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A Review of the Analytical Models in Blast Load Analysis of Reinforced Concrete Structures

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Abstract :

Terrorist activities or human-caused incidents can potentially trigger explosions near elevated constructions or inside them, leading to substantial damage and the fall of debris in structures related to public or private buildings. Consequently, it is crucial to examine how structural behaviors, like those of reinforced concrete slabs, beams, and columns, respond under these circumstances. In order to achieve this goal, an extensive review of relevant literature is carried out, aiming to grasp the possibilities of predicting the behavior of concrete structures when exposed to blast impacts. Also, the possibility of obtaining guidance to improve the buildings not designed for blast loads from literature outcomes on structural elements using analytical techniques as an alternative to experiments tests which will be expensive or private in the defense industry. Regional and international studies showing the response of concrete structures to blast loads have been reviewed. In many studies, researchers have studied the explosive charge loads, stand-off distance, and calculation and analysis methods; also, the different explosion loading models as plastic hinges were studied.

Keywords: Pushover method, Time-history method, Blast loads, Plastic hinge, Structural response, and Stand-off distance.

1.1 Introduction

The latest terrorist incidents demonstrated that public facilities could be unsafe when subjected to blasts. Despite the reality that the most common cause of injuries occurs due to explosion pressure and heat, other threats also pose a danger. Other potential sources of injuries that arise from an explosion are debris that falls, glass that shatters, and, finally, partial or complete building collapse. In light of this, improving the explosion resistance of buildings is crucial to help prevent human deaths. It could be accomplished by implementing appropriate measures to mitigate the impact of blast loads on buildings to minimize the brutal repercussions of the blast. There is a pity that no established standards can provide guidelines for improving the resistance to explosions in buildings; however, this can be accomplished by empirical and numerical analysis methods [1]. Blast waves are considered to have a large velocity and concentrated energy in a very short period of time, lasting only milliseconds. In the event of blast loads, the design approach should overtake the elastic stage to be more cost-effective and reasonable regarding the element size. Consequently, the plastic hinge is considered an optimal approach for a practical design utilizing non-linear methods. The Pushover method is deemed a non-linear static analysis method, but still not well known to analyze structures applied to blast loads [2]. In many studies, researchers have studied the explosive loads, important explosive parameters, and calculation methods; also, the relationships and different models of explosive loading were studied. Li et al. (2007) [3] developed "an Equivalent Static Force" (ESF); also, the design technique with ESF for "single-degree-of-freedom (SDOF) systems" was expanded to include the design of a structural frame made of reinforced concrete undergoing blasting conditions from a distant location. Two reinforced concrete frame constructions with six stories each were used to illustrate how the approach is used. Ngo et al. (2007) [4] offered in-depth explanations of the blast phenomena, various blast load prediction techniques, as well as the responses of the structures. A 52-storey structure was examined for explosion at the ground level using LS-DYNA, taking into account material and geometric nonlinearities, and discovered the failed members of columns, beams, and slabs. Poluraju & Rao (2011) [5] assessed how well the G+3 structure would hold up in the event of the inevitable explosions that are still to come, and a nonlinear pushover study was used. The structure was modeled using SAP2000. Specifically, beams and columns were treated as nonlinear frame components. Levels of performance, such as collapse safety, quick occupancy, and operation, were also provided in the report. The damage was rated as either severe, moderate, light, or very light, depending on the building's performance level. It was determined that the G+3 building needed a displacement of 0.0023m and a base shear of 2185.08 kN to meet its design criteria. Priyanka & Rajeeva (2015) [6] focused on analyzing the dynamic responses of a structure modeled using SAP2000. A six-storey building was subjected to various TNT stand-off distances totaling 500kg. The blast loads were taken into account utilizing the methods outlined in "section 5 of TM5-1300 (UFC 3-340-02)," and nonlinear modal analysis was utilized to analyze the dynamic load of the blast. The results illustrated that the maximum storey drift did not meet the requirements of the IS code. Hanumaiah & Devi (2016) [7] explored the non-linear two-dimensional dynamic response of a (G+10) building applied to blast loads. A reinforced-concrete building was designed for regular loads such as dead, live, and wind loads. A total of five kinds of explosive charges were put into use: 700, 1500, 2500, 3500, and 4500 kg of TNT at distances of 15, 30, 45, 60, and 75 m, and these loads were analyzed by TM-5 1300. A 2D frame analysis of explosions on the rise structural facade indicated that reflected pressure distribution diminishes with structure height. Nourzadeh et al. (2017) [8] investigated the overall response of a ten-storey building to ten different earthquake scenarios to track the severity of deformations from both events. Blast loads have been applied at the nodes according to the standoff distance, angle of incidence, charge weight, and tributary region. Sidesway drifts from the explosion load were found to be substantially greater than drifts caused by an earthquake, according to the results of the blast analysis, which involved modeling the structure in two and three dimensions.

1.2 Historical Background

The effect of blast load on reinforced concrete (RC) frames has been a topic of significant interest and research in structural engineering. As the threat of terrorist attacks and accidental explosions continues to be a global concern, understanding the behavior and response of RC frames under blast loading is crucial for designing resilient structures. A historical perspective for studies in this area can reveal a progression of knowledge and techniques developed to mitigate the destructive effects of blast loads on RC frames. Initial studies focused on military and defense-related facilities, such as bunkers and fortifications. However, as the threat of terrorism grew in the modern, the research also expanded to encompass civilian structures. Today, understanding the response of RC frames to blast loads has become essential for ensuring the safety and resilience of buildings in the face of unforeseen explosions. The following are some research studies in this direction:

1.2.1 Effect of Blast on G+4 RCC Frame Structure

In a case investigation performed by Kashif & Varma (2014) [9] five-story frame-reinforced concrete symmetric structure of four meters and three bays on all sides was employed. The story height is kept at 3 m, as shown in Fig.1. Dimensions of the column assumed 600x600 mm, and the beam was 600x600 mm each. The thickness of the slab is 125 mm, and the compressive strength of the concrete is 30 MPa with an elastic modulus of 32.5 GPa. The 100 kg and 500 kg blasts are applied at a 30 m distance. The detailed calculation of the peak magnitude of the last loading on each point of the front face is given in Tab.1 and Tab.2.

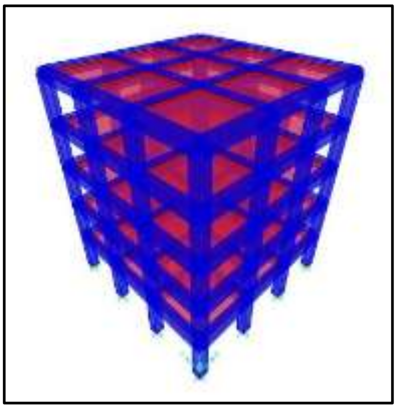


Figure.1: Five-Story RCC Building.

Table.1: For 100kg TNT.

Floor	Point	R(m)	Z(m)	T_d (ms)	P_r	A	P(kN)
1	1	30.69	66.13	13.367	75.24	6	451.45
	2	30.16	64.99	13.126	9.461	12	953.53
	3	30.16	64.99	13.126	79.46	12	953.53
	4	30.69	66.13	13.367	75.24	6	451.45
2	1	3.084	66.96	13.423	73.86	6	443.21
	2	30.55	65.83	13.321	77.4	12	928.8
	3	30.55	65.83	13.321	77.4	12	928.8
	4	31.08	66.96	13.423	73.86	6	443.24
3	1	31.75	68.40	13.507	72.10	6	432.61
	2	31.23	67.3	12.996	73.57	12	8829
	3	31.23	67.3	12.996	73.57	12	882.9
	4	31.75	68.40	13.507	72.10	6	432.61
4	1	32.68	70.41	13.72	68.67	6	412.02
	2	32.18	69.33	13.599	71.18	12	854.05
	3	32.18	69.33	13.599	71.18	12	854.05
	4	32.68	70.41	13.72	68.67	6	412.02
5	1	33.85	72.94	13.994	64.25	3	192.76
	2	33.37	71.90	13.855	66.21	6	397.30
	3	33.37	71.90	13.855	66.21	6	397.30
	4	33.85	72.94	13.994	64.25	3	192.76

Table.2: For 500kg TNT.

Floor	Point	R(m)	Z(m)	T_d (ms)	P_r	A	P(kN)
1	1	30.69	38.674	15.15	225.6	6	1353.7
	2	30.16	38.008	14.9	238.3	1	2860.5
	3	30.16	38.008	14.9	238.3	1	2860.5
	4	30.69	38.674	15.15	225.6	6	1353.7
2	1	30.08	39.163	15.27	220.7	6	1324.3
	2	30.55	38.501	15.14	226.6	1	2719.3

	3	30.55	38.501	15.14	226.6	1	2719.3
	4	31.08	39.163	15.27	220.7	6	1324.3
3	1	31.75	40	15.47	213.8	6	1283.1
	2	31.23	39.357	15.31	217.7	1	2613.3
	3	31.23	39.357	15.31	217.7	1	2613.3
	4	31.75	40	15.47	213.8	6	1283.1
4	1	32.68	41.177	15.87	201.1	6	1206.6
	2	32.18	40.549	15.63	207.9	1	2495.6
	3	32.18	40.549	15.63	207.9	1	2495.6
	4	32.68	41.177	15.87	201.1	6	1206.6
5	1	33.85	42.655	16.27	186.3	3	559.17
	2	33.37	42.048	16.03	193.2	6	1159.5
	3	33.37	42.048	16.03	193.2	6	1159.5
	4	33.85	38.674	15.15	225.6	6	1353.7

It was found from the analysis that the difference in displacement was unequal over building height and dissimilar from wind and earthquake (the structure is not acting like a cantilever structure when exposed to blast load). The level of performance for such a building has arrived at the collapse point (CP) for the smallest value of standoff distance. The frames of five-story buildings designed for conventional loads behave pretty well, with no catastrophic collapse, if exposed to an explosion equivalent to 100 kilograms of TNT at a 30 m standoff distance. If an explosion of 500 kg happens, the level of performance of the building would be critical. The plastic hinges are developed in almost all beams and columns.

1.2.2 Blast Load Analysis And Effect On High-Rise Structures

The G+10 structure was modeled, analyzed, and subjected to a blast load of an explosion of 100kg TNT using sap2000 by Krishna & Sekhar (2018) [10]. The current model expresses the explosion load as a pressure-time triangular relationship. The standoff distance has a significant impact on computing explosion parameters. Distance from blast point to structure increases will be reduced since pressure will drop with a rise in standoff distance. The reinforced concrete framed structure has been designed in the software program, and details of the structure have been displayed in Tab.3. The description of the model can be viewed in Tab.4, and a model of the structure elements has been shown in Tab.5.

Table.3: Structure details.

Grade of concrete, fck (Column, Beam, slab)	M35
Grade of steel, f_{st}	Fe500
Young's modulus of M35 concrete, E	29504.445 Mpa
Young's modulus of steel, E	$2x10^5$ MPa
Concrete density	25 kN/m^3
Steel density	78.5 kN/m^3

Number of bays in the x-direction	4
Number of bays in the y-direction	4
Width of the single bay in the x-direction	5.5m

Table.4: Model description.

Width of the single bay in the y-direction		4.5m
Number of storeys		G+10
Structure Elements	Column	600mm x 600mm
	Beam	600mm x 600mm
	Slab	125 mm

Table.5: Structure element model in RC framed structure.

Nodes	275
Frames	440
Shells	176

The analysis outcomes demonstrate that the displacement variation is uneven across a building's height. The most minor standoff distance performance level of the structure was reached to collapse. A large load will be imposed on joints near beams and columns. G+10 reinforced concrete frame structure designed for regular load situations of performance responsibly well and not subject to catastrophic collapse when exposed to explosion is equal to 100kg of TNT 30m away from the structure. The performance level of structure joints is extremely important near the explosion. Hinges are developed in all beams and columns.

1.2.3 Blast Demand Estimation of RC-moment-resisting Frames using a Proposed Multi-modal Adaptive Pushover Analysis Procedure

The RC-MRFs with three un-same stories have been adopted in work performed by Kiran & Noroozinejad Farsangi (2021) [11]. The load exerted on the structural frame represents a dynamic nonlinear load that is an explosion load. The load applied on the frame takes place rapidly in a millisecond, and its intensity is much greater than the load applied by an earthquake. Fig.2 illustrates the present study's adopted RC- MRFs configurations and blast load acting at a distance from the frame. The four-storey frame is designed with a bay width measuring 9.14m, whereas the remaining frames possess a bay width equal to 6.10m. Tab. 6 presents the physical characteristics of the models, involving the entire periods' range, dead load, live load, and concrete compressive strength utilized in columns and beams. Tab. 7 clarified the natural periods of all models in different modes. Tab.8 shows the dynamic characteristics of a frame under investigation.

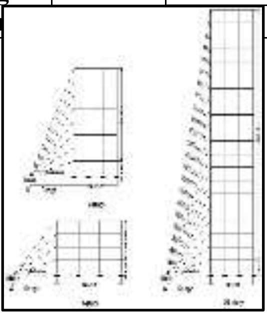
Figure.2: 2D presentation of the RC-MRFs exposed to blast loading considered in this study

Table. 6: Physical properties of the models.

Sl No	Parameter	Magnitude
1	Dead Load	8.38 kN/m^2
2	Live load	2.40 kN/m^2
3	Compressive strength of the beams	34.5 MPa
4	Compressive strength of the columns	46 MPa

Table.7: Characteristics of the analyzed frames.

Sl No	Frame (Storey)	Height (m	Width	Periods (s)		
					II	III



				mode	**mode**	**mode**
1	4	12	9.14	0.64	0.20	0.20
2	8	24	6.10	1.34	0.45	0.25
3	20	60	6.10	1.71	10.64	0.38

Table .8: Dynamic properties of the frames.

Sl No	**Parameter**	**Value**
1	Damping ratio	5%
2	Stiffness	15.11 kN/m
3	Damping	7.38×10^{-2} kN-s/m

The results show that for a frame structure of four storeys, the storey drift error is (15% and 8%) for nonlinear response history analysis (NRHA) and conventional modal pushover analysis(MPA), in that order, relative to multi-mode adaptive pushover (MADP). The peak pressure occurs at the bottom stories, and the minimum pressure happens at the upper stories for the structure frame subjected to an explosion load. The Shear at the base is inversely related to mode shapes. In the eight-storey model, the greatest storey drift percentage appears on the third, fourth, and fifth floors, in that order. The rest of the floors had the lowest storey drift percentages. For a frame structure of 8 stories, displacement error amounts to (8% and 14%) for NRHA and MPA, in that order, relative to MADP. For a high-rise structure (a model with 20 floors), the impact of torsion concerning the variation of torsional angle and explosion load angle has also been considered in the work.

1.2.4 The Study Of the Effect of Blast Load on Multi-Storey Building by Using Time History Method

In the current study carried Charan & Deveraju (2018) [12], a G+4 storey RCC building is exposed to a surface explosion of 100,300 and 500kg explosive charge weight and has a plan dimension of 18m X 18m with the ground storey height of 3.5m and rest of all storey heights equal to 3m each was considered for the investigation. The building has been analyzed for several standoff distances of 30, 40, and 50m measured from the facade utilizing ETABS 2016. The explosion load variables are determined as per IS: 4991-1968, and the explosion load is multiplied by its tributary zone, and these pressures were imposed as a joint load on the building front face, i.e., in the direction of ‘x’ and pressure time history method is carried out. The results showed that the pressure is smaller when the point of explosion is a long way from the building; the pressure is highest at a distance of 30m. The pressure drops exponentially when the standoff distance goes up. The pressure is inversely related to the detonation point. The pressure above 30m is lowered by 54% when the standoff distance is 50m. The safe standoff distance for the building selected is 50m. The pressure drops exponentially with decreasing explosive charge weight. There is a direct relationship between the pressure and explosive charge weight. The pressure over 500kg is lowered by 67.3% when the charge weight of the explosive is 100kg. Column forces (bending moment and axial load) and beam forces (shear force and bending moment) rise when the explosive charge weight is more and decline when the standoff distance is less.

1.3 Conclusion

1. Most researchers considered in their investigations the nonlinear time-history method, which is available in engineering software. This method is more accurate and realistic and gives significantly good results.
2. nonlinear time-history method has seemed rather complex since it needs so many inputs, and the time of analysis is relatively long. A crucial point must be clarified an absence and lack was observed in studies that tried to find the actual relationship between the pushover and time history method of analysis.

3. Some previous investigations simulated material nonlinearity using default plastic hinge analysis programs. By default, the plastic hinge model employed by the software is based on the ASCE 41 model for the seismic load. However, the model may not accurately capture the proper response when subject to blast loads.
4. Numerical techniques like Lagrangian and Eulerian analysis, as well as Euler FCT, ALE, and finite element modeling, can accurately predict blast loads on public and commercial constructions.
5. The high strain rates increased the concrete compressive strength and steel strength at yield, which increased the ductility of RC members.
6. For any plastic hinge model that was used, a different hinge form and distorted shape were shown.
7. The stand-off distance, charge weight, and reaction can all be inversely proportioned and have various effects on structural behavior.

1.4 Recommendations

1. There are several structural methods, like shear walls and steel bracing, that can be implemented to make the building more blast-resistance.
2. Study the influence of explosion on different types of structural systems, such as the frame building having a shear wall element, and perform the analysis by Pushover and Time-history methods and suggest the best location of the shear wall if found it has a significant impact in case of explosions loads.
3. Empirical methods can utilize historical data from previous blast incidents to estimate blast loads. Generally, they involve establishing relationships between the distance from the explosion, charge weight, and the resulting blast pressure.
4. Conducting controlled blast tests on scaled models or full-scale structures can provide valuable data for blast load estimation. The resulting blast effects can be measured and used to calibrate numerical models.
5. Techniques such as externally bonded fiber-reinforced polymer (FRP) composites can be employed to strengthen critical elements and improve their blast resistance.

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