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Blast Loading Effects on Steel Columns

Ashish Kumar Tiwary[1], Aditya Kumar Tiwary[2], Anil Kumar[3]
[1,2,3] *(Dept. of Civil Engineering, Jaypee University of Information Technology, Waknaghat, Solan (HP), India)*

ABSTRACT: *In the past two decades, the explosive devices have become the weapon of choice for the majority of terrorist attacks. Several factors including accessibility of information bomb devices manufacturing, mobility and portability, coupled with significant property damage and injuries, are responsible for significant increase in bomb attacks all over the world. A bomb explosion within or immediately nearby a building can cause catastrophic damage on the building's external and internal structural elements including collapse 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 some cases one or columns of the building are damaged which leads to failure of beam-slab systems above and thereby causing progressive collapse of the part of or entire structure. Thus, columns prone to blast are required to be investigated for high strain loading effects. In an attempt in this direction, this paper presents the modal analysis of a steel column taken from a large building frame subjected to blast loading. Implicit modal analysis was done to assess the robustness of numerical model prepared in explicit dynamic ANSYS-Autodyn 3D.*

Keywords: *Blast loading, Explosion phenomena, Material Behaviour, Analytical Calculation, High Strain Rate.*

I. INTRODUCTION

In the past two decades considerable emphasis has been given on problems involving effects of blast and earthquakes on structures. The blast problem is rather new; information about the development in this field is made available mostly through publication of the Army Corps of Engineers, Department of Defence, U.S. Air Force and other governmental offices and public institutes. Much of the work is done by the Massachusetts Institute of Technology, University of Illinois, and other leading educational institutions and engineering firms across the world. 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, particularly that above ground, 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 some cases one or columns of the building are damaged which leads to failure of beam-slab systems above and thereby causing progressive collapse of the part of or entire structure. Thus, columns prone to blast are required to be investigated for high strain loading effects. In an attempt in this direction, this paper presents the modal analysis of a steel column taken from a large building frame subjected to blast loading. Implicit modal analysis was done to assess the robustness of numerical model prepared in explicit dynamic ANSYS-Autodyn 3D.

II. LITERATURE REVIEW

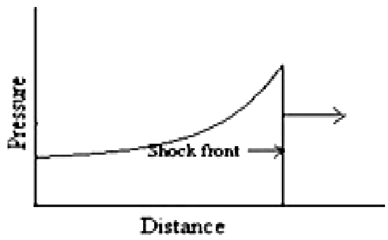
The analysis of the blast loading on the structure started in 1960s. US Department of the Army, released a technical manual titled “Structures to Resist the Effects of Accidental Explosions” in 1959. The revised edition of the manual TM 5-1300 (1990) has been most widely used by military and civilian organizations for designing structures to prevent the propagation of explosion and to provide protection for personnel and valuable equipments.

The methods available for prediction of blast effects on buildings structures are―empirical (or analytical), semi-empirical methods, and numerical methods. Empirical methods are essentially correlations with experimental data. Most of these approaches are limited by the extent of the underlying experimental database. The accuracy of all empirical equations diminishes as the explosive event becomes increasingly near field. Semi-empirical methods are based on simplified models of physical phenomena. The predictive accuracy is generally better than that provided by the empirical methods. Numerical (or first-principle) methods are based on mathematical equations that describe the basic laws of physics governing a problem. These principles include conservation of mass, momentum, and energy. In addition, the physical behaviour of materials is described by constitutive relationships. These models are commonly termed computational fluid dynamics (CFD) models.

A. Khadid et al. **[1]** studied the fully fixed stiffened plates under the effect of blast loads to determine the dynamic response of the plates with different stiffener configurations and considered the effect of mesh density, time duration and strain rate sensitivity. He used the finite element method and the central difference method for the time integration of the nonlinear equations of motion to obtain numerical solutions. A.K. Pandey et al. **[2]** studied the effects of an external explosion on the outer reinforced concrete shell of a typical nuclear containment structure. The analysis has been made using appropriate non-linear material models till the ultimate stages. An analytical procedure for nonlinear analysis by adopting the above model has been implemented into a finite element code DYNAIB. Alexander M. Remennikov **[3]** studied the methods for predicting bomb blast effects on buildings. When a single building is subjected to blast loading produced by the detonation of high explosive device. Simplified analytical techniques used for obtaining conservative estimates of the blast effects on buildings. Numerical techniques including Lagrangian, Eulerian, Euler- FCT, ALE, and finite element modelling used for accurate prediction of blast loads on commercial and public buildings.

III. EXPLOSION AND BLAST LOADING

In general, an explosion is a result of a very rapid release of large amount of energy within a limited space. The sudden release of energy initiates a pressure wave in the surrounding medium, known as a shock wave as shown in Figure 1). When an explosion takes place, the expansion of the hot gases produces a pressure wave in the surrounding air. As this wave moves away from the centre of explosion, the inner part moves through the region that was previously compressed and is now heated by the leading part of the wave. As the pressure waves move with the velocity of sound, the temperature is about 3000ºC and the pressure is nearly 300 kbar causing the velocity to increase. The inner part of the wave starts moving faster and gradually overtakes the leading part of the waves. After a short period of time the pressure wave front becomes abrupt, thus forming a shock front somewhat similar to Figure 2). The maximum overpressure occurs at the shock front and is called the peak overpressure.



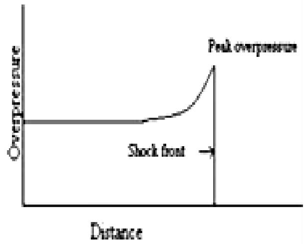


Fig 1 Variation of pressure with distance fig2.Formation of shock front

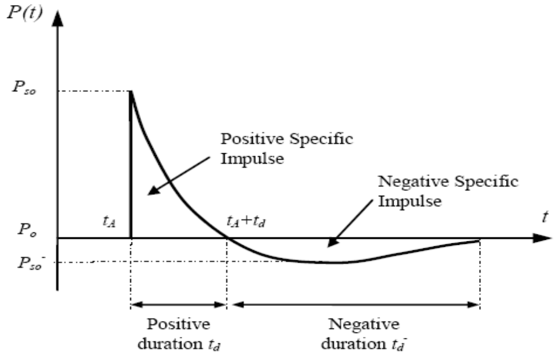


Fig. 3 Variation of overpressure with distance

Further, the overpressure in the shock front decreases steadily; the pressure behind the front does not remain constant, instead, falls off in a regular manner. After a short time, at a certain distance from the centre of explosion, the pressure behind the shock front becomes smaller than that of the surrounding atmosphere and so called negative-phase or suction. The front of the blast wave weakens as it progresses outward, and its velocity drops towards the velocity of the sound in the undisturbed atmosphere. This sequence of events is shown in the overpressure at time t_1, t_2….. t_6 as indicated. In the curves marked t_1 to t_5, the pressure has not fallen below that of the atmosphere, while in curve t_6 at some distance behind the shock front, the overpressure becomes negative (Figure 3).

3.1 How do Blast Loads Act on Buildings?

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.

3.2 Material Behaviours at High Strain Rates

Blast loads typically produce very high strain rates in the range of 10^2-10^4 s^{-1}. This rate changes the dynamic mechanical properties of target materials and, thereby changing the expected damage mechanisms for various structural elements. For reinforced concrete structures subjected to blast effects the strength of concrete and steel reinforcing bars can increase significantly due to strain rate effects. Figure 4 shows the approximate ranges of the expected strain rates for different loading conditions. It can be seen that ordinary static strain rate is located in the range 10^{-5}-10^{-6} s^{-1}, while blast pressures normally yield loads associated with strain rates in the range 10^2-10^4 s^{-1}.

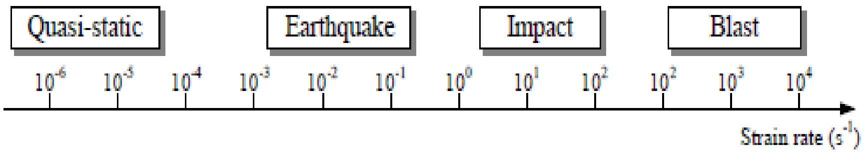


Fig. 4 Strain rates for different types of loading

3.3Dynamic Properties of Steel Under High-Strain Rates

Due to the isotropic properties of metallic materials, their elastic and inelastic response to dynamic loading can easily be monitored and assessed. Norris et al. (1959) tested steel with two different static yield strengths of 330 MPa and 278 MPa under tension at strain rates ranging from 10^{-5} s^{-1} to 0.1/s. Strength increase of 9-21% and 10-23% were observed for the two steel types, respectively. Dowling and Harding (1967) conducted tensile experiments using the tensile version of Split Hopkinton's Pressure Bar (SHPB) on mild steel using strain rates varying between 10^{-3} s^{-1} and 2000s^{-1}. It was concluded from this test series that materials of body centered cubic (BCC) structure (such as mild steel) showed the greatest strain rate sensitivity. It has been found that the lower yield strength of mild steel can almost be doubled; the ultimate tensile strength can increase by about 50%; and the upper yield strength becomes considerably higher, whereas the ultimate tensile strain decreases with increase in strain rate. Malvar (1998) also studied strength enhancement of steel reinforcing bars under the effect of high strain rates. This was described in terms of the dynamic increase factor (DIF), which can be evaluated.

IV. ANALYSIS OF COLUMN FOR BLAST LOADING

A ground floor column of a multi-storey building is analysed in this study. It is assumed that this column is vulnerable to blast lading being located at ground floor. The properties of the column are given in Table-1. The blast pressure coming from different values charge weights of TNT are considered with different positions (standoff distances) of the blast points relative to the column. The blast load was calculated by using Kinney and Graham’s approach (Table-2) for stand-off distances of 3m, 4m and 5m with charge weights of 20kg, 50kg and 100kg of TNT. This approach which is based on the large experimental data provided the following relation to determine the peak pressure from an explosion. The 3D model of a column (Figure5) was analyzed using ANSYS Explicit Dynamics. The effect of the blast loading was modeled in the dynamic analysis to obtain the total deflection, stress and strain in the column.

Table-1: Steel column properties	
Area of cross section (m^2)	16.7
Overall Depth (in)	21.06
Width of flange (in)	6.55
Thickness of flange (in)	0.65
Thickness of web (in)	0.405
Moment of Inertia about string axis (in^4)	1170
Height of steel section (in)	197
Mass Density (kg/m^3)	7830

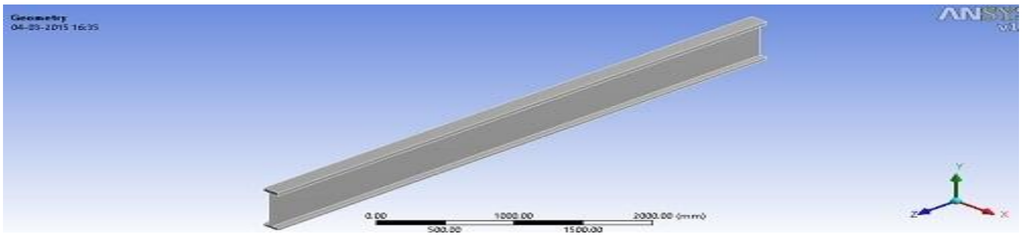


Fig 5 Geometric Model of Steel Colum in ANSYS/Autodyn.

Table-2: Kinney and Graham's approach (1985)	
Peak Incident Pressure (Bar)	$P_{pos} = P_0 \frac{808\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{\left[1+\left(\frac{Z}{0.048}\right)^2\right]\left[1+\left(\frac{Z}{0.32}\right)^2\right]\left[1+\left(\frac{Z}{1.35}\right)^2\right]}}$
Positive Time Duration	$t_{pos} = W^{1/3} \frac{980\left[1+\left(\frac{Z}{0.45}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^3\right] \times \left[1+\left(\frac{Z}{0.74}\right)^6\right]\sqrt{\left[1+\left(\frac{Z}{6.9}\right)^2\right]}}$ (msec)
Positive Impulse	$I_{pos} = \frac{0.067\sqrt{\left[1+\left(\frac{Z}{0.23}\right)^4\right]}}{Z^2\sqrt[3]{1+\left(\frac{Z}{1.55}\right)^3}}$ (bar – ms)
Peak Reflected Pressure	$P_{ref} = C_r P_{pos}$ where C_r = Coefficient of reflection.

The response of the column in terms of net maximum deformation and maximum principal stress developed is obtained for different stand-off distances and charge weights. The results are presented in the form of plots shown in Figure 7and figure 8. It has been clearly observed that the deflection in a column is very much depending upon the stand-off distance, i.e., smaller the distance larger will be the deflection. Similarly, the maximum principal stresses produced by these charge weights at different stand-off distance are shown in Fig 4.3(b). It is evident from the graph that stress of about 350 MPa is recorded when 100 kg TNT charge weight applied during analysis which is high and can cause failure of column at the mid-span (Figure 6).

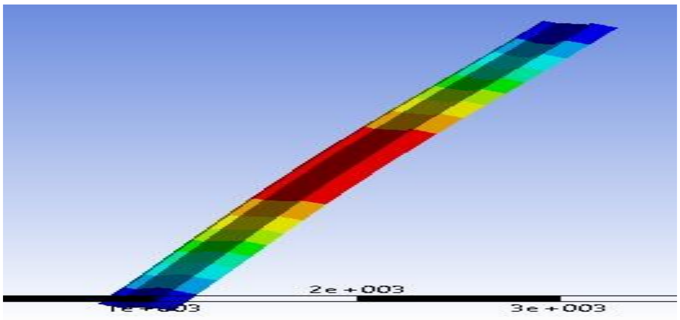


Fig 6 Column deformed under blast pressure.

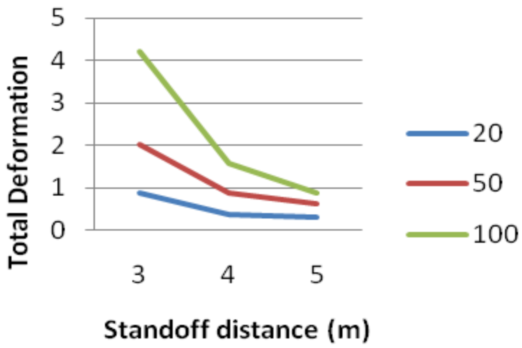


Fig. 7 Stand-off distance Vs Deformation

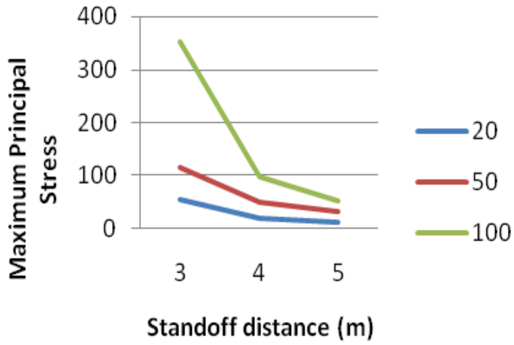


fig 8. Stand-off distance Vs Max. Principal Stress

V. CONCLUSION

The following observations and conclusions are drawn from the study presented.

- The Explicit Dynamic analysis revealed that, for axially loaded columns, there exists a critical lateral blast impulse. Any applied blast impulse above this value will result in the collapsing of the column before the allowable beam deflection criterion is reached.
- 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.
- The surfaces of the structure subjected to the direct blast pressures cannot be protected; it can, however, be designed to withstand the blast pressures by increasing the stand-off distance from the point of burst.
- 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. Increasing ductility levels also improve the building performance under abnormal load (as blast) conditions.

VI. FUTURE SCOPE OF STUDY

The following possibilities may be explored as part of further studies.

- Cases in which the axial load does not remain constant during the column response time are possible. These include situations where the bomb is located within the structure and the blast excites the girders connected to the column. The effect of this time-varying axial load should be studied.
- Cases should be studied when the explosions within a structure can cause failure of interior girders, beams and floor slabs.
- Tests and evaluation of connections under direct blast loads, and recommendations for base plate configurations and designs to resist direct shear failure at column bases.

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