=10^{(c)}$

Formula used to determine incidence impulse, $I_s$

For Z≤2.41

V=0.832468843425+3.07603296666(T)

I=1.57159240621-0.502992763686(V)+0.171335645235($V^2$)+0.045017696305($V^3$)-0.0118964626402($V^4$)

For Z>2.41

V=-2.91358616806+2.40697745406(T)

I=0.71985265584-0.384519026965(V)-0.0260816706301($V^2$)+0.00595798753822($V^3$)+0.014544526107($V^4$)-0.00663289334734($V^5$)-0.00284189327204($V^6$)+0.0013644816227($V^7$)

$I_s=10^{(I)}W^{1/3}$

Formulae to determine normal reflected Impulse, $I_r$

E=-781951689212+1.33422049854(T)

F=1.75291677799-0.949516092853(E)+0.112136118689($E^2$)-0.0250659183287($E^3$)

$I_r=10^{(F)}W^{1/3}$

Formulae to determine wave front velocity, U:

G=-0.755684472698+1.37784223635(T)

H=0,44977431-0.698029763(G)+0.15891679($G^2$)+0.443812098($G^3$)-0.11340202399($G^4$)-0.3698870751($G^5$)+0.1292395675($G^6$)+0.198579812($G^7$)-0.08676362174($G^8$)-0.06203919002($G^9$)+0.03074829266($G^{10}$)+0.01026572344($G^{11}$)-0.0054653325($G^{12}$)-0.000693181($G^{13}$)+0.0003847495($G^{14}$)

U=10H

Formulae to determine positive load duration, $t_s$

For 0.45<Z<2.54

S=-0.1790217052+5.25099193925(T)

B=0.728671776005+0.130143717675(S)+0.134872511954($S^2$)+0.0391574276906($S^3$)+0.00475933664702($S^4$)-0.0042888144598008($S^5$)

For 2.54<Z<7

S=-5.85909812338+9.2996288611(T)

B=0.2009657334-0.0297944268976(S)+0.030632954288($S^2$)+0.0183405774086($S^3$)-0.017396466211($S^4$)-0.01106321963633($S^5$)+0.0056206003097736($S^6$)+0.0001618217499($S^7$)-0.000686018944($S^8$)

For Z>7

S=-4.92699491141+3.46349745571(T)

B=0.5724624769964+0.0933035304009(S)-0.0004849420883($S^2$)-0.00226884995013($S^3$)-0.00295908591505($S^4$)+0.00148029868929($S^5$)

$t_s=10^{(B)}W^{1/3}$

**Table 2: Joint Loads**

| Joint | Load / (kN) | Joint | Load / (kN) |
|---|---|---|---|
| 2 | 6720.06 | 24 | 14628.80 |
| 3 | 5495.44 | 44 | 14628.80 |
| 4 | 4190.13 | 23 | 23429.70 |
| 5 | 1565.30 | 43 | 23429.70 |
| 62 | 6720.06 | 22 | 34416.39 |
| 63 | 5495.44 | 42 | 34416.39 |
| 64 | 4190.13 | 25 | 16843.60 |
| 65 | 1565.30 | 45 | 16843.60 |

### F. Model Analysis by using SAP 2000

The computation model was constructed by considering above structural and architectural parameters. For the dynamic analysis of the building structures should be under seismic waves or wind loads, so it is enough to model only the resisting structure statically. A blast analysis also requires the consideration of all the non-structural elements specially the walls as they play an important role in the propagation of the pressure wave.

Finally, the four storied building model was performed in SAP 2000 and entered the above calculated nodal loads, set the properties and run it in SAP 2000.

## III.RESULTS AND DISCUSSION

The results obtained for an explosive load of 220kg of TNT located in a car, 1m away from the building. The magnitude of the explosive load and its location were obtained from a previous analysis of NTA, USA.

The blast propagated with supersonic speed and was reflected when it encountered an object such as a building. The reflected pressure was at least twice that of the incident shock wave and proportional to the strength of the incident shock, which was proportional to explosive's weight.

If the exterior building walls are capable of resisting the blast load, the shock front penetrates through window and door openings, subjecting the floors, ceilings, walls, contents and people to sudden pressures and fragments from shattered windows, door etc. building components not capable of resisting the blast wave will fracture and become more fragmented and moved by the dynamic pressure that immediately follows the shock front. Building contents and the people will be displaced in the direction of blast wage propagation. In this manner, the blast will propagate through the building.

The blast pressure decayed exponentially and eventually became negative. This then subjected the building to pressures acting in the opposite direction to that of the original shock front. The process subsequently started all over again in the opposite direction, but at a decreased load magnitude.

Air blast parameter such as the durations of the positive and negative blast phases were measured in milliseconds.

Peak blast loads may be several orders of magnitude larger than the largest loads for which conventional buildings are designed. Explosives were compared in terms of the equivalent weight ad energy of TNT equivalence. For a charge 220kg of TNT, the peak pressure of the shock front at a distance of 10m was about 1872kPa.

Designing of structure to resist the effects of blast is a well-practiced mostly by the military. Designing conventional, above grade structures to significantly resist the effects of blast is generally impractical for the following reasons.

- The risk cannot be defined. We do not know with any degree of certainty which building mat be attacked, nor do we know when an attack will occur.
- The threat cannot be quantified. We generally do not know the type of weapon, its size, or mode of delivery.
- Blast pressures are several orders of magnitude greater than ordinary gravity and wind loads, the impact on cost, function and appearance is not acceptable.

When an explosion occurs at or very near the ground surface it is treated as a hemispherical surface burst. In the majority of cases, terrorist activity has occurred in built up areas of cities, where devices are placed o or very near the ground surface (4).

Kingery and Bulmash (2) have developed equations to predict air blast parameters from spherical air bursts and from hemispherical surface bursts. These equations are widely accepted as engineering predictions for determining free-field pressures and loads on structures (1).

According to Yandzio and Gough (4), in a small sale explosion which is often characterized by short loading duration, blast loadings is considered to act locally on the front face of building only. Therefore, only the front face of the building will be subjected to the load. It is usually adequate assume that the decay of blast overpressure is linear. For the positive overpressure phase, a simplification is made where the impulse of the positive phase of the blast is preserved and the decay of the overpressure is assumed to be linear (4).

The Non-planar nature of the air blast wave is important in a close range explosion. Here the assumption of a planar incident wave front is not applicable (as the explosion is close and the building is tall). Hence the effect of incident angle on the reflective impulse is significant. For a particular angle of incidence, a, the reflected impulse $i_{ra}$ can be evaluated using the equation proposed by Lorenz (3).

$$I_m = i_s\,(1+\cos a - 2\cos^2 a) + i_r \cos^2 a$$

## IV. CONCLUSIONS

The study on the response of buildings subjected to air blast loading using finite element method was presented in this paper. The results show that the dynamic deflection of the column subjected to air blast loading. Therefore, the use of normal buildings, especially in ground level columns, can increase the localized damage of the structure and the risk of progressive collapse.

Buildings having setbacks that protect the tower part above the setback level from blast loading show better response in terms of peak displacement, peak acceleration and inter story drift when compared to buildings without setbacks d having identical base dimensions.

The abrupt change in the rigidity of the lateral load resisting system in tall setback buildings leads to abrupt changes in the moments and shears at the setback level. This becomes more pronounced when shear walls are cut at the setback level.

Frames having shear walls closer to the largest suffer less damage in terms of the number of hinges formed when compared with identical frames having shear walls further away from the target.

When a building is subjected to a close-in explosion, the maximum acceleration response occurs immediately after the blast and maximum displacement occurs at a later stage in the time history.

## ACKNOWLEDGEMENT

First of all, I would like to make my gratitude to my project supervisor Dr.P.B.R Dissanayake for giving me the opportunity to carry out a research project under his supervision and also for the trustiness that I can do this type of research project. In addition to his guidance; valuable advices and constant encouragement were invaluable. Then I would like to express my sincere thanks to all other personnel in the university who have extended their helping hands to gather the required information. Finally, I would like to thank all the personnel that helped me in various ways to make this project a success.

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