CONSIDERING THE EFFECT OF VERTICAL GROUND MOTION IN NONLINEAR STATIC PROCEDURE

Mohammadreza SHAVANDI
M.Sc. Graduate, Department of Earthquake Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
mr.shavandi@gmail.com

Armin AZIMINEJAD
Assistant professor, Department of Earthquake Engineering, Islamic Azad University, science and research branch, Tehran, Iran
armin.aziminejad@gmail.com

Mahmood HOSSEINI
Associate Professor, Structural Engineering Research Center, the International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
hosseini@iiees.ac.ir

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ABSTRACT

In the near-field Sites (assume less than 20 km) structures may experience shaking considered as forward-directivity effect that often contain significant pulses in the velocity time history. These ground motions is called near-field earthquake with impulsive characteristics. Pulses in velocity time history affect seismic performance of structures (NEHRP, 2011). Some other characteristics of near-filed earthquakes are: Strong vertical component, large ratio of horizontal Fault-normal component to horizontal fault-parallel component Chopra et al. (2001), High Frequency content (Ghobrah, 2004). Vertical component of ground motion have significant effect on column axial forces and beams ductility demands. One of the nonlinear analysis limitations is that pushover analyses are not able to calculate the effect of vertical component by lateral load pattern and demonstrate accurate result for near-field earthquake. The objective of this paper is to propose a method to improve the accuracy of pushover analysis in the near-field region. For this purpose, in this paper in addition to lateral load pattern (Code distribution load pattern) an appropriate vertical load pattern is considered. Then the structure is pushed in the both direction at the same time. 2 dimensional Steel moment resisting frames, SAC-3 and SAC-9 are Simulated in PERFORM 3D and subjected to 7 impulsive near-field ground motions (Ohtori et al., 2003). Result shows that, use of proposed pushover methods for Code load distribution and RSA load pattern leads to decrease Beam and column plastic hinge rotation errors the accuracy of nonlinear static analysis improved in estimating the performance of structures in near-field earthquakes.

INTRODUCTION

In recent years nonlinear static analysis has been impressive progress. In these analysis which have been called pushover analysis, used simplified nonlinear method for estimating structure Seismic performance. With the publication of capacity spectrum method of ATC-40 report in 1996 and coefficient method of FEMA-356 report in 2000, several researches have been conducted on nonlinear static analysis. Chopra and Goel (2002), suggested a modal pushover procedure that combines response of individual modes to estimate general response of structure. Ground motions shaking near the active fault are different from those earthquakes at larger distance. In the near-fault region ground shaking is affected by rupture mechanism and rupture propagation. Due to these unique characteristics, most of seismic energy is often appeared in pulse motions with the large periods in the velocity time history. The near-field ground motions are caused significant deformations in the structure that would enforce it to damp strong entrance energy in small number of hysteresis cycle that increased risk of brittle failure of structure (Ghobrah, 2004). The destructive effects of such characteristic have been seen in earthquakes like Northridge (1994), Kobe (1995) and Chi-Chi (1998). Also earthquakes recorded in the near-fault demonstrate that vertical acceleration are often larger than horizontal acceleration and the frequency content of them are different from horizontal component. Nonlinear static analyses have limitations like they are not capable of considering the effect of vertical component of earthquakes on column axial forces and beam deformations which may have significant impact. Chopra and Chintanapakdee (2001) evaluated response of SDF system to near-field and far-field ground motions and they showed that the velocity sensitive region for near-fault motions is much narrower and narrower velocity-sensitive region is shifted to longer periods. Also FEMA-440 report (2005) provides additional detailed data used to development and evaluation of pushover analysis performance in near-fault structures. These reports declared that nonlinear static analysis have less accuracy to predicting response of structures located in the near-field sites. Pietra and Pinhoo (2008), the estimation of structural response for near-field and far-field motions evaluated and confirmed that in the accuracy of conventional pushover methods for near-field records have been reduced especially for tall buildings. Mortezaei and Ronagh (2013), proposed modified pushover analysis procedure to improve accuracy of pushover methods for reinforced concrete buildings subjected to near-fault ground motions having fling step.

DESCRIPTION OF THE PROPOSED PROCEDURE

As mentioned, common nonlinear static analysis methods which are suggested in many regulations and guidelines cannot consider directly vertical component of near-field earthquakes. According to this, in this study a new pushover analysis method suggested. In proposed method beside horizontal load pattern, vertical load pattern determined. Horizontal code load pattern is obtained by Eq. (1)

$$c_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} \tag{1}$$

$$K=0.5T+0.75 \tag{2}$$

Where w_i and w_x are the weights of story i or x, h_i and h_x are the height of story and k in Eq. (2) is coefficient that varies from 1 for $T \leq 0.5$ Second to 2 for $T \geq 2.5$ Second. The shape of lateral load pattern varies from an inverted triangular for periods less than 0.5 second to a parabolic for periods greater than 2.5 second to considering higher modes effect.

Also Vertical load patterns defined in two different forms. In the first case vertical load pattern defined corresponding to seismic mass of each story and then applied to each floor of SAC structures. In the Second case vertical load pattern considered corresponding to the structure vertical first mode shape in two different methods. The process is illustrated as follow:

1. Vertical mode shape of each structure is calculated. Then the deformation of each beam-column joints at this mode for each story are averaged and applied as a uniform vertical load pattern.
2. After calculating of Vertical mode shape of each structure, the deformations of right-end for each beam at each story (with linear deformation assumption) are averaged.

After defining vertical load pattern, appropriate intensity should be applied to well considering vertical component effect of near-filed ground motions to capture closer responses to nonlinear dynamic analysis. For this purpose, we determined equation calculating appropriate coefficients to multiply in load patterns.

Equation (3) which is based on dynamic characteristics of structure and specific feature of near-field earthquake is obtained by regression and statistical methods as Eq. (3).

$$C_1 = 0.772 - 0.130\left\{\frac{(B\times H)}{1000}\right\} + 0.0516(M) + 4.799(UPGA) - 3.161(HPGA) - 0.0448(M\times UPGA) + 0.621(M\times HPGA) - 0.016\left(\frac{F_{eq}}{F_S}\right) - 1.602(UPGA)^2 + 1.887(HPGA)^2 - 2.375(UPGA\times HPGA) \quad (3)$$

Where
- B : bay width of frames (m)
- h : Story height (m)
- M : Seismic mass (ton) of structure is due to several component of the building, including the steel framing, floor slabs, ceiling, mechanical/electrical, partitions, and roof.
- $UPGA$: Vertical peak ground acceleration (g)
- $HPGA$: Horizontal peak ground acceleration (g)

F_{eq} : Ground motion frequency (Hz)

F_s : Structure frequency (Hz)

In the next step, horizontal pushover and vertical push down was carried out. The two processes will perform simultaneously in x-lateral and z-vertical direction until horizontal pushover reaching to target displacement.

GROUND MOTION DATABASE

It is recognized that specifications of near-field earthquakes are significantly different from those recorded in the far-field distances. Significant pulses in the velocity time history are often can be may appear in the forward-directivity state and pulse type motions. Near-field Ground motions records in this study are selected from (NEHRP report, 2011). In this report totally 390 records from 35 earthquake were investigated and those records contain forward-directivity (FD motions) presented. A total 7 near-field earthquakes through 90 strong motions selected in which site classification were restricted to A and B, ASCE site class, magnitudes were restricted to $6.5 \le M_w \le 7.5$ and closest distances to fault was restricted to 10 km.

Information to the earthquake data including horizontal PGA, vertical PGA and magnitude are presented in Table 1. The near-field records are applied without any further scaling and were used at their natural intensity.

Table 1.Near-field ground motion database (NEHRP report, 2011)

Earthquake	Record Number	Vertical PGA (g)	Horizontal PGA (g)	Closest Distance (km)	M_w	Duration (s)
Sanfernando	NGA0077	0.699	1.226	0.5	6.61	41.64
Tabas	NGA0143	0.688	0.852	1.79	7.35	32.84
Northridge	NGA1085	0.376	0.828	5.19	6.69	40
Kobe	NGA1119	0.433	0.693	0.27	6.9	40.96
Loma Prieta	NGA0779	0.886	0.966	3.88	6.93	25.005
Landers	NGA0879	0.818	0.789	2.19	7.28	48.125
Cape Mendenico	NGA0825	0.753	1.497	6.96	7.01	30

DESCRIPTION OF STRUCTURES USED FOR EVALUATION DATABASE

2 sample buildings is selected as case study of this evaluation. The 2 dimensional of steel moment-resisting frame buildings of 3 and 9 stories of SAC project were considered. These structures is designed for Los Angeles using UBC94 seismic requirements (Uniform Building Code 1994). These benchmark

structures which have been used in several studies represent low- and medium buildings (Ohtori et al., 2003). Dimensions of simulated structures are shown in Table2.

Table 2. Dimensions and Periods of structures (Ohtori et al, 2003)

Buildings	Story	Natural Frequencies	Height (m)	Bay Widths (m)
SAC 3	3	0.99	11.89	9.15
SAC 9	9	0.443	37.19	9.15

SIMULATING ASSUMPTION

The 3- and 9 story of SAC buildings were modelled in PERFORM 3D. This program provides instruments to build nonlinear analysis models and analyse them. Nonlinear structural behaviour is defined in two different ways. For many elements an elastic-perfectly-plastic (EPP) relationship may be adequate. Trilinear behaviour is more complex than EPP behaviour and optional strength loss and degradations are simulated. In this study, Trilinear behaviours is considered for SAC building frames (figure 1). Also column ductile limitation depends on axial force is used according to FEMA-365 Requirements.

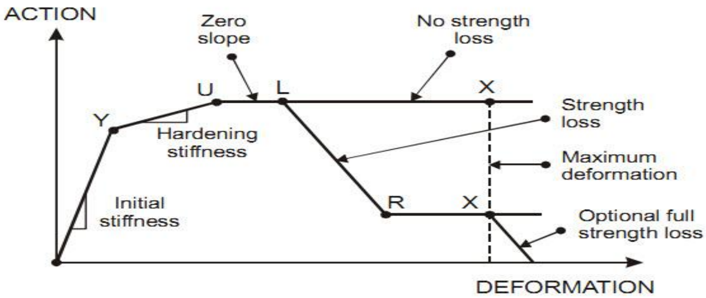

Figure 1. Nonlinear behaviour curvature (PERFORM 3D, 2006)

PERFORM 3D is unable to consider Distributed mass for structures. Thus, Lump mass at the right-end of beams and 0.25, 0.5 and 0.75 of bays were introduced. It is possible to capture vertical component effect of earthquakes on both beams and columns in this distribution.

EVALUATION OF PROPOSED NONLINEAR STATIC ANALYSIS

The validity of nonlinear analysis with three vertical load distributions is evaluated using result of dynamic responses. 3 steel moment-resisting SAC buildings is modelled in PERFORM 3D and subjected to 7 near-fault ground motions. The peak roof displacement of structures under the nonlinear dynamic analysis of each ground motions is considered as pushover target displacement. The maximum plastic hinge rotation of beams and columns due to seven near-fault records are assumed as benchmark values and the result of pushover analyses without and with vertical load patterns are examined. Proposed pushover analysis were performed by two lateral and vertical load pattern and the structures are pushed-over and pushed -down slightly at the same time until reaching structures to their horizontal target displacement.

The proposed procedures containing appropriate vertical load patterns to enclose nonlinear static responses to nonlinear dynamic responses. Therefore these methods are called M-Code, M-Code-SA, M-Code-BA and M-RSA. M-Code contain uniform vertical load pattern corresponding to weight of each story , M-Code-SA have uniform vertical load pattern due to mean deformation of beam-column joints in vertical mode shape and M-Code-BA idealize the deformation of right-end beams of vertical mode shape (with linear deformation assumption). Code lateral distribution is defined for these pushover analyses.

Figure 1 and figure 2. Shows Beams plastic hinge rotations maximum error and columns plastic hinge rotation maximum error for SAC3 respectively which have obtained by code and M-Code procedures. Observe that M-Code method decreased beams plastic hinge rotation maximum errors among five near-field earthquakes (Sanfernanado, Tabas, Loma prieta, Landers and Cape mendenico). For example it has better estimation in Sanfernanado ground motion (3.07% vs. 0.75) and Loma prieta earthquake (6% vs. 1.85%) than code analysis.

According to figure 2 it is clear that the amount of column errors decreased and pushover responses became closer to dynamic responses except in Landers and Northridge earthquakes. M-Code procedure exhibited Error reduction from 10.92% to 1.89 % in sanfernanado earthquake and from 12.24 % to 0.92 % in Kobe earthquake.

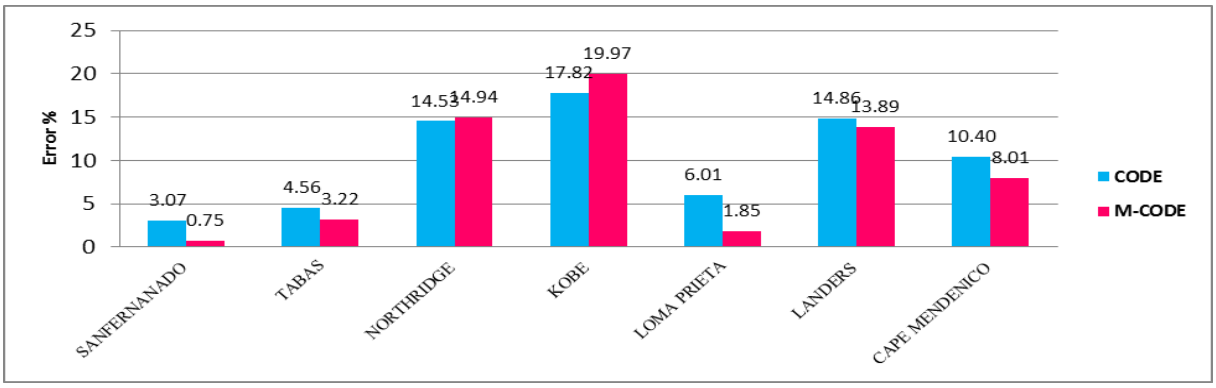

Figure 2. Code and M-Code Maximum error in beam plastic hinge rotation for SAC3 subjected to seven near-field ground motions

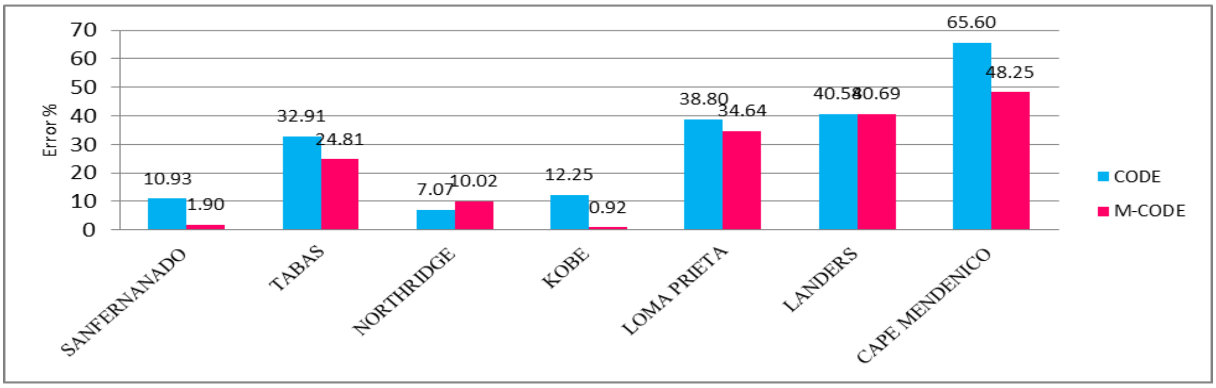

Figure 3. Code and M-Code Maximum error in column plastic hinge rotation for SAC3 subjected to seven near-field ground motions

Beams and columns plastic hinge rotation maximum error are illustrated for medium-rise SAC 9 structure in figure3 and figure4. The positive effectiveness of M-Code procedure is obvious in estimating of beams plastic hinge rotation (figure3). The M-Code provides better estimation than code method for SAC9 in all ground motions. The best results are occurred in Sanfernanado and Landers ground motions where errors decreased from 10.92% to 1.89% and from 27.69% to 11.09% respectively.

Figure 4 shows the performance of proposed M-Code method and it is clear that this method has considerable performance in Tabas, Northridge and Loma prieta earthquakes. For instance, M-Code method hinge rotation estimation for Tabas, Northridge and Loma prieta earthquakes are equal to 16.39% , 7.39% and 23.48% while the code nonlinear analysis presented results about 38.97% , 28.98% and 41.32% respectively.

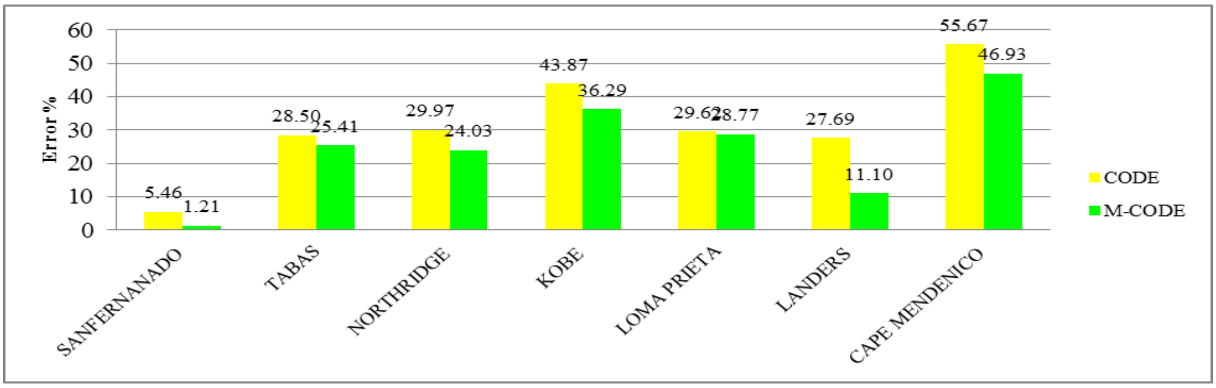

Figure 4. Code and M-Code Maximum error in beam plastic hinge rotation for SAC9 subjected to seven near-field ground motions

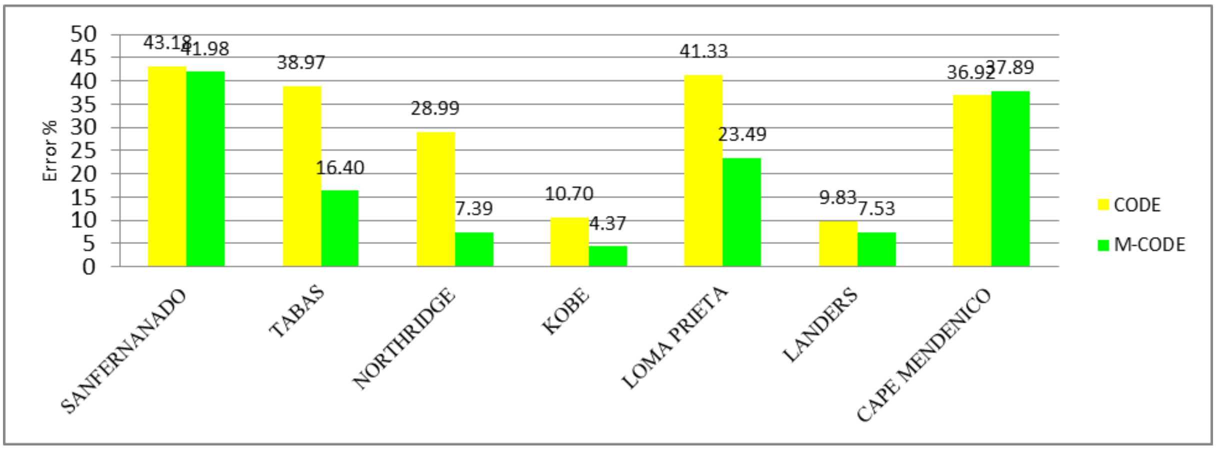

Figure 5. Code and M-Code Maximum error in column plastic hinge rotation for SAC9 subjected to seven near-field ground motions

Also in order to overall evaluation of proposed methods with different vertical load patterns, maximum error in beams and column plastic hinge rotation (figure 6 and figure 7) are presented.

In these figures performance of Code, M-Code, M-Code-SA and M-Code-BA are investigated.in this comparison it is observed that Bothe M-Code and M-Code-BA have close results. As shown in figure 7, overall mean column plastic hinge rotation in nonlinear static analysis with Code load pattern is 29.98% which M-Code and M-Code-BA methods that decrease this amount to 19.86%.

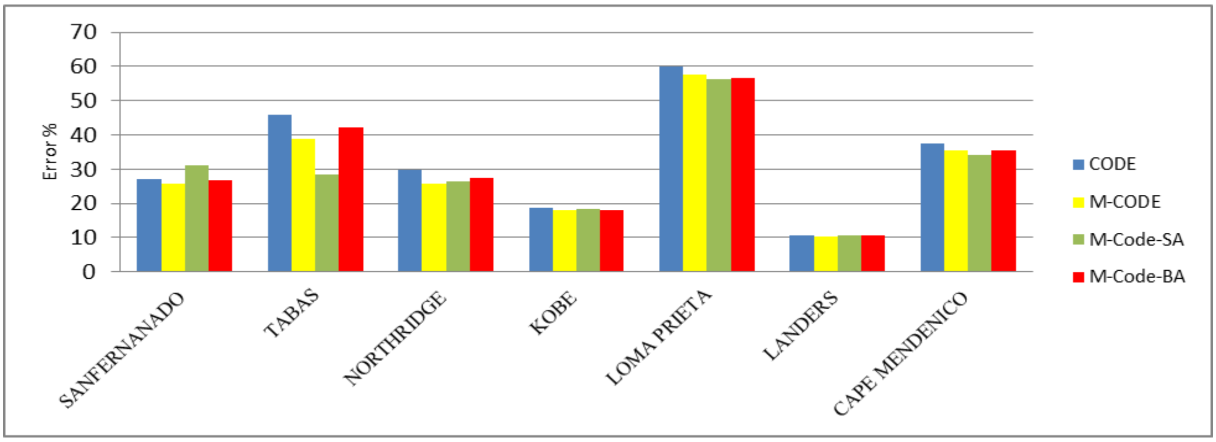

Figure 6. Overall Comparison of Code, M-Code, M-Code-SA and M-Code-BA Maximum error in beam plastic hinge rotation for SAC9 subjected to seven near-field ground motions

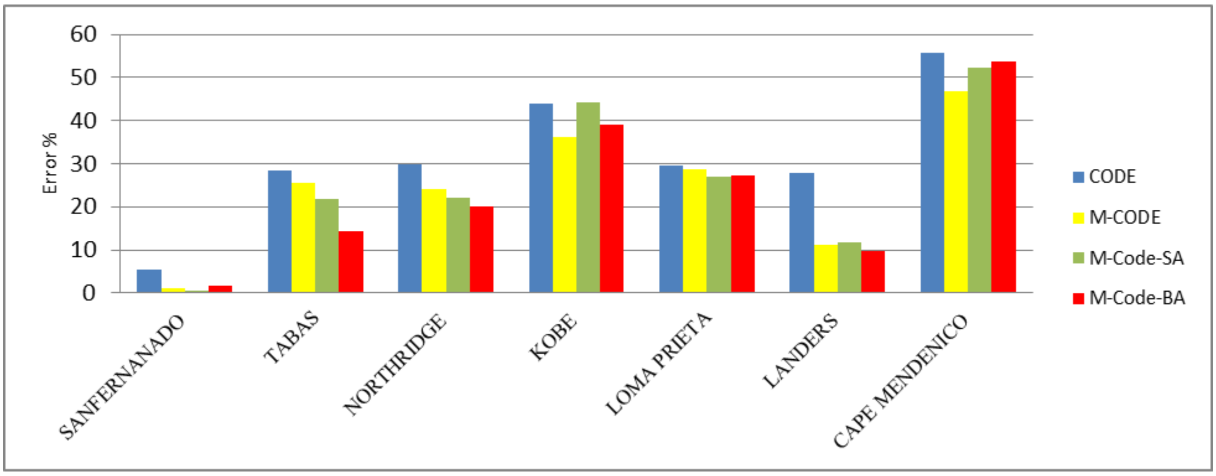

Figure 7. Overall Comparison of Code, M-Code, M-Code-SA and M-Code-BA Maximum error in column plastic hinge rotation for SAC9 subjected to seven near-field ground motions

CONCLUSIONS

It has long been identified that near-field records characterized by forward-directivity effects are more complex than far-field records. Conventional nonlinear static analysis is based on lateral load pattern and such approaches are not realistic in the near-field regions. This intent of this paper is to evaluate the validity of proposed nonlinear static analysis with extra vertical load pattern in the near-field zone. The new pushover methods have an improvement over estimation of beams and columns plastic hinge rotation. Some caution should be exercised for appropriate vertical load patterns and reduction factors should multiply in vertical load patterns in order to collapse prevention.

Based on this study, following observation can be made:

1- The proposed methods with vertical load pattern could decrease beams and column hinge rotation in SAC structures and could improve the accuracy of conventional pushover methods.

2- M-Code procedure which vertical load pattern are proportional to story weight provides more accurate results than code nonlinear analysis and results for SAC3 and SAC9 improved. Mean overall error in beams plastic hinge rotation for SAC3 and SAC9 have 13% and 27% reduction respectively. The Amount of error reduction in column plastic hinge rotation for SAC3 and SAC9 were about 29% and 50% reduction.(it needs to be mention that M-Code and M-Code-BA have close results)

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