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

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A B S T R A C T

The procedure of estimating the RC moment-resisting frames under blast loading using a multi-mode adaptive pushover (MADP) analysis is investigated in the current study. The main advantage of the proposed procedure is the combination of the multi-mode and adaptive pushover analysis approaches, which has not been done in the past for blast loadings. To investigate the efficiency of the proposed approach, several RC moment-resisting frames (RC-MRFs) of the 4-, 8-, and 20- storey are considered in the study. For a better comparison, the conventional modal pushover analysis (MPA), nonlinear response history analysis (NRHA), and the proposed approach are considered in the simulations. To this end, various influential parameters including the lateral force, floor displacement, storey drift, storey drift ratio, etc. are considered. For all models, the first three mode shapes were considered in the analysis procedure, while for the case of 20 storey RC-MRF, the torsional effect is included as well. The results indicated that the proposed MADP procedure has adequate accuracy and efficiency to estimate the blast loading demand on RC-MRFs.

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1. INTRODUCTION[1]

The process of evaluation and design of a structure or elements due to imposed loading can be performed by pushover analysis [1]. The loading pattern for assessing the two- or three-dimensional structures due to lateral loadings which includes linear or nonlinear responses, is mainly based on inertia forces obtained at masses [2]. The structure will then be pushed under these load patterns to reach a pre-defined target displacement [3]. The strength and deformation demands are estimated for the compared available capacities can also be calculated by the inertial forces and deformations at the target displacement levels. This phenomenon is known as pushover analysis [4].

In turkey, the structures are constructed by using precast concrete technologies. These structures were subjected to seismic load and the peak responses were obtained [5].

In some previous studies, the influence of vertical and plan irregularities of the building has been carried out. In the next stage, the results obtained from inelastic dynamic analysis such as inter-storey drifts and plastic rotations correlates by the modified pushover analysis [6]. Many researchers have also considered a single degree of freedom (SDOF) system to estimate the collapse capacity of a structural system due to seismic loading by considering the P-Δ effect [7–13]. In another research, different building structures collapse capacities were analyzed by pushover analysis, and results were compared with nonlinear incremental dynamic analysis. The pushover analysis is simple, efficient, accurate, and lucid while predicting the collapse capacity of different types of structures [2]. Hasan et al. have investigated the nonlinear, inelastic, ideal, rigid, or pinned connections frame structure under earthquake loadings by pushover analysis [14].

Hundreds of different properties and the number of stories of a generic structure were developed in the study of Manafpour and Jalikhani. All structures were exposed to seismic loading and analyses were carried out by

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pushover analysis. The authors have estimated the median seismic collapse capacity by pushover analysis without considering dynamic analysis [15].

In another study by Rahmania et al., the seismic behavior of tall inelastic structures considering higher modes was studied by pushover analysis. The responses of progressive changes in dynamic properties have been identified. To this aim, two steel frames were analyzed by various methods such as upper bound, adaptive upper bound, modal pushover analysis, and nonlinear time history analysis. Among the investigated methods, adaptive upper bound analysis has given the most accurate results [16, 17]. In another study, the lateral displacement profile of the moment-resisting frame structure is estimated by mechanics-based procedure or pushover analysis [18]. In the study of Hall, the seismic analysis of a twenty storey building was analyzed by nonlinear pushover analysis approach [19]. Nonlinear static pushover analysis has also been used to analyze the high-rise structures exposed to seismic force by considering the torsion factor [20].

In the study of Hassan and Reyes, the mid-rise special moment-resisting frames exposed to seismic loadings were analyzed by using modal pushover analysis. The results showed the accuracy of the method compared to nonlinear response history analysis [21]. The limitation of the nonlinear static analysis in terms of the computational effort is saved by modal pushover analysis. The symmetrical and unsymmetrical plan multi-story concrete buildings exposed to seismic force were analyzed by modal pushover analysis in several references [22–27].

The multi-storey structures responses exposed to seismic load were calculated by the Newmark-β method [28–30]. The response due to blast load on a single degree of freedom structures is shown in [31]. The use of damper devices and base isolations techniques were investigated to reduce the responses [32, 33].

The accuracy of the modified modal pushover analysis of a different frame building with ground motion is compared by modal pushover analysis. The higher vibration modes with a linear elastic frame are analyzed by modified modal pushover analysis. The modified pushover analysis saves computational time and effort compare to modal pushover analysis [34]. The higher mode of vibrations of the midrise base isolation system with seismic load response can be calculated by using modal pushover analysis [35, 36]. MPA gives superior results for the response of two actual buildings of 19 and 52 stories with seismic force [37]. The three-steel frames of 3, 9, and 20 stories structures with seismic load analysis were carried out using the floor response spectrum approach. The floor response spectrum is the advanced version of the modal pushover analysis [38]. The three-dimensional analysis for an unsymmetrical both plan and elevations of a frame structure exposed to ground motions data considering two horizontal components is analyzed by modal pushover analysis and the results show the accuracy compare to nonlinear static pushover analysis [39–41]. The unsymmetrical plan for 10, 15, and 20 storey models considering soil-structure interactions were analyzed by consecutive modal pushover analysis [42].

In the study of Maysam Jalilkhani et al, the seismic analysis was carried out by multi-mode adaptive pushover analysis (MADP) for RC moment resisting frames of 4-,8-,12- and 20- stories [43].

Saedi-Daryan et al., the detailed stepwise procedure was explained for the response of the structure exposed to blast load by MPA [44]. The eight-storey structure with shear wall exposed to blast load response was calculated and compared with other methods of nonlinear dynamic analysis [45].

The influence of blast load waves on nonlinear structure responses was calculated by differential equations. The responses were calculated for different mode shapes [45, 46].

Antoniou and Pinho proposed the displacement-based adaptive based pushover analysis method for the response of the MDOF system exposed to seismic loading [47]. Balram Gupta and Sashi K Kunnath proposed the adaptive pushover analysis method for determining the response of mid-rise and high rise structures exposed to seismic load by considering the higher modes [45, 48]. Adaptive based pushover analysis method is considered for obtaining the nonlinear seismic response of structures [49, 50].

The current study is focused on three different frame types that are low rise, mid-rise, and high-rise RC-MRFs under blast loading. To this end, the blast loading effect on 4-, 8- and 20 storey RC-MRFs were carried out by three different analyses approaches. The investigated methods have been the modal pushover analysis (MPA), non-linear response history analysis (NRHA), and the proposed multi-mode adaptative pushover analysis (MADP). Simulations have been carried out using the MATLAB platform and the results indicated the accuracy and efficiency of the proposed MADP procedure for RC-MRFs.

2.TORSION

The torsional effect of the lateral coupling is considered for the analysis of the RC-MRF. The irregularity indices and torsional factors are considered. The following equations are used to calculate the eccentricity of a given storey in the X and Y directions [51–54]:

$$e_{kx} = x_r - x_m \quad (1)$$

$$e_{ky} = y_r - y_m \quad (2)$$

where (x_m, y_m) and (x_r, y_r) are coordinates of the centre of mass and centre of rigidity, respectively. The following equations are used to determine the coordinates:

$$x_r = \frac{\sum K_{yi} x_i}{\sum K_{yi}} \tag{3}$$

$$y_r = \frac{\sum K_{xi} y_i}{\sum K_{xi}} \tag{4}$$

where k_{xi} and k_{yi} are the lateral stiffnesses of floor 'i' along the global X and Y directions. The torsional radius (r_k) are given in below equations

$$r_{kx} = \sqrt{\frac{\sum (K_{xi}.(y_i - y_r)^2) + (K_{yi}.(x_i - x_r)^2)}{\sum K_{yi}}} \tag{5}$$

$$r_{ky} = \sqrt{\frac{\sum (K_{xi}.(y_i - y_r)^2) + (K_{yi}.(x_i - x_r)^2)}{\sum K_{xi}}} \tag{6}$$

The mass radius of gyration of a particular floor is given by

$$r_m = \sqrt{\frac{\sum m_i {d_i}^2}{(m_i)}} \tag{7}$$

where m_i is the lumped mass at the radial distance d_i from centre of mass. The torsional angle is obtained from below equations [51].

$$\theta = \tan^{-1} {}^{\alpha}/_{0.01H} * R \tag{8}$$

where θ is the angle of the inclination, α is the blast load angle, R is the range and H is the height of each floor. The torsional stiffness is given by

$$K_\theta = K_x * \frac{B^2}{2} + K_y * \frac{D^2}{2} \tag{9}$$

where K_θ is the torsional stiffness, while K_x, K_y is the stiffness along X and Y directions, B and D are the length along X and Y directions, respectively.

3. MULTI-MODE ADAPTIVE PUSHOVER ANALYSIS

In this section, the blast load response on the RC moment-resisting frames is calculated by using a multi-mode adaptive displacement-based pushover analysis procedure. Figure 1 represents the flowchart of the multi-mode adaptive pushover analysis.

The following equations are used for the nonlinear analysis of the frame:

$$\widehat{D_n} = \exp\left[\frac{\sum_{i=1}^{N} \ln D_i}{N}\right] \tag{10}$$

where D_i is the absolute peak deformation, and N is the number of the blast wave.

$$u_{rnt} = \emptyset_{nr} \Gamma_n \widehat{D_n} \tag{11}$$

Figure 1 shows the algorithm of multi-mode adaptive pushover analysis. The multi-mode adaptive pushover analysis consumes less time, gives more accurate results compared with other methods of pushover analysis.

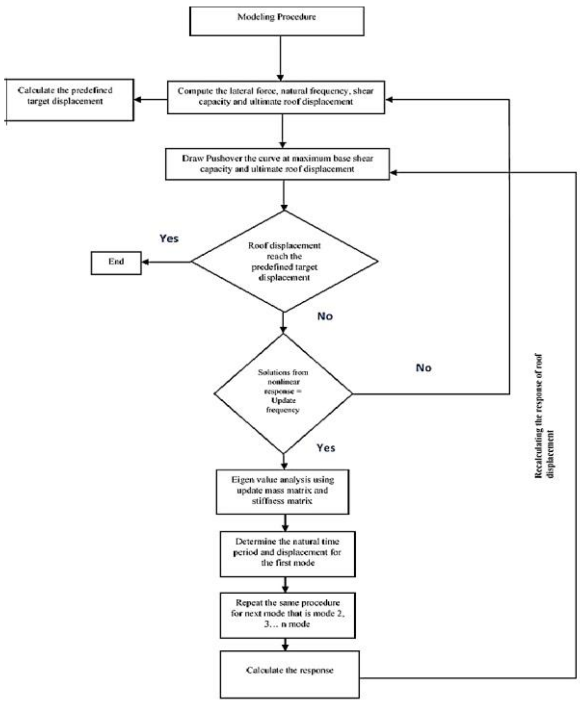

Figure 1. Flowchart of the proposed multi-mode adaptative based pushover analysis

The following steps explain the detailed procedure of the proposed MADP.

- The nonlinear inelastic mathematical model is developed which incorporates the stiffness, mass, and damping matrices.
- Calculate the natural frequencies, mode shapes, lateral force distribution, and perform nonlinear static pushover analysis.
- Determine the base shear and roof displacement for *n*th mode and draw the pushover analysis curve.
- Calculate the target roof displacement. If the roof displacement is equal to the target roof displacement, then the process will end otherwise the properties will be modified and the procedure will be repeated.
- Calculate the response for the structural system for the first mode.
- Repeat the same procedure for the other modes.

4. NUMERICAL MODEL

The RC-MRFs with three different stories are considered in the study. The load acting on the structural frame is a nonlinear dynamic load that is blast load. The load acting on the frame occurs within a millisecond and the magnitude is much larger compared to earthquake loading.

Figure 2 shows the configurations of the used RC-MRFs in the current study. The 4 storey frame has a bay width of 9.14m, while the remaining frames have a bay width of 6.10m. Table 1 shows the physical properties of the models including the fundamental periods' range, dead load, live load, and compressive strength of the concrete used in beams and columns. Table 2 shows the natural periods of all models in different modes. Table 3 shows the dynamic properties of the investigated frames.

Figure 2 shows the RC-MRFs exposed to blast load are considered in the study. The figure shows the blast load acting at a distance range from the frame.

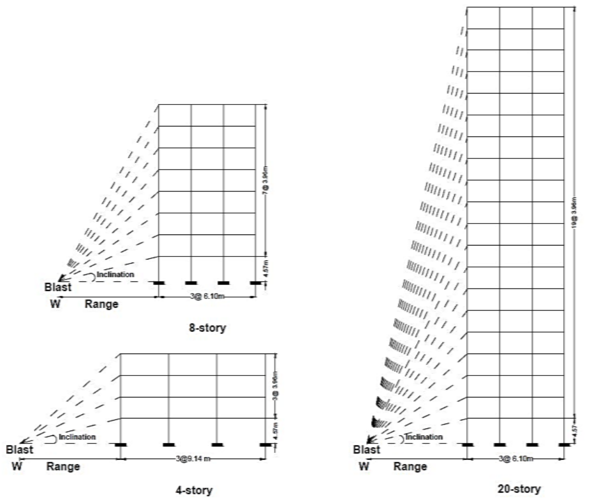

Figure 2. 2-D presentation of the RC-MRFs exposed to blast loading considered in this study

TABLE 1. 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 2. Characteristics of the analyzed frames[45]

Sl No	Frame (Storey)	Height (m)	Width (m)	Periods (s)		
				I mode	II mode	III 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	0.64	0.38

TABLE 3. 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

5. BLAST LOADINGS

The blast load acting on structures has a short period. Table 4 shows the blast load parameters used in this study. The blast load is calculated using Equations (12)-(17).

$$P_s = \frac{670}{Z^3} + 100 \text{ kPa} \quad (P_s > 1000\text{kPa}) \tag{12}$$

$$P_s = \frac{97.5}{Z} + \frac{145.5}{Z^2} + \frac{585}{Z^3} + 1.9 \text{ kPa} \quad (10 < P_s < 1000 \text{ kPa}) \tag{13}$$

where P_s is the maximum static overpressure of the blast load and Z is the scaled distance, which is calculated as:

$$Z = \frac{R}{W^{1/3}} \tag{14}$$

where W denotes the TNT weight. The time variation of the blast load can be determined using the following equations:

$$P(t) = P_o + P_s\left(1 - \frac{t}{T_s}\right)\exp\left(-\gamma \frac{t}{T_s}\right) \tag{15}$$

$$\gamma = Z^2 - 3.7Z + 4.2 \tag{16}$$

$$T_s = W^{1/3} 10^{\left[-2.75 + 0.27 \log R / W^{1/3}\right]} \tag{17}$$

where P_o is the ambient pressure and T_s is the positive time duration of the blast load.

6. RESULTS AND DISCUSSIONS

The considered low rise, mid-rise, and high-rise structural frames are analyzed to determine the accuracy and efficiency of the proposed MADP procedure. The blast load acting on the frame has been the main input of the structural analysis. The analyses were carried out by considering three mode shapes, using modal pushover analysis, nonlinear response history analysis, and multi-mode adaptative pushover analysis. The analyses were carried out in the MATLAB [55] platform.

For seismic performance evaluation of structures, probabilistic approaches are more common [56, 57]; however, for blast loading, a deterministic approach is mainly used. The target displacement for the 4, 8, and 20 storey frames have been obtained as 11.82cm, 16.45cm, and 23.22cm, respectively. The accuracy of the roof displacement was calculated by using MADP analysis.

TABLE 4. Blast load parameter

Sl No	Parameter	Magnitude
1	Weight (W)	1000 TNT(Trinitrotoluene)*
2	Range (R)	100m
3	Scaled Distance (Z)	10 m/kg$^{1/3}$
4	Peak pressure (P_s)	100.67 kPa

* TNT generates blast energy of about 4680 joules per gram (J /g)

6. 1. 4-Story Frame Figure 3 shows the storey drift of the four-storey frame with different analysis approaches. The maximum drift occurs on the first floor and the minimum drift occurs on the second floor by MADP. The MADP will have a higher value on the 3rd floor and the remaining floors will have lower values. Figure 4 shows the pushover curve with three different mode shapes. The maximum base shear with roof displacement occurs at Mode I and the minimum occurs at Mode III. The maximum base shear is 1kN and roof displacement is 50 cm and the minimum base shear is 800 N and roof displacement is 4 cm.

Figure 5 shows the blast load acting on the four-storey frame model. The maximum load acting on the first floor has been 12 kPa at 0.03 sec and the maximum load acting on the fourth floor has been 6kPa at 0.04 sec. Figure 6 shows the mode shape of the four-storey frame.

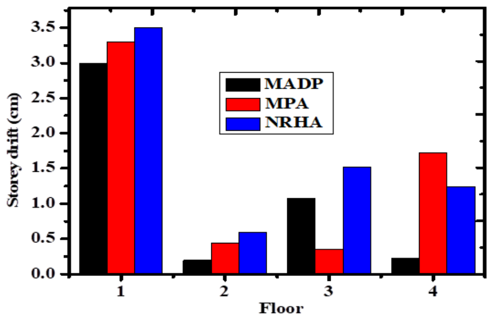

Figure 3. Story drift of 4 story frame

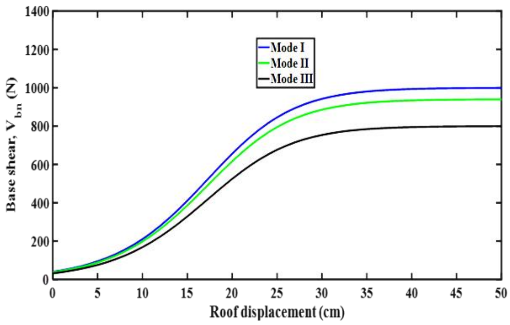

Figure 4. Pushover curve 4 story frame

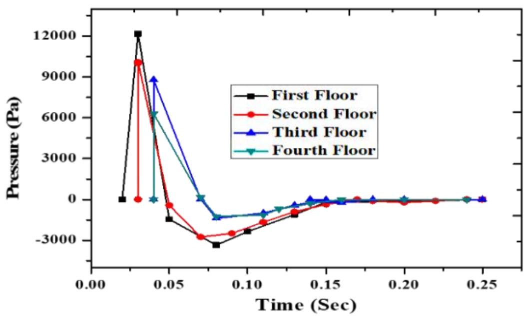

Figure 5. Load acting on 4 story frames exposed to blast load

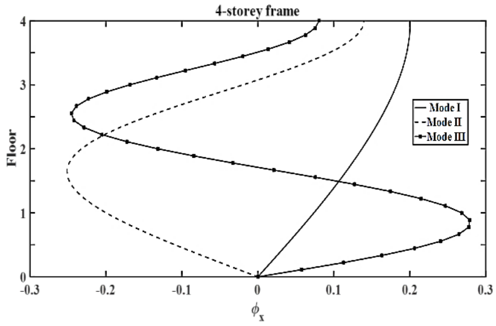

Figure 6. Mode shape of 4 story frame

6. 2. 8-Story Frame Figure 7 shows the storey drift ratio of the eight-story frame with different pushover analyses approaches, while the maximum storey drift ratio is 4, 3 and 0.5 by MPA, NRHA and MADP methods, respectively. The maximum storey drift occurs at fourth floor and minimum storey drift ratio occurs at first floor by various methods, respectively. The NRHA and MADAP show similar results, whereas the MPA has the maximum error.

Figure 8 shows the displacement of different floors with different analysis approaches. The maximum displacement occurs on the seventh floor with a value of 0.3m using modal pushover analysis and the minimum displacement occurs on the first floor of 0.068m using MADP analysis. Figure 9 shows the lateral force distribution of the floors in different modes. The maximum lateral force occurs in the third mode and the minimum lateral force occurs in the first mode. The maximum and minimum lateral forces have been 80 kN and 20 kN, respectively.

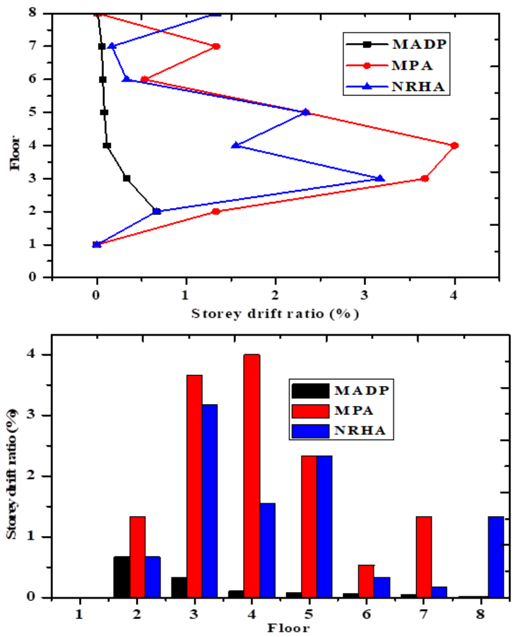

Figure 7. Story drift ratio of 8 story frame

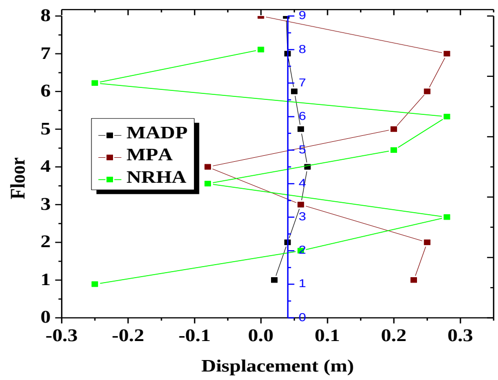

Figure 8. Displacement of 8 story frame

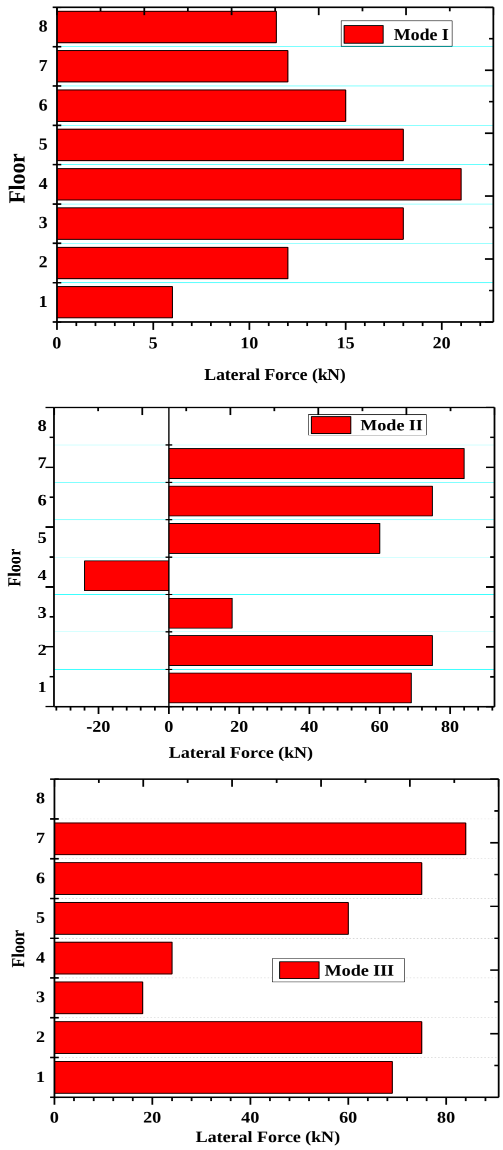

Figure 9. Lateral Force of 8 story frame

6. 3. 20-Story Frame The investigated high-rise model is a 20 storey frame. The effect of torsion and inclination of blast loading have been considered in this model. Figure 10 shows the variations of the inclination angle and torsion angle on the investigated model. It is shown in Equation (8). The maximum inclination of the blast load has been 60degree and the torsion angle was 0.010 radian. Figure 11 shows the mode shapes of the twenty storey frame.

Figure 12 shows the base shear of roof displacement of the twenty storey frame along X direction. The maximum base shear has been 2050 N in mode I and the minimum base shear has been 1600 N in mode III. Figure 13 shows the displacement of the floor level along X direction with different analysis approaches. The nonlinear responses analysis will provide maximum value compared with other methods. The variations of the displacement along the floor are presented. The MADP and MPA show small errors compared to the MADP method. The maximum displacement was 0.4m in the second floor using nonlinear response history analysis. The minimum displacement has been 0.07m using MADP. Figure 14 shows the storey drift ratio of second to fourth floors. The minimum storey drift ratio occurs at 14 to 18 floors.

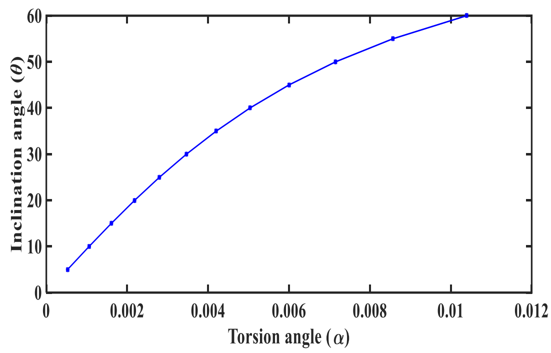

Figure 10. Relationship between inclination angle and torsion angle

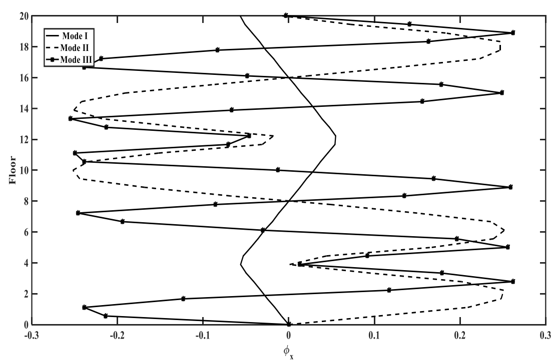

Figure 11. Mode shape of the 20 storey frame

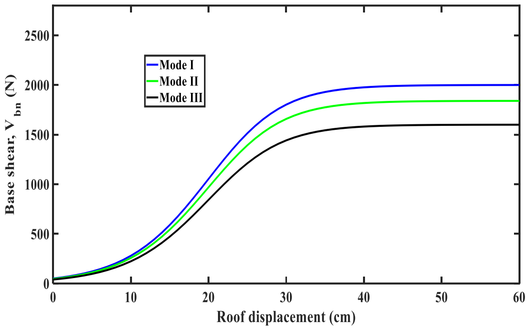

Figure 12. Base shear of the 20 storey frame along X direction

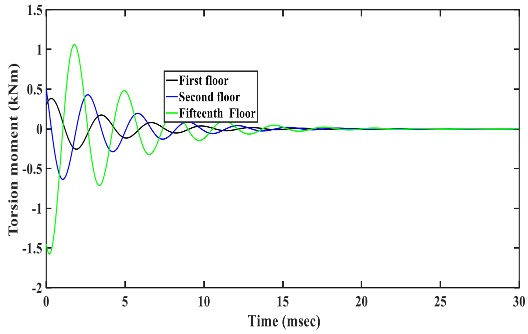

Figure 15. Torsional moment

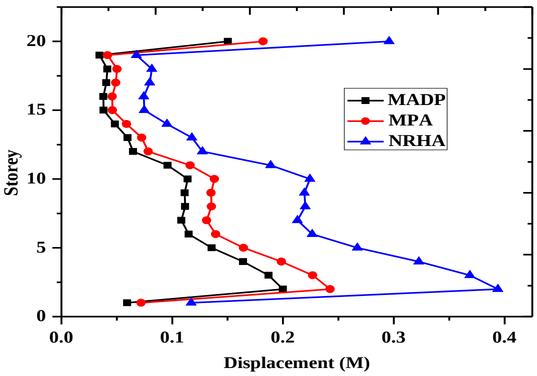

Figure 13. Displacement of the 20 storey frame along X direction

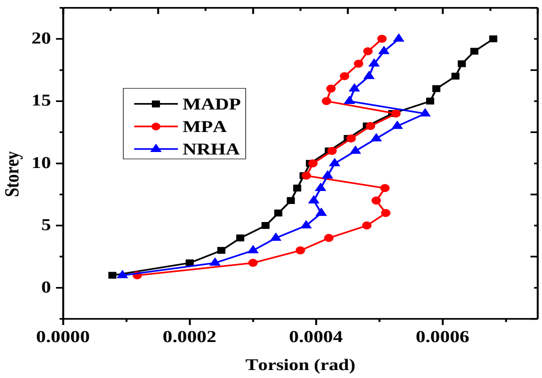

Figure 16. Torsion effect in different floors

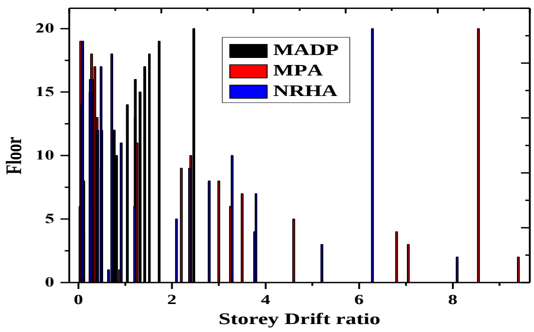

Figure 14. Storey drift ratio of the 20 storey frame along *Y* direction

Figure 15 shows the torsional moment of the fifteenth floor. The maximum torsional moment has been 1kNm at 2m.s. Figure 16 shows the torsion of the twenty-story floor with different analysis approaches. The maximum torsion occurs at 20th floor of 0.0007 rad using MADP analysis. Table 7 shows the percentage of the error of the different frames with different analyses approaches. The maximum error occurs in 20 storey model using nonlinear response history analysis and the minimum error occurs at 4 storey frame using modal pushover analysis.

TABLE 7. Percentage of the error of different approaches and in terms of drift ratio compared to the proposed MADP approach

Sl No	Frame	MPA	NRHA
1	4-storey	10%	25%
2	8-storey	14%	22%
4	20-storey	22%	28%

7. CONCLUSIONS

The current study investigates blast load acting on 4-, 8- and 20- storey frame models. The structural responses were determined using a proposed multi-mode adaptative pushover analysis. Three different mode shapes were considered in the simulation. For 20 storey structure (high-rise model), the torsional effect has been considered as well. The monitored responses were displacement, storey drift, storey drift ratio, base shear, and torsional effect. The main verdicts could be summarised as follows based on the calculated results:

- For 4 storey frame structure, storey drift error will be 15% and 8% for NRHA and MPA, respectively compared to MADP.

-The maximum pressure occurs at lower stories and minimum pressure occurs at higher stories for the

structure frame exposed to blast load.
-The base shear will be inversely proportional to mode shapes.
-In 8 storey model, the maximum storey drift ratio occurs at third, fourth, and fifth floors, respectively. The remaining floors had the minimum storey drift ratios.
-For an 8 storey frame structure, displacement error will be 8% and 14% for NRHA and MPA, respectively compared to MADP.
-For a high-rise structure (20 storey model) the influence of torsion with respect to variation of torsional angle and blast load angle were also considered in the study.
-Torsional moment and blast load along both *X* and *Y* directions have been the input parameters of the high-rise model exposed to blast load.

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Persian Abstract

چکیده

در این مطالعه رویکرد تحلیل استاتیکی غیرخطی به روزشونده با در نظر گرفت اثر مودهای بالاتر جهت بررسی اثر انفجار بر قاب های خمشی بتن مسلح مورد ارزیابی قرار گرفته است. نوآوری مطالعه حاضر در ترکیب اثر مودهای بالاتر و تحلیل استاتیکی غیرخطی به روزشونده بوده که تابحال برای ارزیابی اثر بار انفجار بر سازه‌ها مورد استفاده قرار نگرفته است. به منظور بررسی کارایی روش پیشنهادی، سه سازه بتن مسلح ٤، ٨ و ٢٠ طبقه در این مطالعه مورد بررسی قرار گرفته‌اند. جهت مقایسه بهتر، علاوه بر رویکرد پیشنهادی، روش تحلیل استاتیکی غیرخطی به روزشونده متداول و همچنین تحلیل غیرخطی تاریخچه زمانی نیز بر روی مدل‌ها اعمال گردیده است. بدین منظور پارامترهای اثرگذار متعددی از جمله بارگذاری جانبی، جابجایی طبقات، دریفت طبقات، نسبت دریفت طبقات و ... مدنظر بوده است. در تمامی مدل‌های سازه‌ای مورد بررسی اثر ٣ مود ارتعاشی اول در فرآیند تحلیل در نظر گرفته شده، در حالیکه برای مدل ٢٠ طبقه اثر پیچش در پاسخ سازه نیز لحاظ گردیده است. نتایج این تحقیق بیانگر دقت کافی و عملکرد مطلوب روش پیشنهادی به منظور تخمین پاسخ سازه‌ها تحت بارگذاری انفجار می‌باشد.