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# Analysis of Blast Loading on Structural Components

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**Abstract:** ***The increase in the number of terrorist attacks especially in the last few years has shown that the effect of blast loads on buildings is a serious matter that should be taken into consideration in the design process. Although these kinds of attacks are exceptional cases, man-made disasters; blast loads are in fact dynamic loads that need to be carefully calculated just like earthquake and wind loads. The objective of this study is to shed light on blast resistant building design theories, the enhancement of building security against the effects of explosives in both architectural and structural design process and the design techniques that should be carried out. Firstly, explosives and explosion types have been explained briefly. In addition, the general aspects of explosion process have been presented to clarify the effects of explosives on buildings. To have a better understanding of explosives and characteristics of explosions will enable us to make blast resistant building design much more efficiently.***

**Keywords:** Blast Load, Explosive phenomenon, side-on overpressure, peak overpressure, Explosive

## 1. Introduction

The problem of structural resistance under explosive loads has been under investigation for many years and has been well advanced in the military community. This is also the reason that the majorities of these findings are not accessible to the public and are only restricted to military use. Nevertheless, some documentation that allows the prediction of the effects of an explosive blast is available for use by design engineers. The Eurocode EN 1991-1-7 [1] makes reference to the case of accidental loads and explosions, but it is mainly focused on impact actions, such as collisions from trucks, trains, ships, helicopters or any other vehicle in general. Reference is also made to gas explosions that take place in enclosed spaces but an overall approach for design under blast external loads is still missing. Some design strategies are also recommended aiming to ensure increased robustness in building structures that are to endure localized failure. However, no guidelines are provided in EN 1991-1-7 for the calculation of external blast induced loads.

## 2. Explosions and Blast Waves

### A. Ideal blast wave characteristics

An explosion can be defined as a very fast chemical reaction involving a solid, dust or gas, during which a rapid release of hot gases and energy takes place. The phenomenon lasts only some milliseconds and it results in the production of very high temperatures and pressures.

During detonation the hot gases that are produced expand in order to occupy the available space, leading to wave type propagation through space that is transmitted spherically through an unbounded surrounding medium. Along with the produced gases, the air around the blast (for air blasts) also expands and its molecules pile-up, resulting in what is known as a blast wave and shock front. The blast wave contains a large part of the energy that was released during detonation and moves faster than the speed of sound. Figure 1 shows the idealized profile of the pressure in relation to time for the case of a free air blast wave, which reaches a point at a certain distance from the detonation. The pressure surrounding the element is initially equal to the ambient pressure Po, and it undergoes an instantaneous increase to a peak pressure $P_{so}$ at the arrival time$t_A$, when the shock front reaches that point. The time needed for the pressure to reach its peak value is very small and for design purposes it is assumed to be equal to zero. The peak pressure Pso is also known as side-on overpressure or peak overpressure. The value of the peak overpressure as well as the velocity of propagation of the shock wave decrease with increasing distance from the detonation center. After its peak value, the pressure decreases with an exponential rate until it reaches the ambient pressure at $t_A+t_0$, to being called the positive phase duration. After the positive phase of the pressure-time diagram, the pressure becomes smaller (referred to as negative) than the ambient value, and finally returns to it. The negative phase is longer than the positive one, its minimum pressure value is denoted as Pso and its duration as to. During this phase the structures are subjected to suction forces, which is the reason why sometimes during blast loading glass fragments from failures of facades are found outside a building instead in its interior.

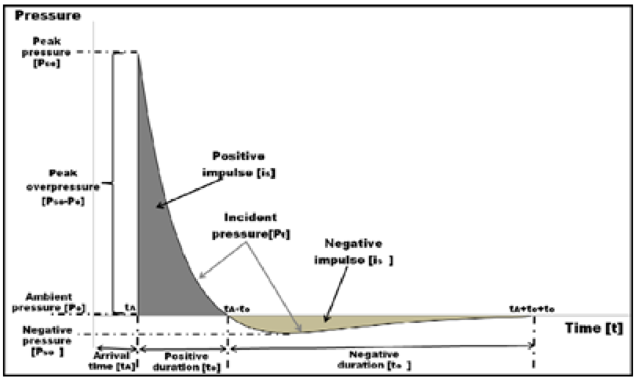


**Figure 1:** Ideal blast wave's pressure time history

The negative phase of the explosive wave is usually not taken into account for design purposes as it has been verified that the main structural damage is connected to the positive phase. Additionally, the pressures that are produced from the negative phase of the blast wave are relatively small compared to those of the positive phase and since these are in the opposite direction, it is usually on the safe side to assume that they do not have a big impact on the structural integrity of buildings under blast loads. However, the pressures that are below the ambient pressure value should be taken into account if the overall structural performance of a building during a blast is assessed and not only its structural integrity. As can be seen from Figure 1, the positive incident pressure decreases exponentially. The following form of Friedlander's equation has been proposed, and is widely used to describe this rate of decrease in pressure values:

$$P_s(t) = P_{so}\left(1-\frac{t}{t_0}\right)e^{-b\frac{t}{t_0}} \qquad (2.1)$$

Where, $P_{so}$ is the peak overpressure, to is the positive phase duration, b is a decay coefficient of the waveform and t is the time elapsed, measured from the instant of blast arrival. The decay coefficient b can be calculated through a non-linear fitting of an experimental pressure time curve over its positive phase. Besides the peak pressure, for design purposes an even more important parameter of the blast wave pulse is its impulse because it relates to the total force (per unit area) that is applied on a structure due to the blast. It is defined as the shaded area under the overpressure-time curve of Figure 1. The impulse is distinguished into positive is and negative$i_s^{-}$, according to the relevant phase of the blast wave time history. Equation (2) gives the expression in the case of the positive impulse, which is more significant than its negative counterpart in terms of building collapse prevention,

$$i_s = \int_{t_A}^{t_A+t_0} P_s(t)dt \qquad (2.2)$$

For the above Friedlander equation (1), the positive impulse can be analytically calculated as

$$i_s = \frac{P_{so}\,t_0}{b^2}\left[\left[b-1+e^{-b}\right]\right] \qquad (2.3)$$

This equation constitutes an alternative way for solving iteratively for the decay parameter b when the values of the is, $P_{so}$ and $t_0$ are known from experimental data.

### B. Scaling laws

One of the most critical parameters for blast loading computations is the distance of the detonation point from the structure of interest. The peak pressure value and velocity of the blast wave, which were described earlier, decrease rapidly by increasing the distance between the blast source and the target surface, as shown in Figure 2. In the figure only the positive phases of the blast waves are depicted whose durations are longer whenever the distance from the detonation point increases.

The effect of distance on the blast characteristics can be taken into account by the introduction of scaling laws. These laws have the ability to scale parameters, which were defined through experiments, in order to be used for varying values of distance and charge energy release. The experimental results are, in this way, generalized to include cases that are different from the situated at the same scaled distance from a target surface, similar blast waves are produced at the point of interest as long as they are under the same atmospheric conditions. Sachs scaling is also suitable in the case of different atmospheric conditions. According to Hopkinson-Cranz law, a dimensional scaled distance is introduced as described by Equation (4).

$$Z = \frac{R}{\sqrt[3]{W}} \qquad (2.4)$$

where, R is the distance from the detonation source to the point of interest [m] and W is the weight (more precisely: the mass) of the explosive [kg].

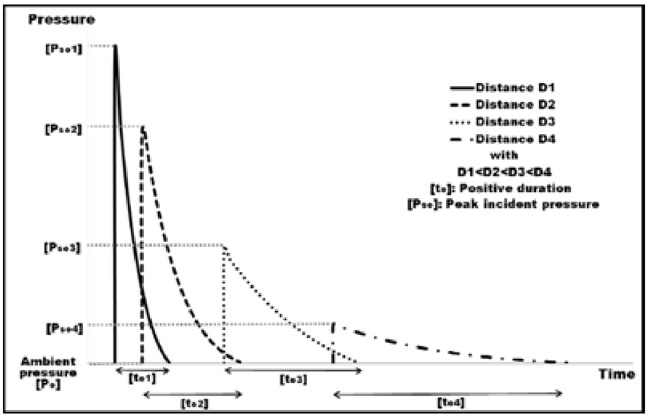


**Figure 2:** Influence of distance on the blast positive pressure phase.

Thus, suppose that an explosive charge of weight $W_1$ and characteristic size $d_1$, situated at distance $R_1$ from the point of interest, produces at this point a blast wave of peak overpressure P, impulse $i_1$, duration $t_{01}$, with arrival time $t_{a1}$ and that$R_1 / \sqrt[3]{W_1} = \lambda$. Then, what this scaling law implies is that a blast wave with the same peak overpressure P and similar form would be produced at this point by another explosive charge $W_2$ of characteristic dimension $d_2 = \lambda d_1$, situated at distance $R_2 = \lambda R_1$. Further, at the given point due to $W_2$ we would have: impulse $i_2 = \lambda i_1$, duration $t_{02} = \lambda t_{01}$, and arrival time $t_{a2} = \lambda t_{a1}$ . It is essential to underline that under this formulation all distance and time parameters of a blast wave are scaled by the same factor λ but pressure and velocity values remain unchanged at similarly analogous times.

### C. Explosive type and weight

In the present paper the focus will be on building structures, as these have proven to be the most common targets of terrorist attacks with the use of explosive devices. Nevertheless, the procedure that should be followed in the case of different structural elements is practically the same. The first step in designing a building to sustain blast loading is the definition of the type and weight of the explosive for which the design will be performed. Several types of explosives are available nowadays, any of which could be used for conducting an attack against a structure. In the majority of the cases solid explosives will be used in improvised explosive devices (IED), because of their transportability, relatively easy manufacturing and the possibility of their placement in vehicles that could be moved in the vicinity, adjacent or within (e.g. underground garages) a building. The wide variety of explosives has led to the adoption of a universal quantity, which is used for all necessary computations of blast parameters.

TNT (Trinitrotoluene) was chosen as its blast characteristics resemble those of most solid type explosives. An equivalent TNT weight is computed according to Equation that links the weight of the chosen design explosive to the equivalent weight of TNT by utilizing the ratio of the heat produced during detonation:

$$W_e = W_{exp} \frac{H^d_{exp}}{H^d_{TNT}} \qquad (2.5)$$

where, $W_e$ is the TNT equivalent weight [kg],

$W_{exp}$ is the weight of the actual explosive [kg], $H^d_{exp}$ is the heat of detonation of the actual explosive [MJ/kg], and $H^d_{TNT}$ is the heat of detonation of the TNT [MJ/kg].

It is worth mentioning that approximately one third of the total chemical energy of the explosives released by detonation. The rest is released at a slower rate as heat of combustion through burning of the explosive products mix with the surrounding air. Several tables that describe the heat output of most known explosives can be found in [8-9]. Table 1 provides estimates of the produced heat of detonation of some common explosives as defined in [8]. These values can be used for the calculation of the equivalent TNT weight with the use of Equation (2.5).

**Table 1:** Indicative Values Of Heat Of Detonation Of Common Explosives [6].

| Name of explosive | Heat of detonation (MJ/Kg) |
|---|---|
| TNT | 4.10-4.55 |
| C4 | 5.86 |
| RDX | 5.13-6.19 |
| PETN | 6.69 |
| PENTOLITE 50/50 | 5.86 |
| NITROGLYSRIN | 6.30 |
| NITROMETHANE | 6.40 |
| NITROCELLULOSE | 10.60 |
| AMON./NIT.(AN) | 1.59 |

**Table 2:** Indicative TNT Equivalent Mass FACTORS [10]

| Name of explosive | TNT equivalent mass factor | |
|---|---|---|
| | Peak overpressure | Impulse |
| TNT | 1 | 1 |
| C3 | 1.08 | 1.01 |
| C4 | 1.37 | 1.19 |
| CYCLOTOL | 1.14 | 1.09 |
| OCTOL 75/75 | 1.06 | 1.06 |
| TERYL | 1.07 | 1.05 |
| HMX | 1.02 | 1.03 |
| AMOTOL | 0.99 | 0.98 |
| RDX | 1.14 | 1.09 |

**Table 3:** Upper Limit of Charge Weight per Means of Transportation

| Carrier | Explosive weight (Kg) |
|---|---|
| Bag | 10 |
| Medium sized car | 200 |
| Large sized car | 300 |
| Pick-up truck | 1400 |
| Van | 3000 |
| Truck | 5000 |
| Truck with trailer | 10000 |

These factors can be used to determine the weight of TNT that produces the same blast wave parameters as the ones from another explosive of certain weight. The comparison of these blast wave parameters can be done either for pressure or impulse values, so the table 1 contains two factors depending on the used method. The weight of an explosive is usually estimated by taking into account a relevant attack scenario, which would involve a vehicle-borne or a personnel-borne improvised explosive device. Clearly, the larger the used vehicle that could be directed towards a structure, the larger the weight of the explosives it could carry leading to higher equivalent TNT weight values. In Table 1 an estimate of the quantity of explosives that could be transported by various vehicle types is presented. The engineer, following the relevant regulations and in consultation with the building owner, should decide on the type of explosive and size of vehicle that could be used for transportation, so as to be able to compute the equivalent weight of TNT for which the structure should be designed. Due to a variety of such uncertainties, it is recommended to apply a safety factor to the charge weights and augment them by approximately 20%.

## 3. Explosion and Blast-Loading Types

Non-contact, unconfined explosions, external to a structure are considered in this report. As shown in Figure 3, they can be distinguished in three basic types, which depend on the relative position of the explosive source and the structure to be protected, i.e. on the height H* above ground, where the detonation of a charge W occurs, and on the horizontal distance RG between the projection of the explosive to the ground and the structure. These three explosion types are:

(a) Free-air bursts: The explosive charge is detonated in the air; the blast waves propagate spherically outwards and impinge directly onto the structure without prior interaction with other obstacles or the ground.

(b) Air bursts: The explosive charge is detonated in the air, the blast waves propagate spherically outwards and impinge onto the structure after having interacted first with the ground; a Mach wave front is created.

(c) Surface bursts: The explosive charge is detonated almost at ground surface, the blast waves immediately interact locally with the ground and they next propagate hemi spherically outwards and impinge onto the structure.

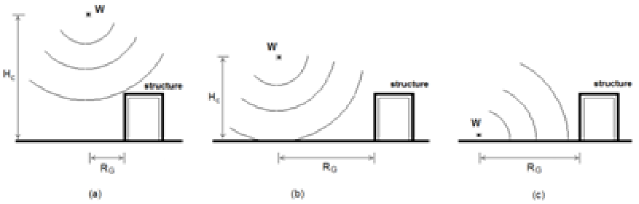


**Figure 3:** Types of external explosions and blast loadings; (a) Free-air bursts, (b) Air bursts, and (c) Surface bursts.

Associated to each of these explosion types is a characteristic blast loading of the structure, as reflections and interference phenomena along the propagation path can greatly modify the wave intensity and consequently the loading pressures. More practical information about this explosion and loading distinction will be provided in the following sections.

## 4. Calculation of Structural Blast Loads Blast Pressure Determination

There are various relationships and approaches for determining the incident pressure value at a specific distance from an explosion. All the proposed relationships entail computation of the scaled distance, which depends on the explosive mass and the actual distance from the center of the spherical explosion.

Kinney [3] presents a formulation that is based on chemical type explosions. It is described by Equation (4.1) and has been used extensively for computer calculation purposes,

$$P_{so} = P_o \frac{808\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\left[\left[1+\left(\frac{Z}{0.048}\right)^2\right]\left[1+\left(\frac{Z}{0.32}\right)^2\right]\left[1+\left(\frac{Z}{1.35}\right)^2\right]\right]} \tag{4.1}$$

where Z ($m/Kg^{\frac{1}{3}}$) is the scaled distance, Equation (2.4), and Po is the ambient pressure. Other relationships for the peak overpressure for spherical blast include those of Brode [10], shown in Equations (4.2) and (4.3). They depend on the magnitude of the explosion, Equation (4.2) is valid where the peak overpressure is over 10bar (=1MPa) (near field explosions) and Equation (4.3) for pressure values between 0.1 bar and 10 bar (0.01MPa-1MPa) (medium bars and far-field explosions). The scaled distance is measured in m/kg1/3 and the pressure Pso in,

$$P_{so} = \begin{cases} \frac{6.7}{Z^2} + 1, \text{for } P_{so} > 10 \ \dots (4.2) \\ \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - \frac{19}{1000} \ \text{for } 0.1 < P_{so} < 10 \dots (4.3) \end{cases}$$

Another formulation, that is widely used for computing peak overpressure values for ground surface blast has been proposed by Newmark[11] and does not contain categorization according to severity of the detonation:

$$P_{so} = 6784\frac{W}{R^3} + 93\sqrt{\frac{W}{R^3}} \tag{4.4}$$

where, $P_{so}$ is in bars, W is the charge mass in metric tons (=1000kg) of TNT andR is the distance of the surface from the center of a spherical explosion in m.

Mills [12] have also introduced an expression of the peak overpressure in kPa, in which W is expressed in kg of TNT and the scaled distance Z is in m/kg1/3, which reads:

$$P_{so} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} \tag{4.5}$$

## 5. RC Column Subjected to Blast Loading

Determine free-field blast wave parameters for a surface burst. A ground floor column of a multi-story building is analyzed in this study. It is assumed that this column is vulnerable to blast lading being located at ground floor. The blast pressure coming from same values charge weights of TNT are considered with same positions (standoff distances) of the blast points relative to the column. The blast load was calculated. The 3D model of a column was analyzed using ANSYS Explicit Dynamics. The effect of the blast loading was modeled in the dynamic analysis to obtain the total deformation, directional deformation, max principle elastic strain, min principal stress, max shear elastic strain, max shear stress, shear elastic strain, shear stress in the column.

Problem: Determine free-field blast wave parameters for a surface burst.
Procedure:
Step 1. Select point of interest on the ground relative to the charge. Determine the charge weight, and ground distance$R_G$.
Step 2. Apply a 20% safety factor to the charge weight.
Step 3. Calculate scaled ground distance$Z_G$:
$Z_G = \frac{R}{\sqrt[3]{W}}$
Step 4: Determine free-field blast wave parameters from Figure 6 for corresponding scaled ground distance$Z_G$:
Read:
Peak positive incident pressure $P_{so}$
Shock front velocity $U_o$
Scaled unit positive incident impulse $i_s/\sqrt[3]{W}$
Scaled positive phrase duration $t_o/\sqrt[3]{W}$
Scaled arrival time $t_A/\sqrt[3]{W}$
Multiply scaled values by $\sqrt[3]{W}$ to obtain absolute values.

Example:
For height h = 6 m,
Solution:
Step 1:
Given: Charge weight=1000 Kg, Rh $=\sqrt{15^2 + 6^2} = 16.2$ m.
Angle of incident (α) = $\tan^{-1}\left(\frac{16.2}{15}\right) = 21.2^0 < 45^0$
Angle of incident (α) = $45^0$
Step 2:
W = 1000kg
Step 3:
For point of interest: $Z_G = \frac{R}{\sqrt[3]{W}} = 1.62 m/kg^{1/3}$
Step 4:
Determine blast wave parameters from Figure6 for
$Z_G = 1.62 m/kg^{1/3}$
$P_r$ = 2000kPa =2 Mpa

$P_{so}$ = 460kPa= 0.4Mpa

$\frac{i_s}{\sqrt[3]{W}}$ =$i_s$= 162.6 kPa-ms/kg$^{1/3}$= 1626.25kPa-ms= 1.6Mpa-ms

$\frac{i_r}{\sqrt[3]{W}}$= $i_r$=459.3 kPa-ms/kg$^{1/3}$ = 4593.01kPa-ms = 4.5Mpa-ms

$\frac{t_A}{\sqrt[3]{W}} = t_A = 1.1[1000]^{\frac{1}{3}} = 1.24$ ms

$\frac{t_o}{\sqrt[3]{W}} = t_0 = 2.0[1000]^{\frac{1}{3}} = 20.52$ ms

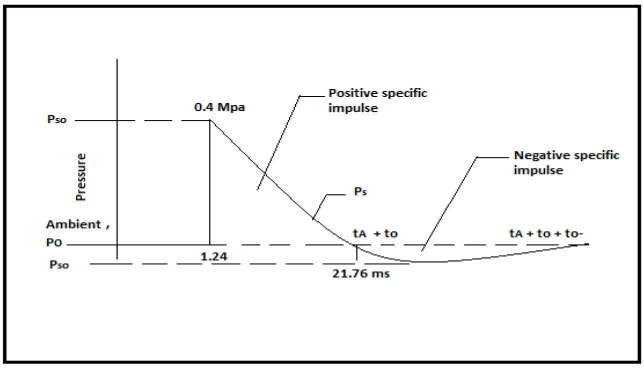
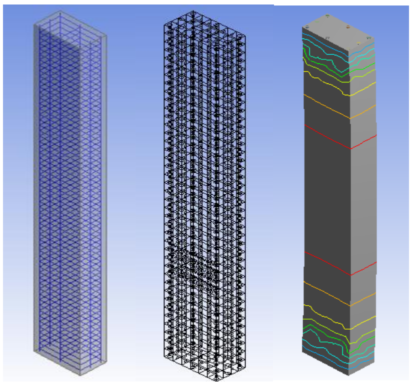


**Figure 4:** Free-field pressure –time variation for height = 6 m

A. Comparison HSC & NSC with stirrup's spacing 100 mm c/c:

HSC: High strength concrete column. NSC: Normal strength concrete column.

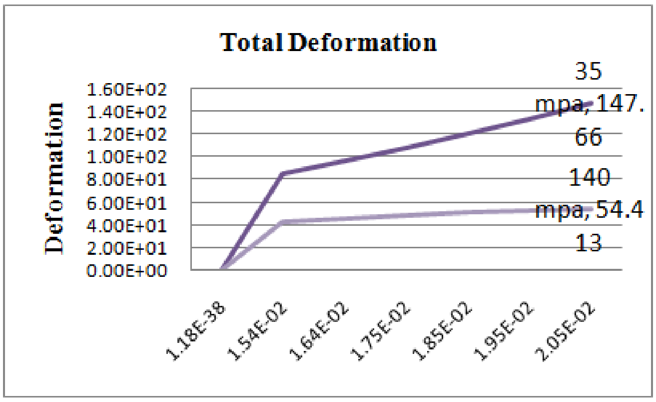


(a) (b) (c)

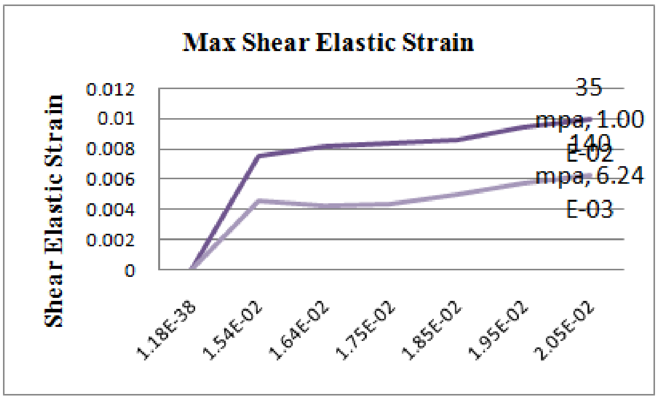
**Figure 5:** HSC & NSC column with lateral spacing of stirrups 100 mm with a) reinforcement b) meshing c) Deformation.

There are three Figures in which, (refer Figure 5.2 & 5.3)

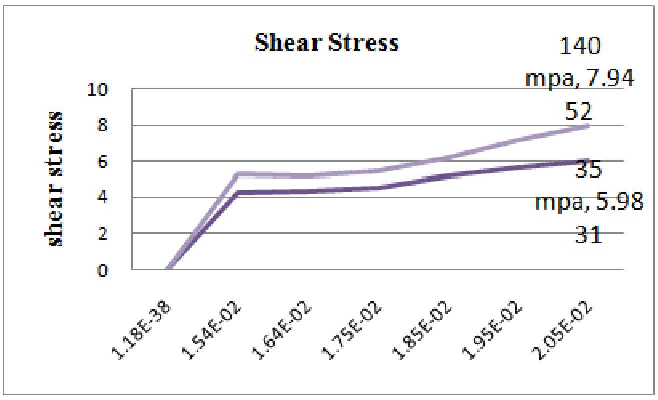
(a) Shows the reinforcement detail with lateral & longitudinal spacing of bars in column.
(b) Shows the meshing of column.
(c) Shows deformed shape of column in which red colure line indicates maximum deformation in column at that point.



**Graph 1:** Time vs Total Deformation



**Graph 2:** Time vs Max Shear Elastic Strain



**Graph 3:** Time vs Max Shear Stress

## 6. Conclusions and Future Scope of Study

### A. Conclusions

The following observations and conclusions are drawn from this study

- Total Deformation of NSC column is 172.23% more than HSC column.
- Max Shear Elastic Strain of NSC column is 60.25% more than HSC column.
- Max Shear Stress of HSC column is 130.74% more than NSC column.
- Max Shear Stress of HSC column is 108.41%more than NSC column. The finite element 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 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.
- 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.

### B. Future scope of study

- 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.
- Tests and design recommendations for base plate configurations and designs to resist direct shear failure at column bases.

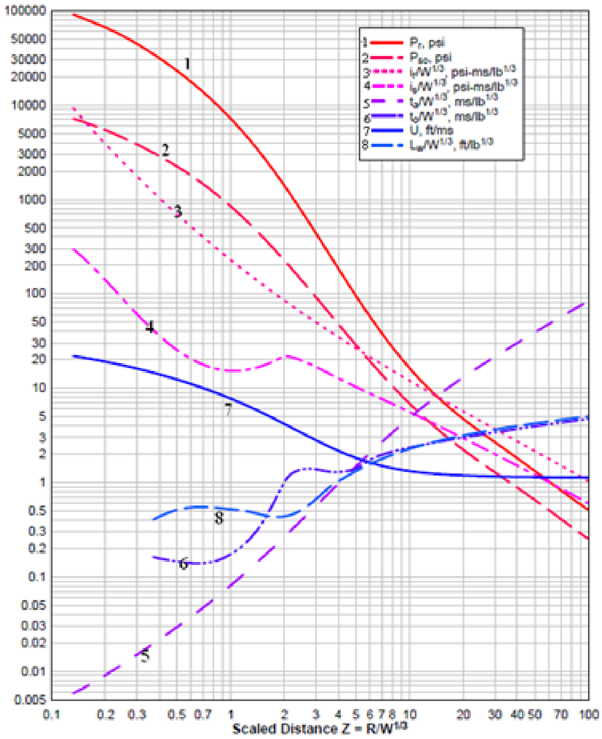


**Figure 6:** Positive Phase Shock Wave Parameter for a Spherical TNT Explosion in Free Air

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