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Effect Of Sequential Blast Loading On Steel Structure

S. V. Totekar[1], and S. N. Madhekar[2]
[1]*PG student Structural Engineering, College of Engineering Pune, sharang.14.8@gmail.com*
[2]*Associate Professor Civil Engineering, College of Engineering Pune, snm.civil@coep.ac.in*

Abstract— Blast analysis is gaining importance as terrorist activities are increasing all around with more devastating tools and techniques. The September 11, 2001 attack on World Trade Centre towers in New York, Murrah Federal Office Building in Oklahoma City on 19 April 1995.showed different strategies used by terrorist for destruction. Blast activity comes with many folds i.e. pressure, fire, ground shock, fragments with massive energy associated with it; which proves hazardous to structure or facilities in turn affecting human and important equipment. Because of these, there is need to understand and provide protecting system for structure to resist blast. An advance numerical technique helps in stimulating explosive events which enable to understand effect and behavior of structure. Material behavior under impact load needs to be considered as under high stain rate strength increases compared to static loading conditions.
In the present study, the four storied steel structure is designed using conventional method and analyzed for progressive collapse on removal of ground floor columns is subjected to different blast scenarios. The structure designed to resist progressive collapse is subjected to single blast load on the front façade in one case while in second case it is subjected to sequential blast with same charge weight and standoff distance but different location of blast altered in length direction. The blast load is calculated for the said cases as per UFC 3-340-02 (2008) at each joint on front façade. The nonlinear nodal time history analysis is performed in SAP2000 with triangular impulse of blast load and hinges are assigned as per FEMA 356 to beams and columns. The displacements and hinge status observed revealed that the structure is unable to sustain said blast load as maximum lateral displacement is crossing the permissible limit as per UFC 3-340-02 (2008). Also the hinges status observed are beyond collapse state for few cases as per FEMA 356. Thus the structure designed using progressive collapse resistance guideline is unable to sustain single blast as well as sequential blast.
Keywords- Single blast, Sequential blast, UFC 3-340-02 (2008), FEMA 356, Nodal time history

1. INTRODUCTION

Blast analysis is gaining importance as terrorist activities are increasing all around with more devastating tools and techniques. Blast activity comes with many folds i.e. pressure, fire, ground shock, fragments with massive energy associated with it which proves hazardous to structure or facilities, in turn affecting human and important equipment. Because of these, there is need to understand and provide protecting system for structure. An advance numerical technique helps in stimulating explosive events which enable to understand effect and behavior of structure. The advancement in material e.g. metal foam which absorbs energy undergoing deformation without bouncing back, also these are advantageous as they can be recycled. Material behavior under impact load needs to be considered as under high stain rate strength increases compared to static loading conditions.

The steel structures have wide application in construction industry as it enhances pace, has better energy absorbing ability. Damping in the system proves to be insignificant as load is impulsive which last for few mili seconds. There are active damping systems which activate within mili seconds e.g. Magneto Rheological dampers and smart material however these proves to be expensive and their used is restricted to developed nations. Blast effects on human need to be understood to take in to account probable injuries or casualties' caused due to blast and after effects like fragmentation and fire. Planning aspect can also substantially affects the blast loading as location of blast, amount of charge weight and method of causing event.

II. BLAST LOADING BASICS

Explosions can be distinguished in detonations and deflagrations. The difference between detonations and deflagrations is the velocity of the reaction zone in the explosive. Deflagrations have a slower reaction zone than the sound speed. Detonations have a faster reaction zone than the sound speed. The most common explosives react with detonations. To compare different explosives the TNT equivalent can be used. The TNT equivalent is a method for quantifying the energy released in the detonation of an explosive substance, by comparing it to that of an equal quantity of TNT. It is known that 1 kg TNT releases the energy of 4.520x106 J.

2.1. Air Blast Waves

Blast overpressure radiates from the point of detonation but decays exponentially with distance from the source and time, and eventually becomes negative (outward-rushing force) subjecting the building surfaces to suction forces as a vacuum is created by the shock wave. The pressure at point is given by Friedlander equation (Baker) depends on time t

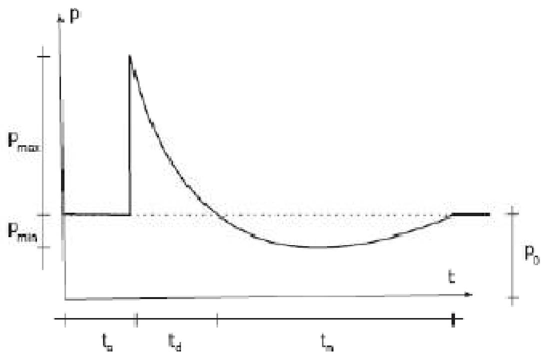

Figure 1 Pressure-time curve for air blast wave

The main characteristics of the development of the blast pressure wave are:

I. The arrival time ta of the shock wave to the point under consideration. This includes the time of the detonation wave to propagate through the explosive charge.
II. The peak overpressure pmax – The pressure attains its maximum very fast (extremely short rise-time), and then starts decreasing until it reaches the reference pressure p0 (in most cases the normal atmospheric pressure).
III. The positive phase duration td, which is the time for reaching the reference pressure. After this point the pressure drops below the reference pressure until the maximum negative pressure pmin. The duration of the negative phase is denoted as tn.
IV. The incident overpressure impulse, which is the integral of the overpressure curve over the positive phase td

The idealized (free air blast) form of the pressure wave of Figure 1 can be greatly altered by the morphology of the medium encountered along its propagation. The effects of the reflection depend on the geometry, the size and the angle of incidence. The reflected overpressure p_r is

$$p_r = 2p_{\max}\left[\frac{7p_o + 4p_{\max}}{7p_o + p_{\max}}\right] \quad \text{....1}$$

All parameters of the pressure time history are normally related to scale distance,

$$z = \frac{r}{\sqrt[3]{w}} \qquad \text{.... 2}$$

2.1.1 Pressure Time Distribution

The pressure at point can be described by the modified Friedlander equation (Baker) and depends on the time t from arrival of the pressure wave at time ($t=t_o-t_a$)

$$p(t) = p_o + p_{\max}\left(1-\frac{t}{t_d}\right)^{-\frac{bt}{t_d}} \qquad \text{....3}$$

Parameters involved in Eqn 2.3 are atmospheric pressure p_o, maximum overpressure p_{max}, duration of the positive pressure t_d and wave decay parameter b. Wave decay parameter b can be calculated from impulse. Blast wave parameters are presented on logarithmic scale with the scaled distance z as abscissa, also these can be obtained using different empirical expressions. The charts and expressions correlating scale distance and blast wave parameters are available in TM-5-1300 or UFC-3-340 manual of DoD of US and also implemented in program CONWEP which is in built in commercial packages like ABAQUS.

2.1.2 Impulse

The impulse of the air blast wave has big influence on the response of the structures. The impulse is area under the pressure time curve with the unit of pressure-sec. It is given by

$$I = \frac{0.067\sqrt{1+(z/0.23)^4}}{z^2\sqrt[3]{1+(z/1.55)^4}} \qquad \text{....4}$$

2.1.3 Negative Phase

Detonation produces a peak overpressure and afterwards the pressure decreases and drops below reference pressure i.e. atmospheric pressure. Effect of negative phase depends on scale distance. For scale distance greater than 50 and less than 20, effect of negative phase can't be neglected.

2.1.4 Wave Form Parameter

The wave decay or form parameter b in the Friedlander equation (Baker) describes the decay of the pressure-time curve. The Friedlander equation has the parameters p_{max}, t_d, and b. p_{max} and t_d can be readily found as described in section 2.1.1. There are several relations available to calculate the decay parameter b by using another known value of the pressure-time curve.

2.1.5 Shock Front Velocity

The arrival time of the shock front at different points can be used to calculate the velocity of the shock front. With the knowledge of this velocity the pressure can be obtained with the Rankine Hugoniot (Cabello) relationship.

2.2 TNT Equivalence

The different explosive materials are converted into equivalent of TNT using energy of TNT as the reference. This helps to simplify the charge weight of explosives in kilogram as a single entity.

III. PROBLEM STATEMENT

In the present study, the four storied steel structure was considered with 9 bays in x direction and

2 bays in y direction as shown in Fig 1.3. Typical bay length was 9.144m in x direction while bay spacing in y direction was 10.97m and 13.41m. The story height was 4.47m. The live load applied was 3.5kn/m^2.

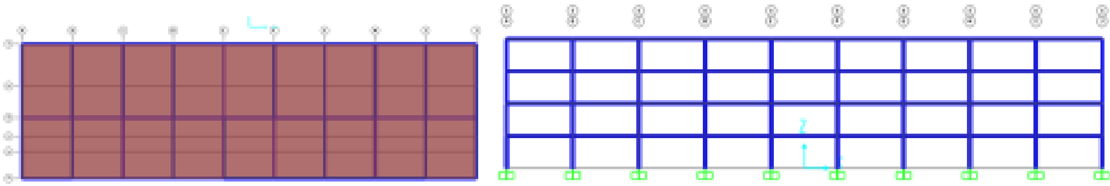

Fig 2 Plan and Elevation of structure

The front façade of steel structures was applied with nodal time with triangular impulsive load function. The blast load was estimated using UFC 3-340-02 (2008) for considered charge weight and standoff distance. The structure was 1st designed using conventional design and analyzed for progressive collapse resistance for column removal scenarios. After accessing for collapse resistance using UFC-4-023-03 (2013), the structure was redesigned and optimized. The redesigned structure was subjected to first single blast and then subjected to sequential blast. The Nonlinear hinges were assigned to column and beams as per FEMA 365 definition.

IV ANALYSIS

The nonlinear nodal time history analysis performed in SAP2000 nonlinear for single blast and sequential blast to compare response of structure. The blast load was calculated for different standoff distance and charge weights. The time lag difference between first and second blast of sequential case is 1milliseconds. The triangular impulsive load was applied at beam column joint. The blast load calculated being tabulated in Table 1.

Table 1 Blast load calculations

Story	Joint	Charge weight, kg	Standoff, m	Scaled distance, /kg$^{1/3}$	Positive duration, ms		Peak pressure, kPa	
1	1	500	29.20	3.68	0	1.25	0	1654
		500	64.77	8.16	1	3	1	193
	2	500	20.84	2.63	0	1.30	0	4134
		500	55.77	7.03	1	2.95	1	262
	3	500	13.55	1.71	0	0.55	0	15847
		500	46.80	5.90	1	2.75	1	386
	4	500	10.00	1.26	0	0.25	0	36517
		500	37.92	4.78	1	2.30	1	827
	5	500	13.55	1.71	0	0.55	0	15847
		500	29.2	3.68	1	2.25	1	1654
	6	500	20.84	2.63	0	1.30	0	4134
		500	20.84	2.63	1	2.30	1	4134
	7	500	29.20	3.68	0	1.25	0	1654
		500	13.55	1.71	1	1.55	1	15847
	8	500	37.92	4.78	0	1.30	0	827
		500	10	1.26	1	1.25	1	36517
	9	500	46.80	5.90	0	1.75	0	386
		500	13.55	1.71	1	1.55	1	15847
	10	500	55.77	7.03	0	1.95	0	262
		500	20.84	2.63	1	2.30	1	4134

V. RESULTS AND DISCUSSION

The response of structure is compared for single and sequential blast to observe behavior of structure. The structure designed after single blast showed 224 members failed stress check compared to 326 members. The displacement, velocity and acceleration responses are compared under single and sequential blast and are tabulated in table no. 1. Plastic moment and plastic rotations are compared for said both cases. The hinges states for single and sequential blast are seen in figure 2

Table 2

Response Parameters	Single Blast			Sequential blast		
	x	Y	z	x	y	z
Velocity (m/s)	0.01	6.65	1.11	13.58	20.73	4.09
Displacement (m)	0.04	0.56	0.01	0.16	1.02	0.04
Acceleration (m/s^2)	287.14	586.99	135.67	518.84	1547.29	271.01
Plastic moment (kNm)	2228.04			3111.57		
Plastic rotation (rad)	0.23			0.26		

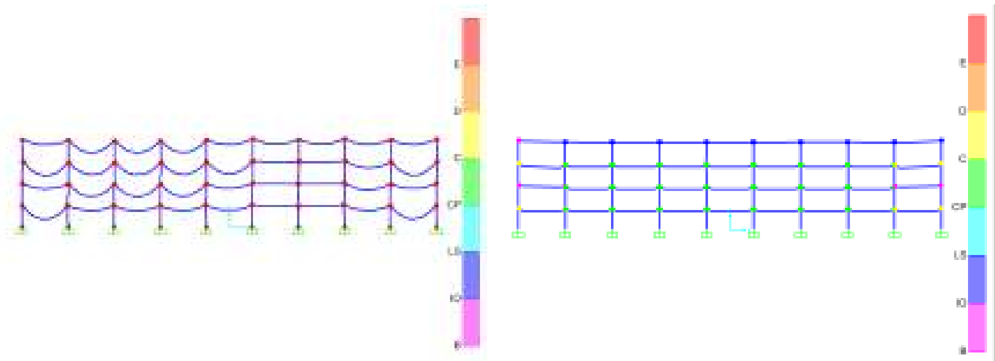

Figure 3 Sequential blast (left) and single blast (right)

VI. CONCLUSIONS

The nonlinear time history analysis using triangular impulsive loading showed 70% of members fail stress check under single blast in comparison to 98% members in case of sequential blast. The majority of hinges formed were in A to B state which transformed beyond E states on application of sequential blast. Implosive failure pattern observed on reanalyzing structure for gravity load after subjecting it for blast loading. The percentage increased in response of displacement, velocity, acceleration is 45%, 68% and 62% respectively on application of sequential blast case. Also the percentage increased in plastic moment and plastic rotation is 28% and 12% respectively. The part of structure collapsed under application of single blast load while on application of sequential blast load, the structure is totally collapsed.

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