Analytical Investigation on non-linear dynamic analysis of reinforced concrete building subjected to blast loading

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Abstract
The blast explosion causes catastrophic failure of structure both externally and internally. In this work analytical investigation is carried out on the blast performance of the reinforced concrete building frame. Reinforced concrete building connection is vital in the Moment Resistant Frames (MRF) and they play a vital role under constant blast load. It is important to design the building for blast loading since they are subjected to large displacements. The non-linear dynamic behavior of the building by time history analysis method is performed by using SAP2000 finite element stimulation software. Blast load is idealized as the triangular pulse for single degree of freedom system and the effect of the blast load at a different standoff distance on the building element is examined. The analytical method could predict the overall flexural, non-linear shear behavior and ductile response of the building at different modes. The results of the stimulations for various failure conditions such as maximum displacement, maximum base shear and spectral acceleration as per IS 1893-2016 for non-linear dynamic responses are investigated in this study.

Keywords: Blast loading, Finite Element simulations Displacement, Base shear, Standoff distance, spectral acceleration

1. Introduction
Reinforced cement concrete (RCC) building frames with columns are load bearing members where the progressive failure takes place from the critical members in the frame and the failure is due to the material loss that leads to catastrophic failure. Many blast attacks due to terrorist attacks or accidental events have caused complete damage of structures causing huge loss to the people and the structure. The damage or failure could be a serious threat to the structural safety. The blast load is considered or categorized as an impulsive loading due to its explosion effect that takes place in really short period. Blast loading taken into account is considered as a triangular one when plotted with pressure vs time graph. Hence the focus is carried out on the Nonlinear dynamic analysis using time history method. The most important parameters of this analysis are positive phase of blast loading, charge weight of the Trinitrotoluene (TNT) and the standoff distances of different explosives. Conventional design of RCC structures, are generally not designed to resist the masses because of explosion since the magnitude of the explosives is significantly higher than the design loads. Engineers increasingly are trying to find solutions at these situations to safeguard the building and their occupants. The main issue comes only when there is a complexity in the inelastic behavior in the structure like high strain rates and high deformations due to its nonlinear behavior. The idea of examination of the blast loading on the building frame structure started in the Department of the Military (USA) and produces a handbook on how to resist the structures subjected to accidental explosions. Since the experimental studies was dangerous and cost wise not effective various preliminary investigations on the analytical studies were investigated. Based on their predictions on the blast effect the building the methods for analysis are:

- Empirical/ analytical method
- Semi-empirical method
- Numerical method
Based on the blast demand there are three different types

- Surface blast/ Hemispherical burst
- Free air burst
- Air burst

The specific objective of this paper is analytically analyzing the nonlinearity of the framework subjected to blast pressure. In this investigation surface burst is considered that is the ground surface vibration due to the high explosive forming pressure waves that are hemispherical from the center of explosion. TNT(Trinitrotoluene) type of detonation causing disintegration of structures is considered here. When detonation occurs, there are disintegration of fragments these fragments are categorized into primary and secondary fragmental units based on the disintegration of the objects. The primary fragments like vehicles, exterior of the vehicles, small mass elements that travel at a very high velocity are affected by the detonation. The secondary fragments like non reinforced walls feel the pressure reflected due to the detonation and the pieces of wall radiate outward and hit the structure. This secondary effect on building has not been a very big concern in design. For dynamic analysis the resiliency of the ground needs to be considered.

1. Nitesh N Moon detailed about the lateral resistance of two columns when analyzed using ANSYS software by time history analysis method. Both columns failing due to shear with different stirrups was studied. For FEA analysis under blast load there exist a critical lateral load due to the blast impulse. The columns were prone to higher vibrations due to the non-uniform blast loads.

2. Ngyuen and Tran with a presumption described about the vertical walls subjected to dynamic effect. The blast effect is analyzed by the time-based responses due to the blast effect.

3. Hrvoje Draganic studied a numerical example for a structure that is affected by the blast effect. Preliminary assessment was done using assumptions and using SAP2000 where the model was designed based on pressure time history analysis.

4. Juraj Kralik and Michal Baranb explained the comparison between the wave effect due to the explosion analytically using AUTODYN software and compared it with the empirical formulas. The simulation due to the explosives loading explained the realistic results of the vibrations in the form of blast pressure and their influence on the components of the building.

5. Sindhura and Elavenil S investigated the effect of the blast loading under different plate thickness and different support conditions. The peak displacement values with respect to the support thickness was discussed.

6. M A Najafgholipoura and A R Arabib assessed the nonlinear shear behavior of the beam column joint, their behavior, joint strength and various modes of failure using SAP2000 based on stimulations three types of connections were designed using formulations. Shalva Marjanishvili and Brian Katz stated the magnitude and consequences of the damages in the framework due to its response by structural resiliency assessment method by following different design method approach and necessary tools. S H Sung and J W Chong stated the blast load prediction method with barriers on the buildings. S Elavenil and G M Samuel Knight carried out an experimental investigation on dynamic behavior of steel fiber reinforced concrete plates under impact load and assessed the results such as displacement, velocity and acceleration. Yan Liu et al., experimentally and analytically analyzed the beams and columns to live explosives and developed empirical expressions for SDOF (single degree of freedom) model and assessed the damages during deteriorations. P Vinotini and S Elavenil developed empirical method using military manuals and found out the dynamic response of a high rise building subjected to blasting effect in MATLAB at different standoff distance. Dan Wang et al., using physical model and numerical stimulation analyzed the blast wave effect on the building and the damages were assessed. Alok Dua et al., experimentally investigated the response of the RC columns of different cross sections subjected to blast effects and the damage index of the column was evaluated. Paki Turgut et al., a case study on high energy combustible gas and the structural damages due to the high-pressure effect was investigated. Eid Badshah et al., investigated on the response of masonry building for free air burst and surface burst explosion and stated different retrofitting techniques to increase the efficiency of the building.
2. Methodology

Figure 1 shows the methodology carried out on the analytical investigation of 10-storey building for blast loading using nonlinear time history analysis on the premises of time-based responses like acceleration, storey level displacement, inter storey drift, and base shear.

Current design codes are used to design the static and dynamic analysis of the multi-level building. The building considered is 10 storey frame which is subjected to two explosives of charge weight 30kg and 60kg at standoff distances. Reinforced concrete buildings are among the foremost common structures and they are unit subjected to variety of static and dynamic masses. The analysis of concrete building under explosion is tough because the impulsive loading as a response has high intensity that occurs within a very short period of time. Generally, explosion is that the outcome of immediate and quick unleash of large amount of energy and is outlined by a physical or chemical process within the material. This happens when the explosives change of potential energy into mechanical work with creation of an undulation i.e., Blast wave and sound.

2.1 Blast phenomena

The design of blast load and their load assessment in the building is very tough because it changes the behavior of the building when prone to such explosive effects, but when not considered they cause structural damages. The blasting phenomena is mainly dependent on the factors like charge weight and the standoff distances where the vibrations are due to the explosions referred from the paper number (1). Blast load is idealized as pressure effect on the building. This is time-based effect therefore time history analysis is employed where the results of blast wave versus the time is studied for understanding the phenomena. Time is a major factor considered in the blast phenomena since it occurs for very short duration to obtain the results. To assess the blast wave effect with atmospheric effect the regular frame building with ideal beams and columns are considered. Columns are fixed at the supports and subjected to nonlinear modal analysis using stimulation software. The main objective of the work is to study the non-linearity of the frame for the overpressure or incident pressure or reflective pressure.

2.2 Peak over pressure ($P_{so}$)

Peak overpressure is referred as $P_{so}$ and the close ambient pressure is referred as $P_o$. The pressure travels at the time $t_d$ and creates a vacuum before returning to close conditions at time $t_d + t_b$. The shock wave penetrates through the windows, doors and other openings shown in figure 2 as if even the building is capable of resisting the blast load finally causing disintegration of the elements of the building referred from paper LPG explosion damage of a reinforced concrete building.
Figure 2. Represents hemispherical and circular shock wave for airburst type explosion which has been referred from the article “Structural Response to blast loading the effects of corrosion on reinforced concrete structures”

2.3 Behavior of the multistorey structures

Blast resistant buildings are designed based on the standards of the industry and company standards by evaluating the risks based on the site parameters that can influence the explosion effect on the building. As per the API recommendations when the peak side overpressure is within 0.281 kg/cm² there will be damages to the internal wall and the roof will deflect. When the peak overpressure ranges from 0.45-0.85 kg/cm² there major damage and collapses sometimes leading to the total destruction of the structure. In this paper for the explosion loading corresponding peak overpressure and time duration is calculated and the frequencies of the explosion is determined based on industrial data from the paper Analytical investigation of high-rise building under blast loading. The buildings can be controlled from the disintegration by strengthening the glazing and its frame to the explosion overpressure. Installing external wall for explosion resistant design.

The vibrations are caused when the building develops less resistance to withstand the blast wave effect aerodynamically. The displacement of the building will take place in the direction of the propagation of the wave. During this progression of the blast wave will propagate through the building. The incident wave velocity and arrival time and decay are the parameters considered during the blast effect which is also called as the dynamic properties of the blast phenomena. The parameters and their values for different charge weights are shown in the table 1&2.

| Floor               | Time of arrival ($t_A$) ms | Decay time ($t_0$) ms | Velocity (U) m/ms |
|---------------------|----------------------------|-----------------------|-------------------|
| Ground level at 0.00m | 5.38                       | 10.2081               | 1.0110            |
| Roof level at 40.00m | 67.16                      | 24.680                | 0.380             |

Table 1: Detonation pressure wave velocity for 30 kg charge weight

| Floor               | Time of arrival ($t_A$) ms | Decay time ($t_0$) ms | Velocity (U) m/ms |
|---------------------|----------------------------|-----------------------|-------------------|
| Ground level at 0.00 m | 3.73                       | 8.0641               | 0.9300            |
| Roof level at 40.00 m | 49.68                      | 17.6050              | 0.2551            |

Table 2: Detonation pressure wave velocity for 60 kg charge weight
The modal analysis from the software determines the natural frequencies of the vibration which is related to the time period. The vibrations of the detonations in terms of velocity which is independent of the frequency is measured using instruments working on electrical or mechanical principles. Table 3 shows the excitation frequencies at which dynamic loads act on the system.

Table 3: Natural time period (s) and varying Frequency (C/S) of the building

| Steps | 10 m | 12.5 m | 15 m |
|-------|------|--------|------|
|       | T(s) | F(C/S) | T(s) | F(C/S) | T(S) | F(C/S) |
| 1     | 0.97 | 1.07   | 0.91 | 1.22   | 0.82 | 2.25   |
| 2     | 0.93 | 1.13   | 0.87 | 1.29   | 0.8   | 2.5    |
| 3     | 0.88 | 1.19   | 0.85 | 1.35   | 0.79 | 2.36   |
| 4     | 0.83 | 1.21   | 0.72 | 1.39   | 0.74 | 2.49   |
| 5     | 0.76 | 1.59   | 0.68 | 1.67   | 0.72 | 2.5    |
| 6     | 0.6  | 1.59   | 0.62 | 1.7    | 0.66 | 2.51   |
| 7     | 0.63 | 1.59   | 0.57 | 1.75   | 0.69 | 2.57   |
| 8     | 0.58 | 1.65   | 0.54 | 1.82   | 0.58 | 2.87   |
| 9     | 0.51 | 1.83   | 0.49 | 1.98   | 0.56 | 2.96   |
| 10    | 0.47 | 2.56   | 0.46 | 2.43   | 0.51 | 3.24   |

2.4 Structural modeling

The model is the representation of the actual mechanical system which is used to calculate the individual displacement for different mode shapes. When vibration in any coordinate influences the vibration in other coordinates the system may be represented by several mutually independent models. Structure of 10-storey is considered which is of reinforced concrete structure. The plan of the structure is symmetrical plan, having the area of 16 m x 16 m. Each spacing of the gridline is 4 m on both sides. The height of each story of the structure is 4 m. The overall height of the structure is 40 m. The plan and elevation of the frame of the structure is modeled in SAP 2000 software is shown in Figure 3. Figure 4 shows the corresponding load case considered in this paper.

![Figure 3](image-url)

**Figure 3**: (a) Plan of the framed structure (b) Elevation of the RC structure

| S. No | Load case name | Load case type       |
|-------|----------------|----------------------|
| 1     | Dead           | Linear static        |
| 2     | Modal          | Modal                |
| 3     | Surface finish | Linear static        |
| 4     | Wall load      | Linear static        |
| 5     | Live load      | Linear static        |
| 6     | Wind load      | Linear static        |
| 7     | EQX            | Linear static        |
| 8     | EQZ            | Linear static        |
| 9     | THX            | Non-linear modal history (FNA) |
| 10    | THY            | Non-linear modal history (FNA) |
| 11    | TH10M          | Non-linear modal history (FNA) |

Table 4: Load case details
2.4.1 Specifications of the building
The total height of the structure is 40 m with 4 m floor height typically on all levels. For dynamic analysis the static moduli of elasticity are assumed. The $f_y$ of rebar (yield strength) is 300 MPa with modulus of elasticity 210 GPa. Reinforcing steel that are not suitable for static should be used for members subjected to dynamic loads. The reinforcement of such members shall not be made from smooth reinforcing steel. The frame is symmetric with beams of size 300x700 mm and column size of 900x900 mm. The reinforced concrete wall is referred as an infill material and the thickness of the slab is considered as 175 mm. Reinforced concrete wall is considered as an infill and load bearing member and the infill thickness considered is 150 mm between the slabs of 150 mm. The dynamic analysis using ritz vector method of modal analysis is carried out to solve the nonlinear blast effect. The buckling and the bending of the building subjected to dynamic behavior for 30 kg and 60 kg bomb is shown in the figure 5 and 6 respectively.

![Figure 4: Deformation of the building for 30kg bomb weight](image)

![Figure 5: Deformation of the building for 60kg bomb weight](image)

3. Results and Discussion
The behavior of the building with the time varying blast effect considering different standoff distances from one phase of the building is investigated in this paper. The effect of the time-based acceleration is significant in the analysis. And the stress contour for varying frequencies is shown in the figure 7. It is observed that under close bomb range, the lateral displacement is higher. Over the period the peak positive reflected pressure decreases substantially with the increase in the length between the blasting nozzle and the building. The reasonable difference indicates the effect of the explosives for the maximum displacement.
3.1 Base Shear

Base shear is calculated based on the seismic zone factor, $sa/g$ is calculated based on the soil type for different soils, Importance factor is taken for as residential, response reduction factor with ordinary moment resisting frame and overall, it is multiplied with seismic weight of the structure. Base shear is calculated from IS 1893:2016 as follow and is shown in the figure 8.

$$V_b = A_h W$$

$$V_b = \text{Base Shear}$$

$$A_h = \left(\frac{Z}{2}\right) \frac{(Sa/g)}{(I/R)}$$

$Z =$Seismic Zone Factor $= 0.24$

$Sa/g =$Design acceleration coefficient of different soil

$I =$Importance Factor $= 1.2$

$R =$Response Reduction Factor for OMRF $= 3$

$W =$Seismic weight of floors

**BASE SHEAR**

|          |          |
|----------|----------|
| In X direction | $6.973 \times 10^3$ kN |
| In Y direction | $6.973 \times 10^3$ kN |

3.2 Deformation

The deformation shape and damage distribution at the near-collapse limit state for buildings designed under blast pressure according to the IS-4991-1968 is shown in the above figure 5 and 6.
3.3 Displacement
The maximum floor displacement for two different charge weight varied around 28.5% which determines the geometric deformations of the structure. As the length between the blast container increases the effect of the blast decreases by up to 40%. Hence, it is concluded that the overall displacement of the building at 10 m blast distance is massive than that of blast distance at 12.5 m and 15 m. The floor displacements for different bomb weights of 30 kg and 60 kg are shown in the fig 9&10 respectively. The maximum displacement was observed to be 0.025 mm for 60 kg charge weight at the nearest explosion. The reasonable difference indicates the effect of the explosives for the maximum displacement. All the displacements values obtained where within the safe limit as is 1893-2016 (i.e. 0.004h = 160mm)

![Figure 8: Floor Displacement for 30 kg explosive in mm](image)

3.4 Acceleration
The effect of the time-based acceleration is significant in the analysis. Figure 11 & 12 shows the lateral resistance of the frame. It is observed that under close bomb range the lateral displacement is higher. The acceleration dynamic response increases with the increase in the charge weight. From the figure 9&10 the spectral acceleration increases with the increase in the time and attains the maximum value of about 19.5 m/s² the acceleration amplitude increases depending on the quantity of the explosive. It reached the maximum amplitude at 1 s and slowly subsides as the time increases. From the analysis, it is investigated that maximum acceleration was observed to be on the top story of the building.

![Figure 9: Floor Displacement for 60 kg explosive in mm](image)
The building is loaded globally and is subjected to short duration blast effects where the peak pressure is based on the expression where charge weight and standoff distances. Figure 13 represents the blast wave effect. These two factors are the keystones for the defensive design. The global damage assessment cannot be done but the damages due to the explosion can also be a damage to the surrounding buildings.

**Figure 10**: Time (sec) vs Spectral acceleration in (m/s²) for 30 kg explosive

**Figure 11**: Time (sec) vs Spectral acceleration in (m/s²) for 60 kg explosive

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**Figure 12**: Represents the explosion effect on Frame building for different peak overpressure referred from paper 16 Suraj D Bhosale and Shrinivas R Survansh.
4. Conclusions
The vibration behavior determines the effect of system under dynamic loading and it is based on the model of the entire system and several degrees of freedom. The overall floor displacement of the building at 10 m blast distance is massive than at 12.5 m and 15 m. The pressure wave always radiates outward. From the force results for varying frequencies, it is observed that under close bomb range, the lateral displacement is higher. The dynamic response is investigated for different standoff distances and for different bomb weights and their time- based responses were observed and was referred from paper Dynamic response of fiber reinforced concrete plates under the impact load. The peak reflected pressure varies decreasingly with the increase in the height of the structure. At first local failure is observed and then the catastrophic damage is occurred in the building. Acceleration is relatively higher with the higher bomb weight and there might be a direct effect on the structure due to higher bomb weights which create a direct impact on the structure.

- The maximum storey drift found in Y direction is 0.00135 which is less than 0.004 as per IS 1893:2016.
- The maximum base shear in Y direction is found to be 6.973x 103 kN.
- The maximum displacement is 0.023 mm for 60 kg charge weight at the nearest explosion.
- The reduction in the acceleration by 33.33% for the standoff distance of 10 m for charge weight of 30kg in comparison to 60kg charge weight. Similarly at 12.5 & 15 m standoff distance there is a reduction in the acceleration value by 90% and 86.67% respectively.

The incident over pressure is observed with relatively low pressure at top and maximum at the bottom. The pressure was with respect to standoff distance the pressure was higher at 10 m from the building phase and found more at a distance of 12.5 m and 15 m range.

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