Prediction of Blast Loading and Its Impact on Buildings

Parag Mahajan[#1] Pallavi Pasnur[#2]

Department of civil Engineering, Dr. D.Y. Patil School of Engineering & Technology,
Knowledge City, Charoli (BK), Lohegaon, Pune-412105
Maharashtra, India

Abstract— **A bomb explosion within or immediately nearby a building can cause catastrophic damage on the building's external and internal structural frames, collapsing of walls, blowing out of large expanses of windows, and shutting down of critical life-safety systems. Loss of life and injuries to occupants can result from many causes, including direct blast-effects, structural collapse, debris impact, fire, and smoke. The indirect effects can combine to inhibit or prevent timely evacuation, thereby contributing to additional casualties. In addition, major catastrophes resulting from gas chemical explosions result in large dynamic loads, greater than the original design loads, of many structures. The analysis and design of structures subjected to blast loads require a detailed understanding of blast phenomena and the dynamic response of various structural elements. This paper presents a comprehensive overview of the effects of explosion on structures. An explanation of the nature of explosions and the mechanism of blast waves in free air is given. This paper also introduces different methods to estimate blast loads and structural response.**

Keywords— **Damage Behaviour, Blast Loading, Effects on structures, Failure modes, Progressive Collapse Analysis**

I. INTRODUCTION

Due to different accidental or intentional events, the behaviour of structural components subjected to blast loading has been the subject of considerable research effort in recent years. Conventional structures normally are not designed to resist blast loads; and because the magnitudes of design loads are significantly lower than those produced by most explosions, conventional structures are susceptible to damage from explosions. With this in mind, developers, architects and engineers increasingly are seeking solutions for potential blast situations, to protect building occupants and the structures.

In the design of structures to resist blast loads, there are two important considerations, prevention of catastrophic failure or progressive collapse and reduction of projectiles due to fragmentation. Control of deflection, crack width, vibration and other serviceability related criteria are not normally deemed essential. The flexible nature of FRP laminates, their thinness and lightweight and the ease with which they can be bonded to most surfaces render them attractive because they do not alter in any significant way the original mass, geometry and appearance of a structure. The addition of mass to a structure generally increases its blast resistance, but it also increases its dead load; the latter may be undesirable due to the increased sustained load on the columns and foundation before and after the blast event. In blast resistance design both high strength and ductility are important; FRP retrofit normally increases the strength substantially but at the expense of some reduction in ductility of flexural members. This trade-off between strength and ductility and its effect on blast resistance of retrofitted structures need investigation.

Strategies for blast protection have become an important consideration for structural designers as global terrorist attacks continue at an alarming rate. Conventional structures normally are not designed to resist blast loads and because the magnitudes of design loads are significantly lower than those produced by most explosions, conventional structures are susceptible to damage from explosions. No civilian buildings can be designed to withstand the kind of extreme attack that happened to the World Trade Centre in USA. Building owners and design professionals alike, however, can take steps to better understand the potential threats and protect the occupants and assets in an uncertain environment. With this in mind, developers, architects and engineers increasingly are seeking solutions for potential blast situations, to protect building occupants and the structures.

These structures should be protected from the blast effects, which are likely to be the targets of terrorist attacks. The dynamic response of the structure to blast loading is complex to analyse, because of the non-linear behaviour of the material. Explosions result in large dynamic loads, greater than the original design loads, for which the structures are analysed and designed. Analyses and design of blast loading requires detailed knowledge of blast and its phenomena.

II. EXPLOSIONS AND BLAST PHENOMENON

An explosion is defined as a large-scale, rapid and sudden release of energy. Explosions can be categorized on the basis of their nature as physical, nuclear or chemical events. In physical explosions, energy may be released from the catastrophic failure of a cylinder of compressed gas, volcanic eruptions or even mixing of two liquids at different temperatures. In a nuclear explosion, energy is released from the formation of different atomic nuclei by the redistribution of the protons and neutrons within the interacting nuclei, whereas the rapid oxidation of fuel elements (carbon and hydrogen atoms) is the main source of energy in the case of chemical explosions.

Explosive materials can be classified according to their physical state as solids, liquids or gases. Solid explosives are mainly high explosives for which blast effects are best known. They can also be classified on the basis of their sensitivity to ignition as secondary or primary explosive. The latter is one that can be easily detonated by simple ignition from a spark, flame or impact. Materials such as mercury fulminate and lead azide are primary explosives. Secondary explosives when detonated create blast (shock) waves which can result in widespread damage to the surroundings. Examples include trinitrotoluene (TNT) and ANFO.

The detonation of a condensed high explosive generates hot gases under pressure up to 300 kilo bar and a temperature of about 3000-4000C°. The hot gas expands forcing out the volume it occupies. As a consequence, a layer of compressed air (blast wave) forms in front of this gas volume containing most of the energy released by the explosion. Blast wave instantaneously increases to a value of pressure above the ambient atmospheric pressure. This is referred to as the side-on overpressure that decays as the shock wave expands outward from the explosion source. After a short time, the pressure behind the front may drop below the ambient pressure (Figure 1). During such a negative phase, a partial vacuum is created and air is sucked in. This is also accompanied by high suction winds that carry the debris for long distances away from the explosion source.

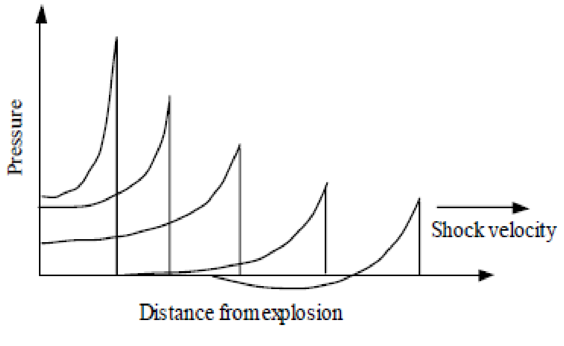

Figure 1: Blast wave propagation

III. EXPLOSIVE AIR BLAST LOADING

The threat for a conventional bomb is defined by two equally important elements, the bomb size, or charge weight *W*, and the standoff distance (*R)* between the blast source and the target (Fig.2). For example, the blast occurred at the basement of World Trade Centre in 1993 has the charge weight of 816.5 kg TNT. The Oklahoma bomb in 1995 has a charge weight of 1814 kg at a standoff of 5m. As terrorist attacks may range from the small letter bomb to the gigantic truck bomb as experienced in Oklahoma City, the mechanics of a conventional explosion and their effects on a target must be addressed.

Throughout the pressure-time profile, two main phases can be observed; portion above ambient is called positive phase of duration (*td*), while that below ambient is called negative phase of duration (*td*). The negative phase is of a longer duration and a lower intensity than the positive duration. As the stand-off distance increases, the duration of the positive-phase wave increases resulting in a lower-amplitude, longer-duration shock pulse. Charges situated extremely close to a target structure impose a highly impulsive, high intensity pressure load over a localized region of the structure; charges situated further away produce a lower-intensity, longer-duration uniform pressure distribution over the entire structure. Eventually, the entire structure is engulfed in the shock wave, with reflection and diffraction effects creating focusing and shadow zones in a complex pattern around the structure. During the negative phase, the weakened structure may be subjected to impact by debris that may cause additional damage.

STAND-OFF DISTANCE

Stand-off distance refers to the direct, unobstructed distance between a weapon and its target.

HEIGHT OF BURST (HOB)

Height of burst refers to aerial attacks. It is the direct distance between the exploding weapon in the air and the target.

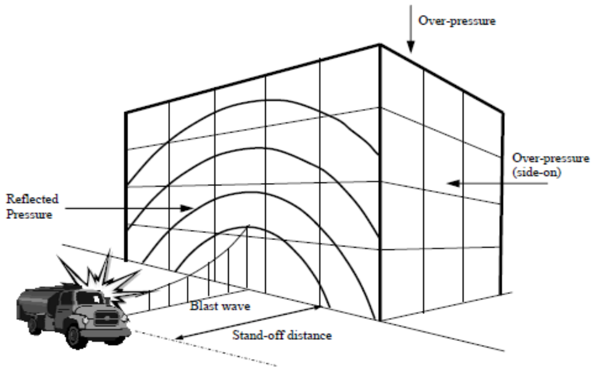

Figure 2: Blast Loads on a Building.

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, doors, etc. Building components not capable of resisting the blast wave will fracture and be further fragmented and moved by the dynamic pressure that immediately follows the shock front. Building contents and people will be displaced and tumbled in the direction of blast wave propagation. In this manner the blast will propagate through thebuilding.

IV. PREDICTION OF BLAST PRESSURE

Blast wave parameter for conventional high explosive materials have been the focus of a number of studies.

The estimations of peak overpressure due to spherical blast based on scaled distance $Z=R/W^{1/3}$ was introduced by Brode (1955) as:

$P_{SO} = 6.7/Z^3 + 1$ bar ($P_{SO} > 10$ bar)

$P_{SO} = 0.975/Z + 10455/Z^2 + 5.85/Z^3 - 0.019$ bar ($0.1 < P_{SO} < 10$)

In 1961, Newmark and Hansen introduced a relationship to calculate the maximum blast pressure (Pso), in bars, for a high explosive charge detonates at the ground surface

$$P_{SO} = 6784\,(W/R^3) + 93\,(\sqrt{(W/R^3)})$$

In 1987, Mills introduces another expression of the peak overpressure in kpa, in which W is the equivalent charge weight in kilograms of TNT and Z is the scaled distance.

$$P_{SO} = 1772/Z^3 - 114/Z^2 + 108/Z$$

As the blast wave propagates through the atmosphere, the air behind the shock front is moving outward at lower velocity. The velocity of the air particles, and hence the wind pressure, depends on the peak overpressure of the blast wave. This later velocity of the air is associated with the dynamic pressure, $q(t)$. The maximum value, $q(s)$ say, is given by

$$Q(s) = 5\,P_{SO}2/2\,(P_{SO}+7\,P_O)$$

If the blast wave encounters an obstacle perpendicular to the direction of propagation, reflection increases the overpressure to a maximum reflected pressure Pr as:

$$Pr = 2\,P_{SO}\left((7P_0 + 4\,P_{SO})/(7P_0 + P_{SO})\right)$$

A full discussion and extensive charts for predicting blast pressures and blast durations are given by Mays and Smith (1995) and TM5-1300 (1990). Some representative numerical values of peak reflected overpressure are given in Table 1.

Table 1. Peak reflected overpressures *Pr* (in MPa) with different *W-R* combinations

W ***R***	**100 kg TNT**	**500 kg TNT**	**1000 kg TNT**	**2000 kg TNT**
1m	165.8	354.5	464.5	602.9
2.5m	34.2	89.4	130.8	188.4
5m	6.65	24.8	39.5	60.19
10m	0.85	4.25	8.15	14.7
15m	0.27	1.25	2.53	5.01
20m	0.14	0.54	1.06	2.13
25m	0.09	0.29	0.55	1.08
30m	0.06	0.19	0.33	0.63

V. HOW BLAST LOADS ARE DIFFERENT FROM SEISMIC LOADS

Blast loads are applied over a significantly shorter period of time (orders-of-magnitude shorter) than seismic loads. Thus, material strain rate effects become critical and must be accounted for in predicting connection performance for short duration loadings such as blast. Also, blast loads generally will be applied to a structure non-uniformly, i.e., there will be a variation of load amplitude across the face of the building, and dramatically reduced blast loads on the sides and rear of the building away from the blast. Figure 2 shows a general comparison between an acceleration record from a point 7 km from the 1994 Northridge epicenter and the predicted column loads for the 1995 Oklahoma City bombing.

It is apparent that the 12-second-long ground shaking from the Northridge event lasted approximately 1000 times longer than the 9 ms initial blast pulse from the Murrah Building blast. The effects of blast loads are generally local, leading to locally severe damage or failure. Conversely, seismic "loads" are ground motions applied uniformly across the base or foundation of a structure. All components in the structure are subjected to the "shaking" associated with this motion.

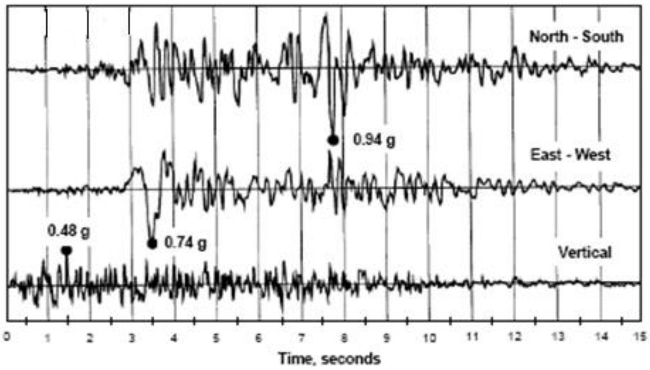

Figure 3 Response of seismic loading on structure

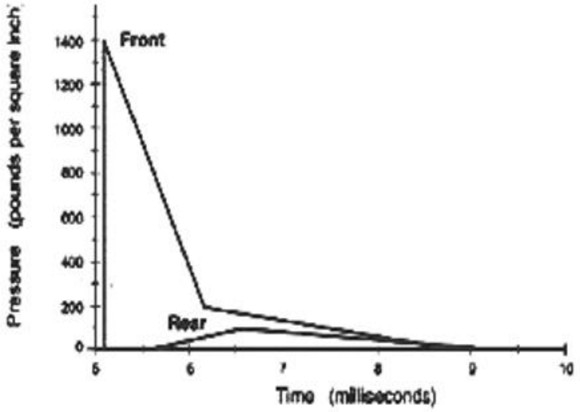

Figure4. Comparison between seismic load and the blast load

VI. STRUCTURAL RESPONSE TO BLAST LOADING

Blast loading is a short duration load also called impulsive loading. Mathematically blast loading is treated as triangular loading. The ductility and natural period of vibration of a structure governs its response to an explosion.

Ductile elements, such as steel and reinforced concrete, can absorb significant amount of strain energy, whereas brittle elements, such as timber, masonry, and monolithic glass, fail abruptly. In the investigation of the dynamic response of a building structure to bomb blast, the following procedures are followed

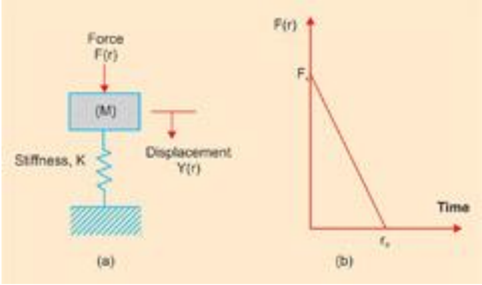

Figure 5: (a) SDOF system (b) Blast loading

(a) The characteristics of the blast wave must be determined;
(b) The natural period of response of the structure (or the structural element) must be determined;
(c) The positive phase duration of the blast wave is then compared with the natural period of response of the structure.

Based on (c) above, the response of the structure can be defined as follows:

- If the positive phase duration of the blast pressure is shorter than the natural period of vibration of the structure, the response is described as impulsive. In this case, most of the deformation of the structure will occur after the blast loading has diminished.
- If the positive phase duration of the blast pressure is longer than the natural period of vibration of the structure, the response is defined as quasi-static. In this case, the blast will cause the structure to deform whilst the loading is still being applied.
- If the positive phase duration of the blast pressure is close to the natural period of vibration of the structure, then the response of the structure is referred to as dynamic. In this case, the deformation of the structure is a function of time and the response is determined by solving the equation of motion of the structural system.

Equation of motion for a undamped forced system is given by

$$M\ddot{Y}(t) + K\acute{Y}(t) = F(t)\text{- - - - - - - - - - -} \quad (a)$$

The force is given by

$$F(t) = F_0 \ (1- T / t_d) \text{ - - - - - - - - - - -} \quad (b)$$

Initial conditions for triangular pulse is $Y_0=0$, $V_0= 0$
The total displacement of an un-damped SDOF system is given by

$$Y(t) = Y_0 \cos\omega t +(V0 /\omega) \sin\omega t + 1/m\omega\int^t_0 F(t) \sin\omega (t-T)dt\text{---}(c)$$

Displacement

$$Y(t)= Fm/K(1-\cos\omega t)+ Fm/ktd ((\sin\omega t/\omega) -t) \text{ - - - - - - - -}(d)$$

Velocity

$$\acute{Y}(t)=dy/dt= Fm/K[\omega\sin\omega t+1/td (\cos\omega t-1)] \text{ - - - - - - - - - -}(e)$$

In which ω is the natural circular frequency of vibration of the structure and T is the natural period of vibration of the structure which is given by equation

$$\omega = 2\pi/T \quad \sqrt{=}K/M \text{ - - - - - - - - - - - - -}(f)$$

The maximum response is defined by the maximum dynamic deflection Y_m which occurs at time tm. The maximum dynamic deflection Y_m can be evaluated by setting dy/dt in Equation (c) equal to zero, i.e. when the structural velocity is zero. The dynamic load factor, DLF, is defined as the ratio of the maximum dynamic deflection Y_m to the static deflection Y_{st} which would have resulted from the static application of the peak load F_m, which is shown as follows:

$$DLF = Y_m / Y_{st} \text{ - - - - - - - - - - - -}(g)$$

$$DLF=1/(2\pi td/T) \{ \sin 2\pi (t/T) - \sin 2\pi (t/T - td/T) \} - \cos 2\pi t/T \text{ ------}(h)$$

The dynamic load factor of blast loading is given by equation (h) to be considered in evaluating the correctness of evaluating the dynamic stresses.

VII. FAILURE MODES OF BLAST-LOADED STRUCTURES

Blast loading effects on structural members may produce both local and global responses associated with different failure modes. The type of structural response depends mainly on the loading rate, the orientation of the target with respect to the direction of the blast wave propagation and boundary conditions. The general failure modes associated with blast loading can be flexure, direct shear or punching shear. Local responses are characterized by localized bleaching and spalling, and generally result from the close-in effects of explosions, while global responses are typically manifested as flexural failure.

A. Global Structural Behavior

The global response of structural elements is generally a consequence of transverse (out-of-plane) loads with long exposure time (quasi-static loading), and is usually associated with global membrane (bending) and shear responses. Therefore, the global response of above-ground reinforced concrete structures subjected to blast loading is referred to as membrane/bending failure.

The second global failure mode to be considered is shear failure. It has been found that under the effect of both static and dynamic loading, four types of shear failure can be identified: diagonal tension, diagonal compression, punching shear, and direct (dynamic) shear (Woodson, 1993). The first two types are common in reinforced concrete elements under static loading while punching shear is associated with local shear failure, the familiar example of this is column punching through a flat slab. These shear response mechanisms have relatively minor structural effect in case of blast loading and can be neglected. The fourth type of shear failure is direct (dynamic) shear. This failure mode is primarily associated with transient short duration dynamic loads that result from blast effects, and it depends mainly on the intensity of the pressure waves. The associated shear force is many times higher than the shear force associated with flexural failure modes. The high shear stresses may lead to direct global shear failure and it may occur very early (within a few milliseconds of shock wave arrival to the frontal surface of the structure) which can be prior to any occurrence of significant bending deformations.

B. Localized Structural Behavior

The close-in effect of explosion may cause localized shear or flexural failure in the closest structural elements. This depends mainly on the distance between the source of the explosion and the target, and the relative strength/ductility of the structural elements. The localized shear failure takes place in the form of localized punching and spalling, which produces low and high-speed fragments. The punching effect is frequently referred to as bleaching, which is well known in high velocity impact applications and the case of explosions close to the surface of structural members. Bleaching failures are typically accompanied by spalling and scabbing of concrete covers as well as fragments and debris.

Figure6: Breaching failure due to a close-in explosion of 6000kg TNT equivalent

C. Pressure-Impulse (P-I) Diagrams

The pressure-impulse (*P-I*) diagram is an easy way to mathematically relate a specific damage level to a combination of blast pressures and impulses imposes on a particular structural element. An example of a P-I diagram is shown in Figure 7 to show levels of damage of a structural member. Region (I) corresponds to severe structural damage and region (II) refers to no or minor damage. There are other *P-I* diagrams that concern with human response to blast in which case there are three categories of blast-induced injury, namely : primary, secondary, and tertiary injury.

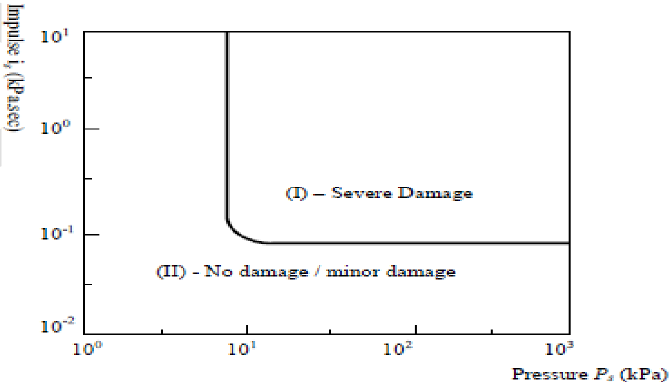

Figure 7: Typical pressure-impulse (*P-I*) diagram

VIII. CASE STUDY: COLUMN SUBJECTED TO BLAST LOADING

A ground floor column of a multi-storey building was analyzed. The parameters considered were the concrete strength (40MPa for NSC column and 80 MPa HSC column) and spacing of ligatures (400mm for ordinary detailing-OMRF (ordinary moment resisting frame) and 100mm for special seismic detailing-SMRF (seismic moment resisting frame)). It has been found that with increasing concrete compressive strength, the column size can be effectively reduced. In this case the column size was reduced from 500 x 900 mm for the

NSC column down to 350 x 750 for the HSC column. While the axial load capacities of the two columns are still the same. The blast load was calculated based on data from the Oklahoma bombing report (ASCE 1996) with a standoff distance of 11.2m. The simplified triangle shape of the blast load profile was used (fig 8).

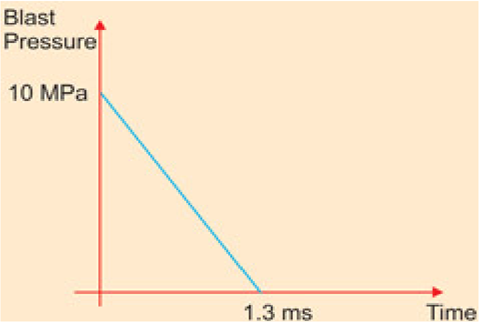

Figure 8: Simplified blast loading

The duration of the positive phase of the blast is 1.3 milliseconds. The 3D model of the column was analyzed using the nonlinear explicit code LS-Dyna 3D (fig 9) which takes into account both material nonlinearity and geometric nonlinearity. The strain rate- dependent constitutive model proposed in the previous section was adopted. The effects of the blast loading were modeled in the dynamic analysis to obtain the deflection time history of the column.

From this case study on the response of HSC and NSC columns subjected to bomb blast a strain-rate dependent constitutive model for concrete is proposed which is applicable to both normal strength and high strength concretes. It was found that shear failure was the dominant modes of failures for close-range explosion. HSC columns were shown to perform better than NCS columns (with the same axial load capacity) when subjected to extreme impulsive loading, they also had higher energy absorption capacity. Results from the study concluded that the impulsive loading is very different from the static loading in terms of the dynamic inertia effect and structural response.

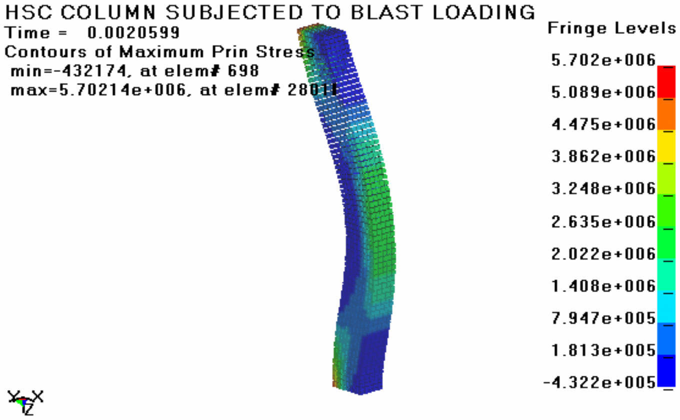

Figure 9. 3D model of the column using Explicit code LSDyna

IX. CONCLUSIONS

1. 1. The column response to non-uniform blast loads was shown to be significantly influenced by higher vibration modes. This was especially true for the unsymmetrical blast loads.

2. 2. The comparison between the normal strength column and the higher strength column showed that the critical impulse for the higher strength column case is significantly higher. This increase can be attributed to the added stiffness.

3. 3. For high-risks facilities such as public and commercial tall buildings, design considerations against extreme events (bomb blast, high velocity impact) are very important. It is recommended that guidelines on abnormal load cases and provisions on progressive collapse prevention should be included in the current Building Regulations and Design Standards. Requirements on ductility levels also help to improve the building performance under severe load conditions.

4. The surfaces of the structure subjected to the direct blast pressures cannot be protected; it can, however, be designed to resist the blast pressures by increasing the stand-off distance from the point of burst.

5. It is not economical to design all buildings for blast loading. Public buildings, tall structures and city centers have to be designed against terrorists' attacks and sudden explosions.

ACKNOWLEDGMENT

I would like to take this opportunity to express my profound gratitude and deep regard to Prof. Pallavi Pasnur, for her exemplary guidance, valuable feedback and constant encouragement throughout the duration of the project. Her valuable suggestions were of immense help throughout my project work. Her perceptive criticism kept me working to make this project in a much better way. Working under her was an extremely knowledgeable experience for me. I would also like to give my sincere gratitude to all the friends and colleagues who filled in the survey, without which this research would be incomplete.

REFERENCES

[1] A.Ghani Razaqpur, Ahmed Tolba and Ettore Constestabile, Blast loaing response of reinforced concrete panels reinforced with externally bonded GFRP laminates. Science direct, Composites: Part B 38 (2007)535-546.

[2] Alok Goyal, Blast resistant design: Critical issues, proceedings of the sixth structural engineering convection, pp IPXI-1-10, Dec 2008

[3] Anatol Longinow A, and Mniszewski KR., "Protecting buildings against vehicle bomb attacks," Practice Periodical on Structural Design and Construction, ASCE, New York, pp. 51-54, 1996.

[4] B. Lu, P. Silva, A. Nanni, and J. Baird, Retrofit for Blast-Resistant RC Slabs with Composite Materials, University of Missouri–Rolla, SP-230—76

[5] B.M. Luccioni1, R. D. Ambrosini & R.F. Danesi1, Assessment of blast loads on structures, WIT Transactions on Engineering Sciences, Vol 49, 2005

[6] Mario Paz, Structural dynamics, second edition, CBS publishers and distributors, 2004.

[7] Philip Esper, investigation of damage to buildings under blast loading and recommended protection measures, 9th International Structural Engineering Conference, Abu Dhabi, November 2003

[8] Ray Singh Meena, BE thesis report, National Institute of Technology, Rourkela (2009)

[9] Smith and Hetherington (1994) Blast and ballistic loading of structures, Oxford Butterworth-Heinemann.

[10] T. Ngo, P. Mendis, A. Gupta & J. Ramsay, "Blast Loading and Blast Effects on Structures – An Overview", The University of Melbourne, Australia, EJSE Special Issue: Loading on Structures (2007)

[11] T.D. Ngo, P.A. Mendis, & G. Kusuma, "Behavior of high-strength concrete columns subjected to blast loading, The University of Melbourne, Australia (2002).