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DYNAMIC AND PUSHOVER ANALYSIS OF MULTI-STOREY REINFORCED CONCRETE BUILDING USING DIFFERENT LOAD DISTRIBUTION PATTERN

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One of nature's most dangerous phenomena are earthquakes which cause significant harm to both people's lives and property. In this study, four alternative approaches are used to demonstrate the distribution of lateral loads and compare its impacts on the results of a non-linear static pushover analysis of a ten-storey reinforced concrete (RC) building and study its response to the impact of an earthquake. In order to determine how the structure would respond to earthquake effects, pushover analysis which is an alternative way of time history analysis was adopted and the predicted results are compared with those of nonlinear time history analysis. Given that the building is situated in an area that is actively experiencing earthquakes and has rocky soil, the distributed lateral force is assumed to be equivalent to the design base shear. The study indicated an almost good suitable fit between two categories of pushover loading methods regarding security of the building, maximum base shear, and maximum displacement. The paper also presents a comparison between the results of nonlinear time history analysis at a particular roof displacement with that of pushover analysis.

Keywords: building, dynamic, earthquake, nonlinear, pushover, time history

1 INTRODUCTION

The static nonlinear analysis method, commonly referred to as pushover analysis, is a streamlined approach for estimating the nonlinear behavior of buildings and their response to earthquakes. The seismic demand and capacity curves intersect at the performance point, which is where this method finds the performance point. This point illustrates the capability of the structure to resist seismic loads. One of the most widely used software for this type of analysis is the program SAP2000 Version 20 [1] which can model the development of plastic hinges in the beams and columns due to incrementally applied pushover loading. A lateral load that corresponds with the established international codes is applied to the multi-story building during the pushover analysis. This loading is an approximation of the possible seismic loading that the structure may experience. All stories receive these loads gradually and incrementally. A variety of load distribution patterns were utilized, including FEMA loading, inverted triangular, uniform, and mode shape distributions [2]. Crack development, reinforcing yielding, and finally, the formation of plastic hinges in the columns and beams represent the first indications of failure. Building failure stages and accompanying simplifications are depicted in Fig. 1. [3]. The non-linear time history analysis is usually considered as an accurate and realistic method to predict the nonlinear dynamic response of building subjected to earthquake loading. The methodology of the present work consists of two stages: Stage one: Conducting a nonlinear pushover analysis method of a ten storey RC building, from which the most important findings are maximum roof displacement, maximum base shear at failure, the formation of plastic hinges, and specifying the performance point to determine the safety of the building under the influence of earthquakes. The second stage: conducting a nonlinear time history analysis of the same structure subjected to a specified earthquake record and the results at a particular time step are compared with that of the pushover method.

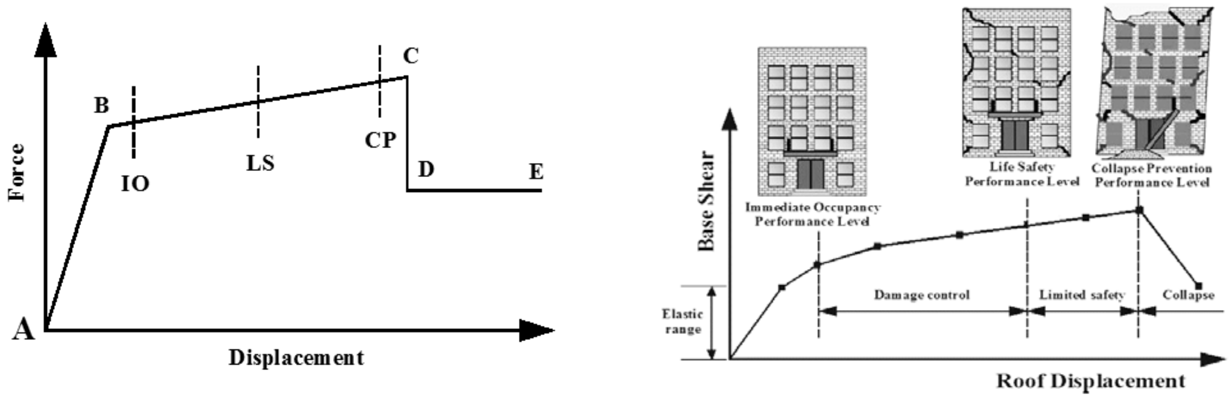


Fig. 1. Failure stages and performance levels of building [3]

Sarkar, et al. [4] adopted a new approach for defining a laterally loading pattern utilizing SAP2000 software for pushover analysis of vertically a symmetric multi-storey stepped structures taking into account higher modes of free vibration. Depending on a nonlinear time history analysis of building frames with various asymmetrically stepped by successively removing one bay and one step height from the building's top storey. According to the Indian code, both these and regular frame buildings were designed [5]. The suggested load profile was compared to a similar static load distribution based on Indian Standard [5], fundamental mode shape, proportional uniform mass distribution, load profile for upper bound pushover analysis. The proposed load profile distribution was based on first three time period of the structure. When the newly proposed lateral load is implemented utilizing a modified displacement coefficient approach, the target displacement for the stepped structural building is found to matches consistently with the displacement demand supplied by the time history analysis. Baros and Stavros [6] used the pushover approach to analyze asymmetrical structures. To investigate the torsional response of the building, lateral loads was gradually applied in two orthogonal horizontal projections. The reliability and accuracy of a pushover method were evaluated by comparing the results to those of a nonlinear time history analysis. Samir, et al. [7] Implement the pushover analysis based on ATC 40 [8] spectrum method to analyze six storey buildings to estimate their resistance to seismic events. The UBC algorithm [9] was used to calculate the base shear and the distribution of the lateral loads. Since the performance point is situated in the elastic limit zone, the findings showed that the buildings were secure against seismic effects. Furthermore, it was found that every plastic hinge had been produced at performance levels that fell below the immediate occupancy limit. Zhang, et al. [10] Analyzed six storey building to estimate its resistance to seismic events by utilizing SAP2000 software. The pushover analysis was used to estimate the storey drift and roof displacement. The results indicated that as building corrosion increased, so did the storey drift ratios. The plastic hinge formation was seen to extend from the ends of the beams and columns in the lower story to the upper storey of the building at the advanced phases of loading. Mohamed et al. [11] used two methods to establish a lateral loading pattern (triangle and uniform loadings). Based on the results of a nonlinear static pushover analysis, using the SAP2000 program, it was shown that adopting an inverted triangle loading pattern led to more accurate results than uniform loading. The pushover analysis of eighteen storey reinforced concrete building was presented by Pierre and Hidayat [12]. The design of earthquake loads was based on spectral response design. Beams and columns of the structure are assigned a hinge property that lumped the plasticity at the two ends of each element. The paper showed that plastic hinge formation in the members of the building at different loading stages. The formation of plastic joints started in the majority of beam elements at the performance point. The predicted performance point indicated an acceptable safety margin for the structure. Sullivan et al [13] presented a simplified approach for the pushover analysis of RC structures and provided a procedure for considering the displacement value of these buildings. Their approach was based on guidelines proposed to account for different mechanisms of yielding. The reliability and effectiveness of the proposed method were approved by comparing the predicted force-displacement response with that of nonlinear static analysis. The validity of the method was evaluated on a series of case applications consisting of analyzing two dimensions RC frames having 2, 3, 4, and 6 storey. The work presented an assessment of the proposed method by comparing the results predicted with that of a static pushover analysis for both lateral displacement profile as well as the base shear at different limit stages. The method is also applied for the analysis of 3D reinforced concrete structures. A simplified pushover analysis of the RC frame based on a rigorous analytical model was presented by Rabi et al [14]. The model can be used for assessing the seismic capacity of shear type RC frame based on three Limit States (LS) namely: the Damage LS, Life Safety LS, and Collapse LS. All these states are specified through closed form relationships and are dependent on the geometry and material properties of the members of the frame. The method was validated by comparing its analytical results of three 2D reinforced concrete frames, with the numerical results of pushover analysis based on finite element method. The results indicated a satisfactory match in terms of both total base shear and top displacement for these frames, which had 3, 5, and 6 storey. The complexity of the proposed equations and relationships of the simplified methods proposed in Ref. [13] and [14], make their application limited to 2D frames and they did not compensate for the pushover analysis based on the finite element method that is available in several available software. The effects of the presence of the shear wall in the seismic response of G+7 residential building, using pushover analysis, was discussed by Jindal et al [15]. A displacement control pushover analysis was carried out to predict the effects of the existence of the shear wall at three different locations. In the nonlinear analysis, the plastic hinges for beams and columns were modeled by moment curvature relationships. Displacement control criteria were used by increasing the displacement incrementally at the top nodes. The pushover curve and hinge development are included in the analytical results. The hinges were found to form in the beams prior to the columns and it was observed that the maximum base shear capacity was higher than the design base shear. The maximum drift ratio was predicted in the model without a shear wall. The results show that shear walls enhanced the structure's ability to resist lateral loads.

2 BUILDING DESCRIPTION

In the present study, the analyzed building is a ten-storey reinforced concrete structure. The building is designed with plane dimensions of (15.15 x 17.9m) and its storey height is (3m) making the overall building height (30m). Design base shear was calculated according to Indian standards [5]. Before beginning the pushover analysis, an initial loading step of (0.3 Live Load and a Dead Load) is taken into consideration in the gravity direction. The plane and the 3D model of the building are shown in Fig. 2. Tables 1 and 2 show the basic details and material properties of the members of the building. Nonlinear analyses using the pushover method and time history analysis were performed assuming the building to be located in the seismic zone (V) according to Indian standards [5] assuming rocky soil. Both types of analysis were carried out using SAP2000 V20 [1]. Displacement control was used for pushover analysis and the moment-curvature relationship for each member was utilized to represent the performance of the plastic hinge in the beams and columns. Each column's end, the (P-M2-M3) nonlinear hinge properties were used; while for beams, the (M3) hinge properties were assigned at both of its ends.

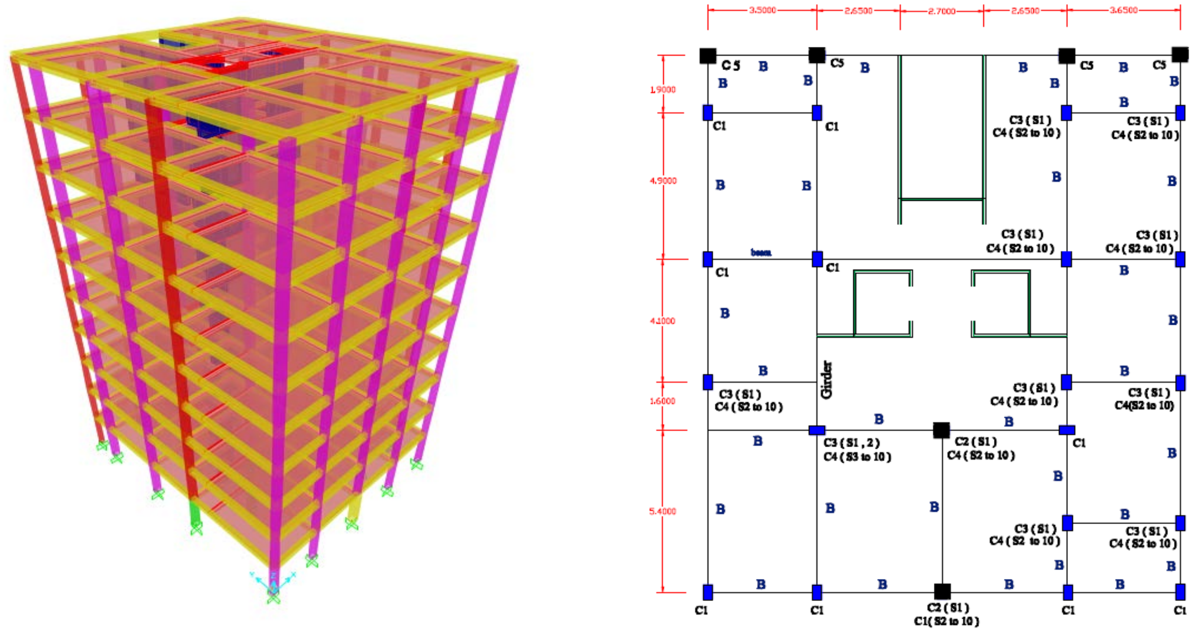
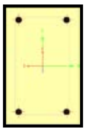
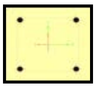
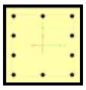
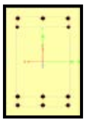
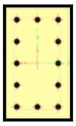
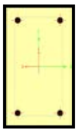


Fig. 2. Using SAP2000, a planar and three-dimensional picture of the building

Table 1. Basic building information

	Contents	Description
1	Number of storey	G+9
2	Height of Each Floor	(3) m
3	Thickness of Shear Wall	200mm
4	Slab thickness	150mm
5	Dead load	2 kN/m^2
6	Live load	2 kN/m^2
7	partition load	12 kN/m
8	Concrete compressive strength (fc')	28 MPa
9	Yielding of steel (fy)	400MPa
11	Response spectra	As per IS code [5]
12	Type of soil	Rocky soil
13	importance factor (I)	1
14	Seismic zone	V
15	Zone factor (Z)	0.36
16	Response reduction factor (R)	5
17	Damping	5%
18	Applied initial load (Self Weight, 0.3 Live loads and Dead load)	44022kN

Table 2. section characteristics of the beams and columns

Identification	b*h (m)	Reinforcement	Arrangement	Identification	b*h (m)	Reinforcement	Arrangement
Column (C1)	0.3*0.5	2φ25 Top 2φ25 Bottom		Column (C5)	0.3*0.3	2φ20 Top 2φ20 Bottom	
Column (C2)	0.5*0.5	10φ25		Beam (B)	0.3*0.5	3φ16and 2φ12 Top 6φ16 Bottom	
Column (C3)	0.3*0.5	12φ25		Girder	0.3*0.6	3φ25and 2φ12 Top 3φ25 Bottom	
Column (C4)	0.3*0.5	2φ25 Top 2φ25 Bottom					

3 ESTIMATION OF LATERAL LOAD IN THE STATIC NONLINEAR ANALYSIS

In the pushover analysis four different loading patterns were applied in the X-direction. This direction was chosen because the building's second mode is in that direction, while the first mode is a torsional mode. These loads are calculated as follows:

a) Uniform distribution load pattern [16]:

$$F_i = W_i \tag{1}$$

Where Wi: storey weight and i=storey number

b) Mode Shape pattern (Mode 2)

$$F_i = W_i \emptyset_{ij} \tag{2}$$

Where $\emptyset_{ij}$ is the vector of mode shape i for the "jth" storey.

It should be noticed from the predicted mode shape, that for each node there are six degrees of freedom (3 displacements and 3 rotations in the X, Y, and Z directions) so; moments are also developed in the nodes of each storey by multiplying each of the three rotations by the weight (Wi) of that storey. In the current work and to avoid generating these moment components, the suggested and implemented procedure for calculating the lateral load distribution was summarized in the following steps:

1. From free vibration analysis, the mode shape that corresponds to the required direction of application of lateral loading is found.
2. Isolating the translational mode component in the direction of loading for the i^{th} storey, ignoring the other degrees of freedom, the lateral load is determined as follows:

$$F_i = W_i \emptyset_i \tag{3}$$

3. This load is distributed evenly across the nodes of that storey.

c) Inverted Triangular distribution: ATC-40 [8]

The calculated lateral load was according to ATC-40 [8] using Eq. (4)

$$F_i = \frac{W_i h_i}{\sum W_i h_i} V_b \tag{4}$$

Where V_b is the building's base shear force, determined in accordance with Indian standard [5] utilizing Eq. (5)

$$V_b = \frac{ZISa/g}{2R} W_T \tag{5}$$

Sa/g=Average response spectral acceleration coefficient in X- direction and W_T is the total weight of the building and R is a reduction factor according to the code [5].

d-The FEMA criteria [2]:

Eq. (6) is utilized to calculate the force in the i^{th} storey in this method.

$$F_i = \frac{W_i {h_i}^k}{\sum W_i {h_i}^k} V_b \tag{6}$$

Where k "is a factor that depends on the building's fundamental period (Tn)", and k is according to the limits.

$$k = \begin{bmatrix} 1 & \text{if } T_n < 0.5\ seconds \\ 2 & \text{if } T_n > 2.5\ seconds \end{bmatrix} \tag{7}$$

By extrapolating from the constraints provided in Eq. (7), and based on the fundamental period in the X direction, determined from the model analysis of the structure, which is equal to 1.102 seconds, accordingly; k is equal to 1.3. The Fig. 3 shows the lateral load distribution patterns according to FEMA, Uniform and inverted triangular load patterns used in the pushover analysis of the present work.

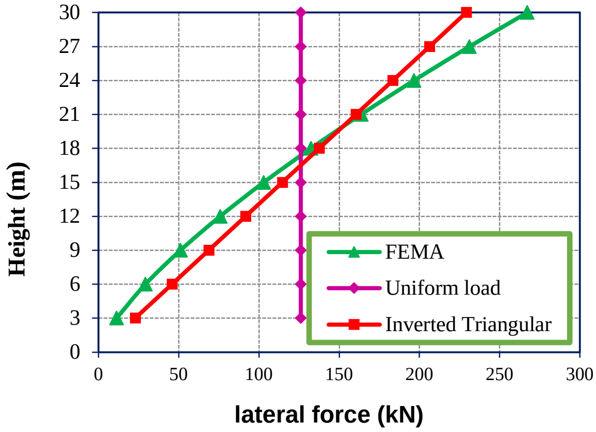


Fig. 3. Lateral load distribution used in the pushover analysis method

4 NONLINEAR TIME HISTORY ANALYSIS

To discuss the results of the nonlinear pushover analysis and compare the structural response with that under an actual earthquake, the nonlinear time history dynamic analysis of the same building was carried out. For this type of analysis, the structure is subjected to the Sylmarff-1.TH earthquake function and based on the Hilber Hughes Taylor method available in SAP2000 V20 [1]. The acceleration record of this earthquake was applied in the X direction and the main interesting output of this analysis is the variation of base shear and roof displacement with time. Some other results from nonlinear time history analysis are also presented, while the main debated results of pushover analysis are the variation of lateral displacement along with the storey height and storey drift as well. Also, the predicted performance points using different lateral load patterns for the pushover analysis of the building are presented.

5 RESULT AND DISCUSSION

5.1 Base Shear, Displacement, and story Drift

The predicted base shear lateral roof displacements of the building for the four lateral load distributions used in the pushover analysis are presented in Fig. 4. The figure showed that the structure responded stiffly to uniform lateral loads, whereas under the FEMA [2] and inverted triangular lateral loads the structure showed a flexible and almost similar response. This is because the location of the force resultant for these two load patterns (inverted triangular and FEMA) is around two-thirds of the height of the building, while the resultant of the uniform lateral force distribution is located at the mid-height of the building, causing less moment at the base of the building than FEMA and inverted triangular lateral loads distribution causing less lateral displacement at a particular base shear. The variation in lateral displacement with building height using different lateral pushover load patterns at roof displacement equal to (0.273m), in addition to the result predicted from time history analysis are shown in Fig. 5; while Fig. 6 shows the storey drifts along with the building height. This displacement (0.273) was chosen because it is the maximum positive displacement predicted from time history analysis as will be shown later. Figs. 5 and 6 show that at the particular roof displacement (0.273m), the building under the uniform loading experiences a higher displacement along with the height of the building compared with other loadings. The maximum storey drift for all cases takes place at the fifth storey except the uniform load case in which the maximum story drift was at the fourth story. The same was presented at the failure load in Fig. 7 and Fig 8 for the four lateral load distribution patterns. The variation of storey drifts with building height near failure load are exhibited in Fig. 8, which indicates that maximum storey drifts for all cases taking place at the fifth story except the uniform load case in which the maximum story drift is at fourth storey, the same as that predicted at a displacement of (0.273m) shown in Fig. 6 with almost double values.

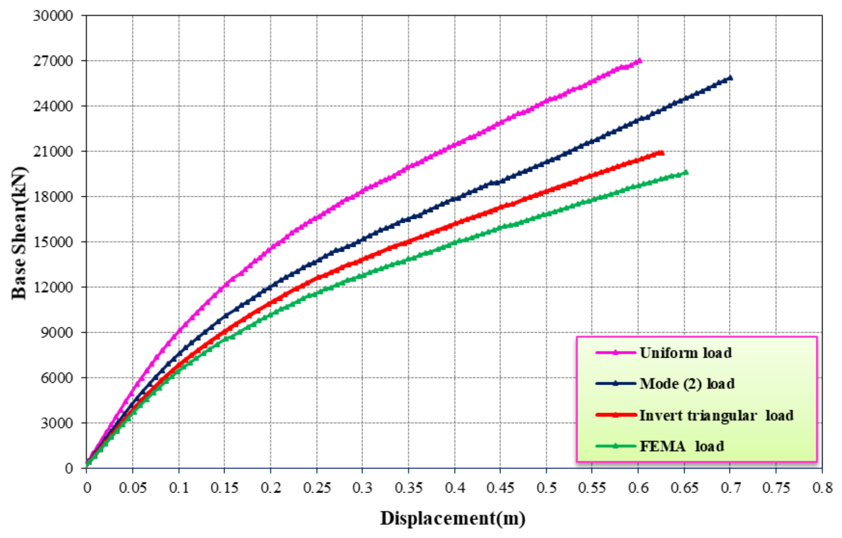


Fig. 4. Predicted variation of base shear with roof displacement at different loading steps

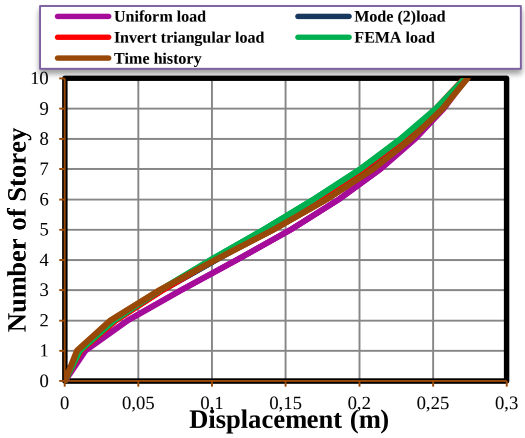


Fig. 5. Lateral displacements with building height at roof displacement (0.273m)

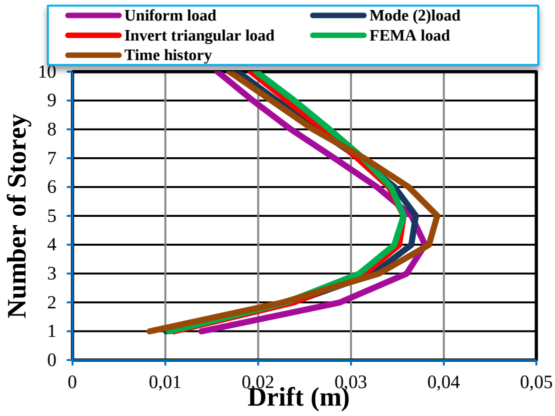


Fig. 6. Story drift along with building height at roof displacement (0.273m)

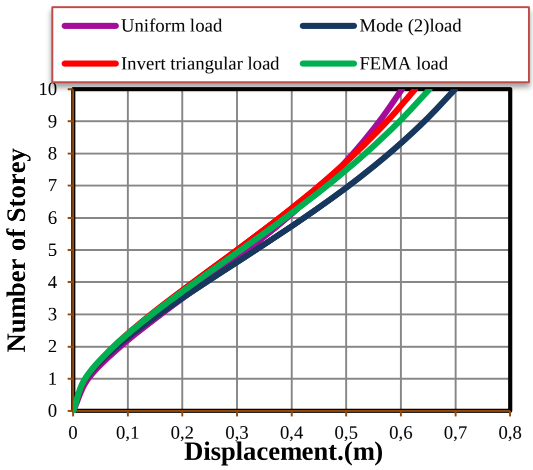


Fig. 7. Lateral displacements at different storey near failure

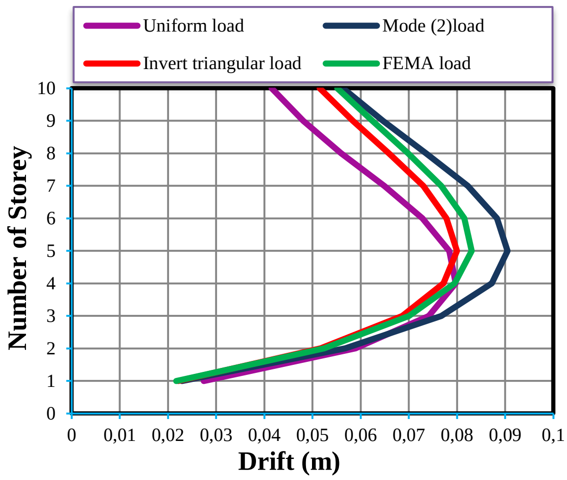


Fig. 8. Storey drift at different storey near failure

6 PERFORMANCE POINT

The performance point, which is used to calculate the building's permitted maximum inelastic displacement, is the point where the capacity and demand curves intersect. In the present work, the Capacity Spectrum Method based on ATC-40 [8] was adopted since it is the most widely used and considered as an appropriate method for predicting the performance point. The estimated performance point for various lateral loading patterns is summarized in Table

3 based on the pushover analysis. The table displays a nearly comparable performance point, with respect of base shear and roof displacement, for the inverted triangular and FEMA distribution.

Table 3. Values of performance point

Load Patterns	Base shear (kN)	Displacement (m)
Uniform	12458.98	0.154
Mode (2)	7741.32	0.098
Inverted Triangle	10168.391	0.178
FEMA	9546.52	0.181

7 FORMATION OF PLASTIC HINGES

The plastic hinges development in the beams and columns of the building at the state of performance points for the different lateral load distribution patterns as shown in Figs. 9 to 12. The type, location, and state of the plastic hinges are depicted in these figures in the three-dimensional shape of the building and in the X-Z plane at zero Y coordinates. Because the performance points for inverted triangle and FEMA are nearly identical, the plastic hinge formation in these two cases is nearly identical, these are shown in Fig. 11 for inverted triangular load distribution and Fig. 12 for FEMA load distribution respectively. The predicted plastic hinge formation from time history analysis at maximum positive displacement (0.273m) is presented in Fig. 13, which shows the advanced stage of plastic hinges formation, particularly in some beams.

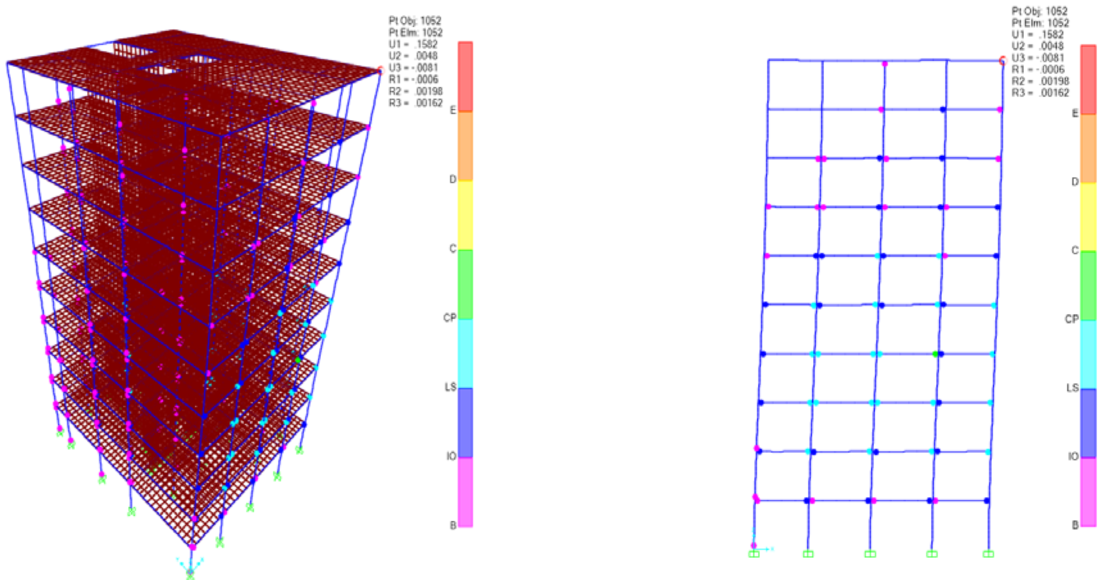


Fig. 9. Development of plastic hinges due to the uniform load distribution near the performance point

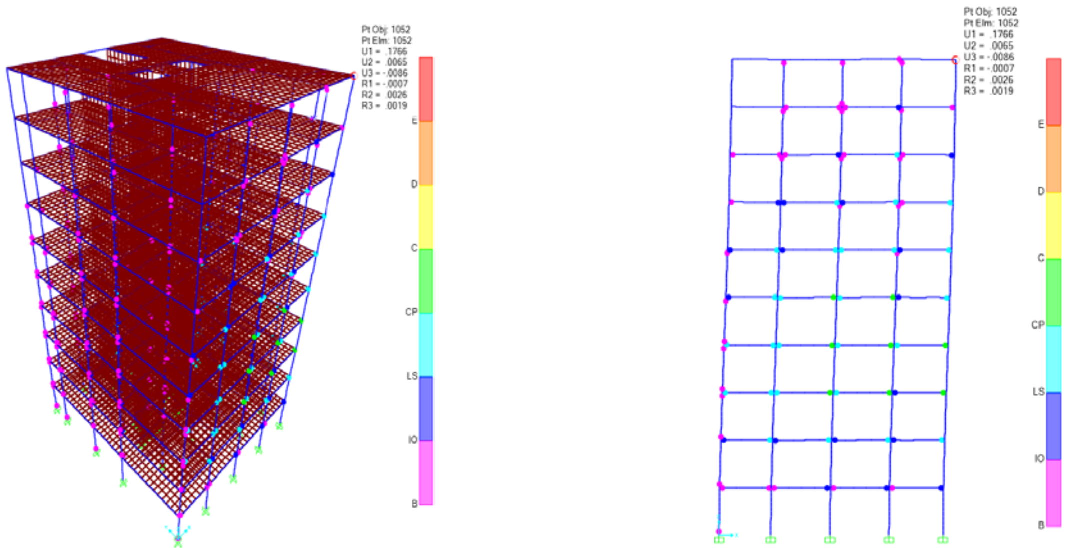


Fig. 10. Development of the plastic hinges due to Mode Shape near performance point

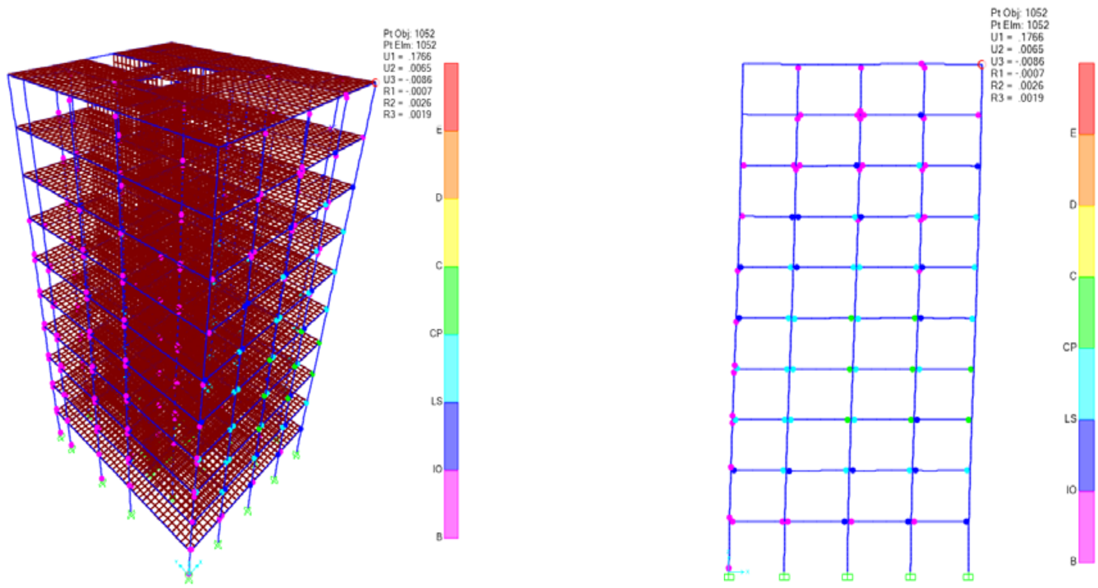


Fig. 11. Development of the plastic hinges due to the inverted triangular method near the performance point

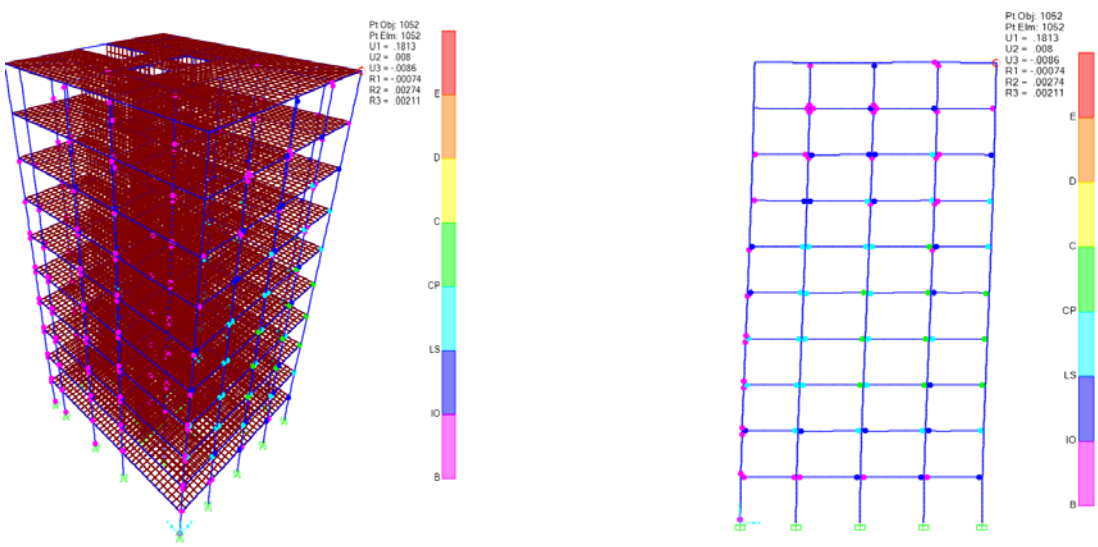


Fig. 12. Development of the plastic hinges due to FEMA load method near performance point

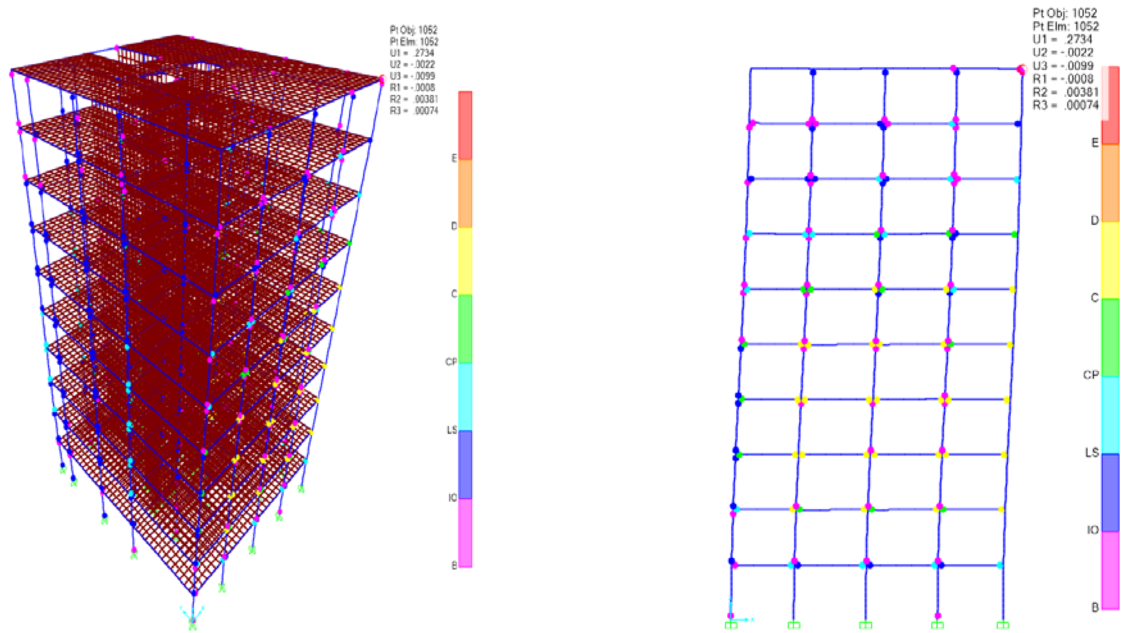


Fig. 13. Plastic hinges from time history analysis at time 3.66 with max displacement (0.273m)

Fig. 14 depicts the fluctuation in roof displacement with time predicted from nonlinear time history analysis of the building subjected to earthquake. It can be noticed that the maximum displacement is equal to 0.273m at a time of 3.62second; while the maximum negative displacement is 0.348 at a time of 4.3 sec. Fig. 15 shows the predicted variation of base shear with time which shows that a maximum positive base shear of 16890kN was taking place at the time of 3.52 seconds.

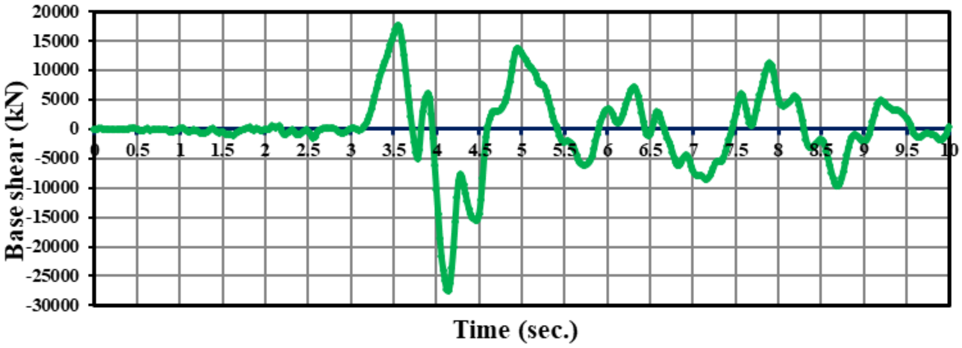


Fig. 14. fluctuation of roof displacement with time

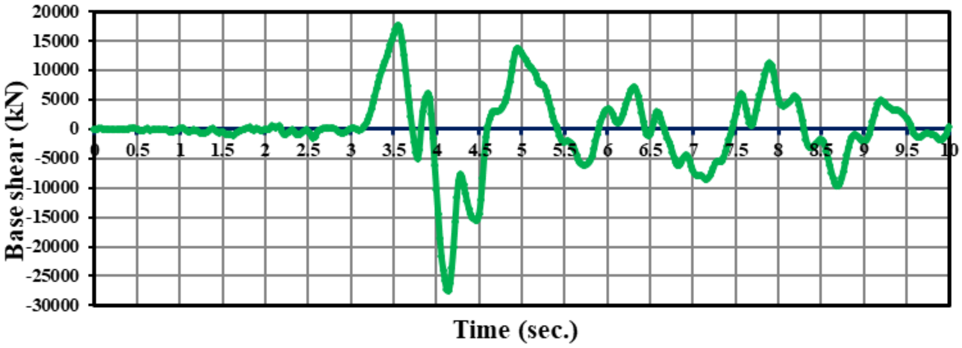


Fig. 15. base shear variation with time

8 CONCLUSIONS

The present work demonstrated the effects of using four different lateral load distributions, namely uniform, FEMA, Mode, and inverted triangular load distributions on the results of a nonlinear static pushover analysis of 10 storey RC building. The predicted results have shown an almost identical and compatible response of the building under the two types of loading, FEMA and inverted triangle. The comparison between these two methods was represented in terms of failure load, base shear-lateral roof displacement curve, the variation of lateral displacement, storey drift along with the height of the building, performance point, and the mode of formation of plastic hinges in the members of the building at the performance point state. The results of uniform lateral load distribution have shown stiff performance in terms of base shear-lateral displacement of the roof in comparison with the other three loading patterns and this leads to less formation and development of plastic hinge for this type of loading. Also, the predicted performance point for the building subjected to a uniform load pattern is higher than the other three loading patterns. The results of pushover analysis of the considered building show that it is secured under the impact of the considered earthquake.

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