Steel and Composite Structures, *Vol. 32, No. 1 (2019) 67-77*
DOI: https://doi.org/10.12989/scs.2019.32.1.067

Optimal lateral load pattern for pushover analysis of building structures

Alireza Habibi [*1], Hooman Saffari [2a] and Mehdi Izadpanah [3b]

[1] *Department of Civil Engineering, Shahed University, Tehran, Iran*
[2] *Department of Civil Engineering, University of Kurdistan, Sanandaj, Iran*
[3] *Department of Civil Engineering, Kermanshah University of Technology, Kermanshah, Iran*

(*Received June 30, 2018, Revised March 12, 2019, Accepted May 30, 2019*)

Abstract. Pushover analysis captures the behavior of a structure from fully elastic to collapse. In this analysis, the structure is subjected to increasing lateral load with constant gravity one. Neglecting the effects of the higher modes and the changes in the vibration characteristics during the nonlinear analysis are the main obstacles of the proposed lateral load patterns. To overcome these drawbacks, whereas some methods have been presented to achieve updated lateral load distribution, these methods are not precisely capable to predict the response of structures, precisely. In this study, a new method based on optimization procedure is developed to obtain a lateral load pattern for which the difference between the floor displacements of pushover and Nonlinear Dynamic Analyses (NDA) is minimal. For this purpose, an optimization problem is considered and the genetic algorithm is applied to calculate optimal lateral load pattern. Three special moment resisting steel frames with different dynamic characteristics are simulated and their optimal load patterns are derived. The floor displacements of these frames subjected to the proposed and conventional load patterns are acquired and the accuracy of them is evaluated via comparing with NDA responses. The outcomes reveal that the proposed lateral load distribution is more accurate than the previous ones.

Keywords: pushover analysis; lateral load; optimization procedure; nonlinear dynamic analysis; floor displacements

1. Introduction

The damage of structures in severe earthquakes showed that some structural components experienced inelastic behavior and revealed the necessity of doing nonlinear analysis to predict the actual response of structures. Pushover analysis is one of the proposed nonlinear analyses by seismic guidelines in which the performance of structures is statically assessed subjected to an incremental load pattern distributed along the height of buildings. The ability of this lateral load pattern to consider the higher mode effects as well as to update throughout the analysis has a significant effect on improving the accuracy of the predicted responses. Although the primary patterns such as a uniform, linear, parabolic are very simple, they have some disadvantages such as considering the major vibration mode of structures regardless the higher modes effects and being constant along the analysis.

Using pushover analysis in earthquake engineering dates back to the study of Gulkan and Sozen (1974) or earlier (Elnashai, 2001), Saiidi and Sozen (1981) presented a simplified linear static analysis process for multi-dimensional structures. Akbas *et al.* (2009) evaluated the energy response of steel frames through dynamic pushover analyses. According to their study, whereas for low-rise frames in which the first mode is dominant, results of pushover analysis are appropriate, for medium- and high-rise buildings, the lateral load patterns simply introduced based on the first mode present conservative outcomes. Pushover analysis has been applied in many researches comprising Izadpanah and Habibi (2015 and 2018), Ozgenoglu and Arıcı (2017), Costa *et al.* 2017, Tiana and Qiu (2018), etc. Lawson *et al.* (1994) and Krawinkler (1995) evaluated the benefits and drawbacks of pushover analysis. The lateral load pattern as one of the main components of pushover analysis has been evaluated in some researches. Paret *et al.* (1996) studied two 17-story steel frame buildings to assess the failure mechanism caused by higher mode effects. They concluded that higher modes play an outstanding role in the failure mechanism of these frames. Gupta and Kunnath (2000) proposed an adaptive spectrum-based pushover method. They presented an updated lateral load pattern changing along the analysis depending on the changes of the dynamic properties. They compared the outcomes of their method with the results of the dynamic analysis for eight buildings with various dynamic properties and showed that their procedure can appropriately predict the responses of structures even for those buildings with discontinuous in strength and stiffness. Jan *et al.* (2004) introduced a new pushover method in which a new formula for calculating the lateral load distribution and the upper-bound modal combination rule for obtaining the target roof displacement were presented. Chopra and Goel (2001) developed modal pushover analysis (MPA) in which all significant modes of vibration contribute to achieving the response of structures. This

*Corresponding author, Associate Professor,
E-mail: ar.habibi@shahed.ac.ir
[a] M.Sc. Student, E-mail: hoomansaffari@gmail.com
[b] Ph.D., Assistant Professor,
E-mail: m.eazadpanah@yahoo.com

ISSN: 1229-9367 (Print), 1598-6233 (Online)

method was modified by Chopra *et al*. (2004), In the modified modal pushover analysis (MMPA), the inelastic response achieved from first-mode pushover analysis has been combined with the elastic contribution of higher modes. Antoniou and Pinho (2004) evaluated the accuracy of force-based adaptive and non-adaptive pushover methods in computing the capacity of a reinforced concrete building by comparing the results with the outcomes of nonlinear dynamic analysis (NDA), They concluded that none of the aforementioned methods cannot predict the deformation pattern of building appropriately. In another study, they put forward a new displacement-based adaptive pushover method and illustrated that this procedure, throughout the entire deformation range, presents more appropriate results rather than force-based adaptive pushover method (Antoniou and Pinho 2004), The performance of conventional and adaptive pushover methods for eight different reinforced concrete structural systems was evaluated using a proposed methodology by Papanikolaou and Elnashai (2005), Attard and Fafitis (2005) developed a pushover analysis taking higher vibration mode effects into account. They proposed their methodology based on elastic structural dynamic theory. To reflect the higher mode effects, their proposed load pattern is acquired using one mode shape at each yielding stage of capacity curve. Papanikolaou *et al.* (2006) performed similar research on eight different reinforced concrete buildings with various levels of irregularity in plan and elevation, structural ductility and directional effects. Kalkan and kunnath (2006) suggested an adaptive modal combination method. In their presented procedure, the target displacement is updated dynamically by combining energy-based modal capacity curves. The outcomes proved that the suggested method can predict critical demand parameters, properly. Kim and Kurama (2008) developed Mass Proportional Pushover (MPP) to obtain peak seismic lateral displacement demands for building structures. In this method, the influences of higher vibration modes on the lateral displacements are concentrated into a single invariant lateral force distribution. The aforementioned lateral load is proportional to the total seismic masses at the floor and roof levels. Comparing the outcomes of MPP and MPA with NDA for three moment resisting steel frames demonstrated that MPP presented more accurate roof and lateral displacements. Mao *et al*. (2008) developed a modal pushover method to consider the effects of higher modes for tall buildings. They proved that the aforementioned method presents better results from MPA that was presented by Chopra and Goel (2001), Optimal combination of modal pushover analysis was presented by Shakeri *et al*. (2010), In this research, an alternative combination method instead of the elastic modal combination that is not valid in inelastic phases was introduced. Shayanfar *et al.* (2013) used the Cuckoo Search algorithm (CS) to present an optimal modal lateral load distribution. They considered the lateral load pattern as a linear combination of three first vibration modes of structure with different weight coefficients. In their method, the weight coefficients are achieved via optimization procedure such that the responses of pushover analysis have better accuracy than conventional load pattern. Etedali and Irandegani (2015) introduced a power lateral load pattern such that the lateral force of each story is proportion to the relation of the height of each story to the total height of the structure. The suggested load pattern was a representative of two lateral load patterns namely uniform and triangular lateral load patterns. To obtain suitable power in the proposed lateral load pattern, they considered various values for power and compared the capacity curves of each frame subjected to the presented lateral load distribution with those of IDA. Sarkar *et al*. (2016) suggested a new procedure to acquire the lateral load pattern of stepped buildings as well as a modification to the displacement coefficient method of ASCE/SEI 41-13 of these frames. Amini and Poursha (2018) proposed an adaptive force-based multimode pushover to take the influence of higher modes and the progressive changes in the dynamic characteristics along the inelastic analysis in anticipating the response of seismic analyses. They concluded that the presented method can acceptably calculate the seismic response of midrise buildings. Fakhraddini *et al*. (2018) developed a modified lateral load pattern for steel eccentrically braced frames based on a parametric study. They considered a group of 26 eccentrically braced frames under a set of 20 earthquake ground motions and used nonlinear regression analysis to obtain the new load pattern. There are some other researches studying lateral load distributions such as Chen *et al*. (2014), Endo *et al*. (2016), Ghanoonibagha *et al* (2016) and Ganjavi *et al*. (2016).

Studying the previous proposed lateral load distributions shows that they have proposed some lateral load distributions based on algebraic combination of some vibration modes of buildings that have three main disadvantages: a) little is known about the best algebraic method to combine the vibration modes (linear, Square Root of Sum of Squares or SRSS, Complete Quadratic Combination or CQC and so on), moreover, defining a predefined combination for lateral load pattern imposes the optimization algorithm to find results according to the aforementioned pattern, b), Studying the previous proposed lateral load distributions shows that in some of them, to consider the higher mode effects, different procedures based on a combination of structural elastic modes have been introduced. In these models, vibration modes are assumed independent; therefore, the influence of yielding of elements in each mode is not considered in others, so these models are not capable to take the interaction of vibration modes in the inelastic range into consideration, c) changes of structural properties throughout the inelastic region of structural behavior and particularly, the influence of nonlinear behavior of structural elements on the vibration modes are neglected. In this study, since the lateral load distribution is directly acquired based on the responses of nonlinear dynamic analysis, the influence of higher modes as well as the changes of structural properties throughout the analysis are considered appropriately. Therefore, the modal-based load patterns (e.g. Attard and Fafitis, 2005; Shayanfar *et al*., 2013) cannot be generally useful for all structures, although they can be appropriate for some structures.

The main objective of this study is to determine a lateral load pattern with the best compliance with dynamic analysis. For this purpose, a reverse engineering approach is applied to minimize the difference between the results of NDA and pushover results. To evaluate the proposed technique, the Optimal Lateral Load Pattern (OLLP) for three special steel moment resisting frames with various numbers of stories and bays to make different dynamic properties are chosen. These frames are analyzed using IDARC-2D (Reinhorn *et al*. 2009) and the performance points of them are achieved using the capacity spectrum method. Since the method has been developed based on the nonlinear time-history results, the proposed load pattern can be used for evaluation of other modified load pattern proposed by other researchers. In the present study, the lateral floor displacements of these frames subjected to the proposed lateral load pattern of this study and some others, such as uniform, linear and parabolic lateral load pattern (ULLP, LLLP, PLLP) are compared with the responses of NDA. The results show that the optimal pattern has the least error while the uniform one has the worst approximation. The error of the linear pattern is more than the parabolic distribution.

2. Proposed methodology

The aim of this study is to present an effective load pattern based on an optimization procedure that has the best agreement with the NDA. To do so, firstly, the lateral floor displacements of NDA are calculated and set as a benchmark. Secondly, the lateral load pattern which produces the least difference between the lateral floor displacements of the NDA and those of the pushover analysis is achieved. It is worth emphasizing that the aforementioned lateral load pattern is obtained through performing only one run of analysis and since it is completely determined based on the results of NDA, the influence of higher modes as well as the changes of structural properties throughout the analysis are considered.

Optimization procedures have been used in many structural researches such as Mansouri *et al*. (2018), Nour Eldin *et al*. (2018), Kim *et al*. (2017), Habibi and Bidmeshki (2017), Qiao *et al*. (2017) and Zhang *et al*. (2017), An optimization problem is defined and solved to obtain the optimum lateral load pattern in this research. The significant requirements of each optimization problem are design parameters, objective function, and appropriate constraints. The parameters that are required to explain an optimization problem are named design variables. The design variables are the parameters that changing their values influences the problem. In this research, the lateral forces of floor levels are assumed as variables. As illustrated, minimizing the error of pushover analysis in estimating the lateral floor displacements rather than NDA is the aim of this study. So the error is considered to be the objective function of the problem. In this regard, the proposed objective function of Lopez Menjivar & Pinho (2004) is chosen as the target one. Each engineering optimization problem commonly has some limitation influencing the problem. In common, these restrictions are introduced as constraints; therefore, it is evident that the best results are acquired when the error function is minimized and all of the constraints are satisfied. In this research, the assumed constraints fall into two categories. The former is applied to make more logical and conventional results. The latter is used to increase the convergence speed and also to prevent unreal results. It is worth pointing out that one of the advantages of the proposed methodology is its capability for changing variables to other engineering matters such as capacity spectrum, roof displacement, damage indices or even the combination of them according to the opinion of the user. From the physical and structural dynamic point of view, each optimization problem needs at least two constraints. In this study, based on engineering experience and also the recommendations of seismic instructions, the base shear of buildings is assumed a percentage of total weight (e.g. ten percent of total weight), Another adopted constraint in this study is to assume the positive values for lateral forces along the height of buildings. Considering the mentioned constraint leads to a global solution by the optimization algorithm. Moreover, this leads to a positive lateral load distribution similar ones suggested by seismic codes (lateral loads in seismic codes are positive), Nonetheless, this assumption of the present study can be evaluated and improved in future studies.

The lower bound of all design parameters (lateral force in each floor level) is zero and the upper bound is the weight of the considered story. Accordingly, the optimization problem is formulated as follows

$$
\begin{gathered}
\mathrm{Min:Error}_{\Delta}(\%) = 100 \times \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{\Delta_{i-NTHA}-\Delta_{i-push}}{\Delta_{i-NTHA}}\right)^2} \\
S.t: \sum_i X_i \le \alpha \times W_T \\
0 \le X_i \le W_i
\end{gathered}
\tag{1}
$$

Where $\Delta_{i\text{-}NTHA}$ and $\Delta_{i\text{-}push}$ are the i^{th} floor lateral displacements resulting from nonlinear time history and pushover analysis, respectively. n is the number of stories. The considered objective function uses the weighting coefficients and so it is capable of appropriate distribution of errors. W_T is the total weight of the building, α is the coefficient of total weight (in this study, α = 0.1), W_I is the weight of the first story. In this study, it is assumed that floor lateral displacements resulting from nonlinear time history analysis used in Eq. (1) are known. Although, the dependency of the above problem on time-history results is one of the research limitations that can be resolved in future studies by performing several numerical and statistical analyses based on the proposed method and establishing proper relations for determination of the optimal load pattern without needing time-history results.

To solve the optimization problem, employing a proper algorithm is so important. The optimization methods fall into two categories including ‘exact methods’ and ‘approximate methods’. Exact methods are not practical for large problems due to converging and time-consuming problems. The approximate methods can converge to appropriate outcomes for large problems in a short time. These methods comprise two approaches: (a) heuristic; (b) meta-heuristic (Quintero-Duran *et al*. 2017). In the former, there are some disadvantages such as finding the local optimum point instead of the global one and also not be matched with many optimization problems. To tackle these obstacles, a meta-heuristic approach was introduced that can pass the local optimum points to find global ones as well as are capable to use in a wide range of optimization problems. In this study, a genetic algorithm procedure that is an approximate meta-heuristic method is used to find the optimum lateral load pattern.

The applied procedure can be outlined as follows.

(1) Designing structure according to considered code.
(2) Selecting appropriate earthquakes and providing the acceptable average response spectrum for them according to seismic instructions.
(3) Performing the nonlinear dynamic analyses of the structure subjected to selected earthquakes in step 2. After obtaining the peak of roof displacement in each seismic ground motion and lateral displacements of the other floors, the average of lateral displacements of each floor level in all selected earthquakes is taken as benchmark displacement.
(4) Performing pushover analysis of the structure subjected to an acceptable lateral load pattern and obtaining the performance point using capacity spectrum method (ATC40).
(5) Achieving the OLLP by applying the optimization problem.
(6) Performing pushover analysis subjected to obtained OLLP in step 5, and comparing the lateral displacements in performance point with benchmark displacements. If the convergence criterion is satisfied, the obtained lateral load pattern will be the optimum, otherwise, return to step 4.

The above-listed steps are summarized in Fig. 1.

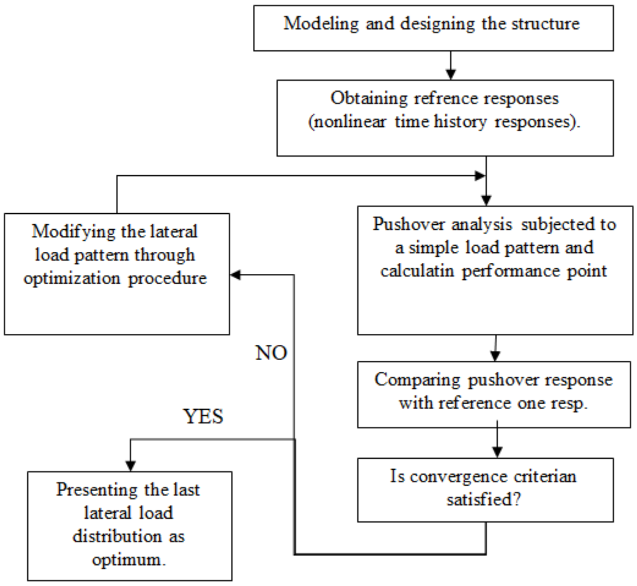

Fig. 1 The proposed procedure for computing OLLP

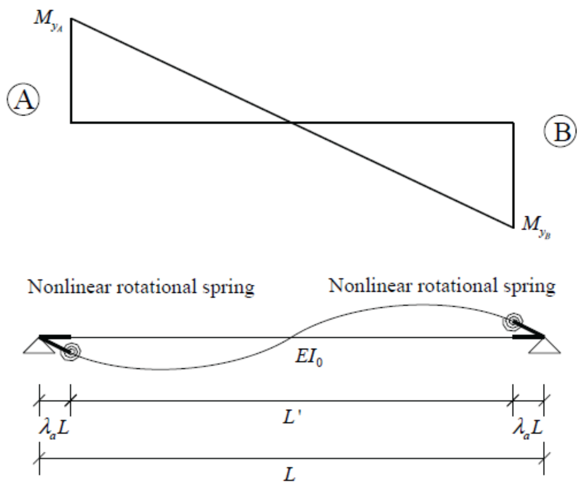

Fig. 2 lumped plasticity model

3. Nonlinear analysis of frames

To apply the proposed methodology for determining the optimal load pattern, pushover analysis of a structure is performed subjected to a lateral load pattern at each optimization stage. Also, nonlinear dynamic results are used to evaluate and minimize the error in the optimization procedure. In this study, IDARC 2D is used to perform pushover and nonlinear dynamic analyses. In both analyses, gravity loads are applied on members before lateral loads. The force control nonlinear static analysis is considered in which the structure is subjected to the distribution of incremental lateral forces while the incremental displacements are acquired. To perform nonlinear dynamic analysis, a combination of Newmark-Beta integration method and the pseudo-force method is applied and the solution is done in an incremental form (Reinhorn *et al*. 2009). The unconditionally stable, constant average acceleration for numerical integration is considered. To model the nonlinear behavior of elements, the concentrated plasticity model is applied in which each member includes two zero-length nonlinear rotational springs at the ends and an elastic element. The inelastic behavior of members is concentrated in rotational springs. Moreover, in this model, rigid end zones are taken into consideration for a joint (Reinhorn *et al*. 2009) (Fig. 2).

In Fig. 2, EI_0 is the elastic bending stiffness, M_{yA} and M_{yA} are the yield moments of the element ends. λ_A and λ_B are the proportions of the rigid zone in element ends. L is the element length encompassing rigid zones and L' is the element length without rigid zones. The bilinear hysteric model is assumed to simulate the nonlinear behavior of sections as depicted in Fig. 3.

To compute the performance point in the nonlinear static analysis, capacity spectrum method (ATC40) is used in this study. Determining performance point in this method is a trial and error process and performance point must satisfy two criteria, simultaneously: (a) performance point should lie on capacity spectrum method; (b) performance point should lie on the reduced demand spectrum method. In this method, the capacity and demand spectrums are displayed in term of acceleration, displacement response spectrum (ADRS) coordinate. For each point on the inelastic range of capacity spectrum method, effective damping is introduced that the reduced response spectrum is calculated using it. The procedure to compute the performance point is detailed in ATC40.

The responses of NDA have an outstanding role in this research. As the considered case studies in this research are designed using UBC-97 code for soil profile type SC with shear ware velocity 360 < V_s < 750 (m/s), seismic source type C and seismic zone factor *2B*; therefore, seven far fault (distance from the closest fault is more than 28 km) earthquake acceleration records are chosen that are listed in Table 1. The average response of these seismic ground motions is taken as the response of the NDA. These records are modified and scaled according to the explained method in UBC-97 to have a response spectrum with a minimum difference from the UBC-97 design spectrum as depicted in Fig. 4.

It is also noteworthy to mention that since the proposed method is a general optimization based method, for all performance levels, it will be possible to obtain the proper lateral load distribution if the nonlinear dynamic responses are available.

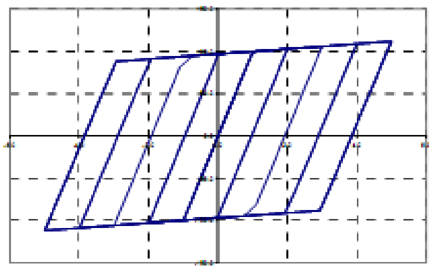

Fig. 3 Bilinear hysteric model

4. Numerical examples

Three special moment resisting steel frames are evaluated in this research. These frames are 5-story, 2-bay, 10-story, 3-bay and 15-story, 3-bay frames covering a wide range of the number of stories. For all frames, the seismic mass uniformly imposed on all stories and spans is 2640 kg/m. The height of all stories is 3m and the length of spans is 4 m. The yields and ultimate stresses are assumed 2400 and 3700 kg/cm^2. The frames are designed based on UBC-97 criteria. The used sections of beams in all floors are single IPE according to the stahl tables and for columns are single or double IPE sections without spacing are used.

Table 1 Ground motion records considered for nonlinear dynamic analysis

EARTHQUAKE	STATION-INDEX	M	PGA (g)	DURATION(Sec)
CAPE MENDOCINO 1992/04/25 18:06	Petrolia - PET000	7.1	0.590	36
DUZCE Turkey 1999/11/12	Duzce - DZC270	7.1	0.535	25.885
LANDERS 1992/06/28 11:58	Yermo Fire Station - YER270	7.3	0.245	44
IMPERIAL VALLEY 1979/10/15 23:16	El Centro Array #4 - H-E04140	6.5	0.485	39
NORTHRIDGE 1994/01/17 12:31	Sylmar - Converter Sta - SCS052	6.7	0.612	40
PARKFIELD 1966/06/28 04:26	Cholame #2 - C02065	6.1	0.476	43.69
TABAS, Iran 1978/09/16	Tabas TAB-TR	7.4	0.852	32.84

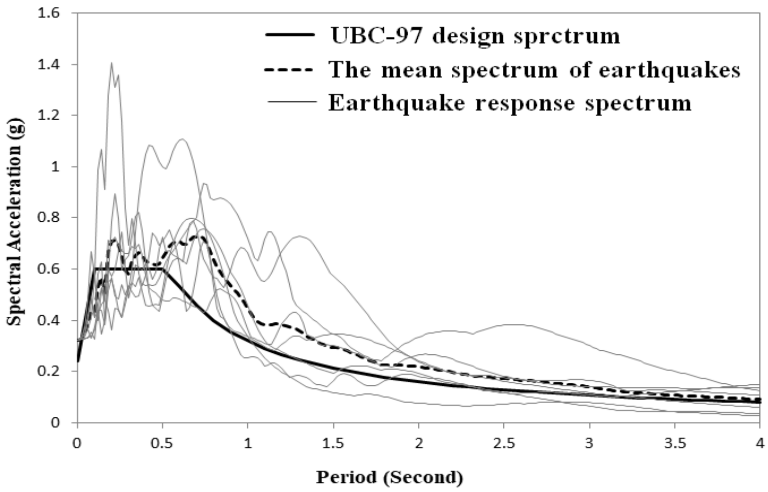

Fig. 4 Average response spectrum of the scaled accelerations

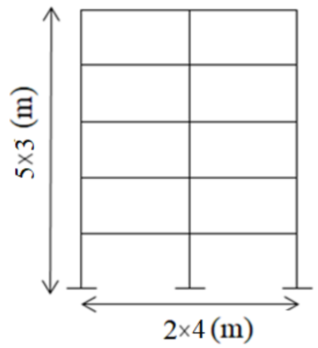

Fig. 5 5-story, 2-bay frame

Table 2 Section properties for 5-story, 2-bay frame

Element type story	Edge columns	Middle column	All beams
Story 5	IPE220	IPE330	IPE240
Story 4	IPE220	IPE330	IPE240
Story 3	IPE240	IPE450	IPE270
Story 2	IPE270	IPE450	IPE270
Story 1	IPE270	IPE450	IPE270

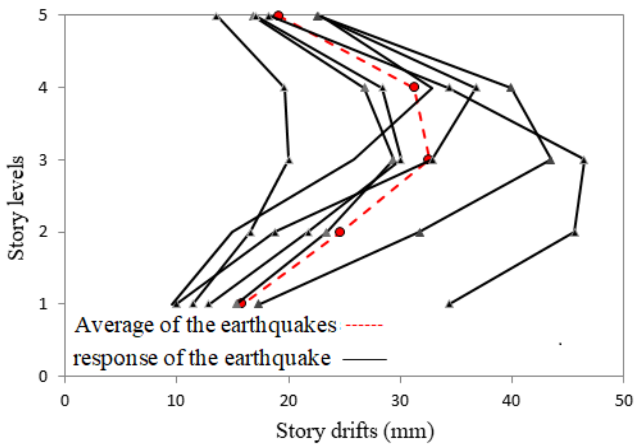

Fig. 6 Story drifts of each floor level in selected earthquakes and the average of them

4.1 Example 1

The first example is 5-story, 2-bay frame (Fig. 5). The designed sections of this frame are tabulated in Table 2. The main period of this frame is 1.2 second.

In Fig. 6, the lateral story drifts of this frame extracted for each earthquake, in the peak of roof displacement for each earthquake are presented likewise the average of the aforementioned earthquake drifts considered as the benchmark is shown that is considered as the benchmark.

After calculating the benchmark displacements, the OLLP is derived using the proposed optimization procedure. The obtained lateral force distribution of OLLP is depicted in Fig. 7.

In Fig. 8, the process of improving the outcomes and the mean value of the objective function along the optimization procedure for each generation are displayed. In this figure, 'Best fitness' refers to the fitness of the best individual and 'Mean fitness' is simply the average of the fitness values across the entire population. Generally, the best fitness tends to get better over time, quickly at first and then slowing down as the algorithm finds better solution that is harder to improve upon. The gap between best and average fitness decreases over time until the algorithm completely converges.

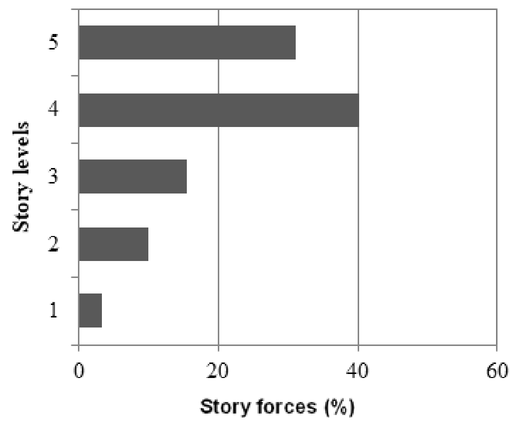

Fig. 7 The optimal lateral load distribution for the 5-story frame

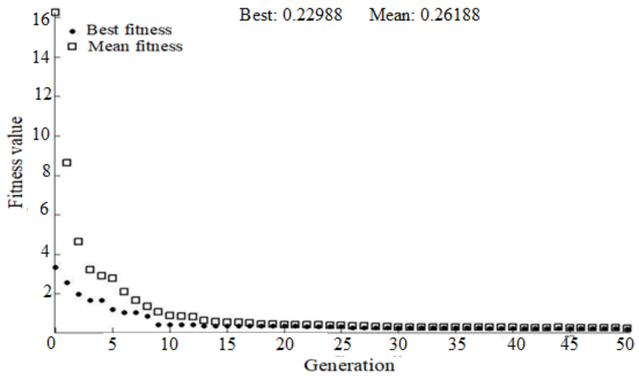

Fig. 8 The fitness value for each generation for 5-story frame

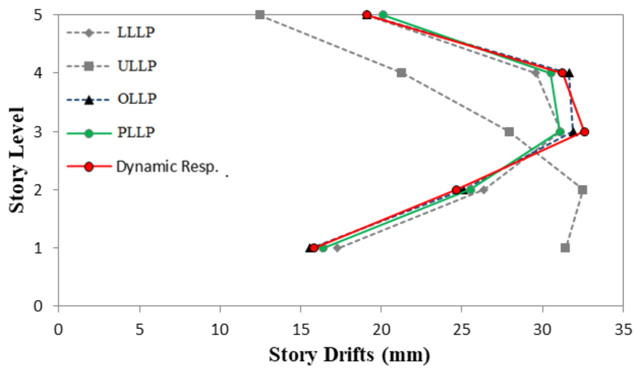

Fig. 9 Comparing the story drifts of LLLP, ULLP, OLLP, PLLP with dynamic ones for 5-story frame

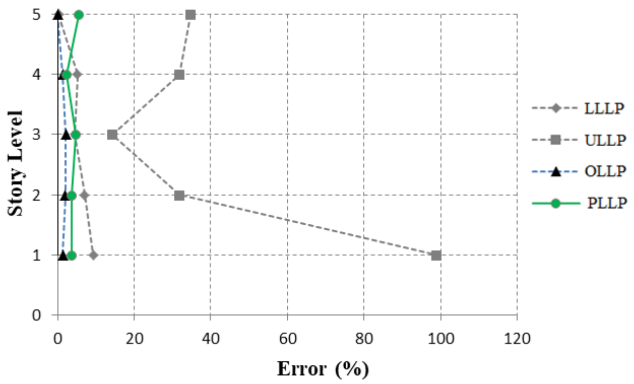

Fig. 10 The percentage of error of LLLP, ULLP, OLLP, PLLP for 5-story frame

After calculating the OLLP, the lateral displacements of the floor levels subjected to optimal, uniform, linear and parabolic lateral load pattern are obtained and depicted in Fig. 9. The percentage of error of pushover analyses comparing to nonlinear time history analysis is demonstrated in Fig. 10.

As it is clear in Fig. 9, all lateral load patterns except uniform one present appropriate result. Although the OLLP has the least error, the errors of linear and parabolic load patterns are lower than 10 percent. It can be concluded that

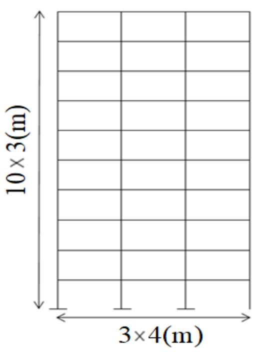

Fig. 11 10-story, 3-bay frame

Table 3 Section properties for 5-story, 2-bay frame

Story \ Element type	Edge columns	Middle column	All beams
Story 10	IPE240	2IPE120	IPE220
Story 9	IPE240	2IPE160	IPE240
Story 8	IPE240	2IPE200	IPE240
Story 7	IPE270	2IPE220	IPE240
Story 6	IPE300	2IPE240	IPE270
Story 5	IPE300	2IPE270	IPE270
Story 4	2IPE240	2IPE270	IPE270
Story 3	2IPE240	2IPE300	IPE270
Story 2	2IPE270	2IPE330	IPE270
Story 1	2IPE270	2IPE330	IPE270

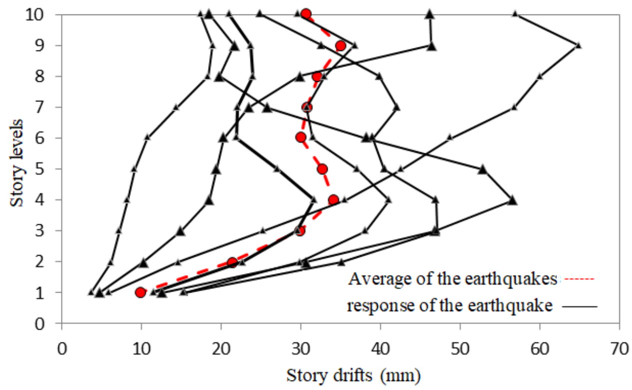

Fig. 12 Story drifts of each floor level in selected earthquakes and the average of them for 10-story frame

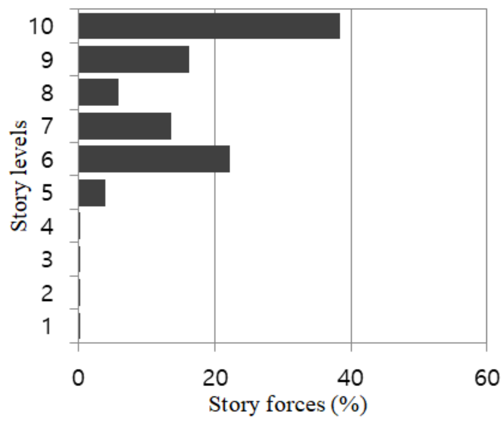

Fig. 13 The optimal lateral load distribution for the 10-story frame

for low rise frames the linear and parabolic lateral load patterns present acceptable results. In fact, for this kind of frames, the first vibration mode contributes to the dynamic responses more than higher modes.

4.2 Example 2

A 10-story, 3-bay steel frame is taken as the second example into account (Fig. 11). The section properties of this frame are shown in the Table 3. The first period of this frame is 1.51 second.

Similar to the first example, the lateral story drifts of earthquakes and the average of dynamic responses are calculated and displayed in Fig. 12. The achieved optimal lateral load forces and the changes in the value of objective function comparing to mean values for different generations are presented in Figs. 13 and 14.

As it is shown in Fig. 13, the lateral load for the first to the forth stories are the least. It is evident that although by increasing number of forces applied on the stories as the variables, design parameters the rate of convergence is decreased, the optimal load pattern is achieved before 50 generations (Fig. 14), For the initial generations, the gap between the best values of the objective function and the mean of all parameters is significant, but for the last

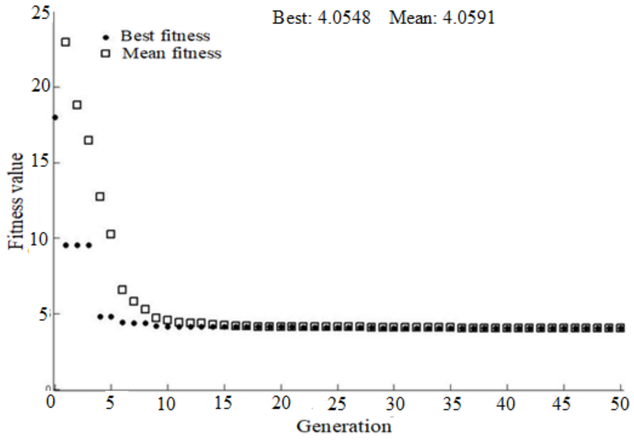

Fig. 14 The fitness value for each generation for the 10-story frame

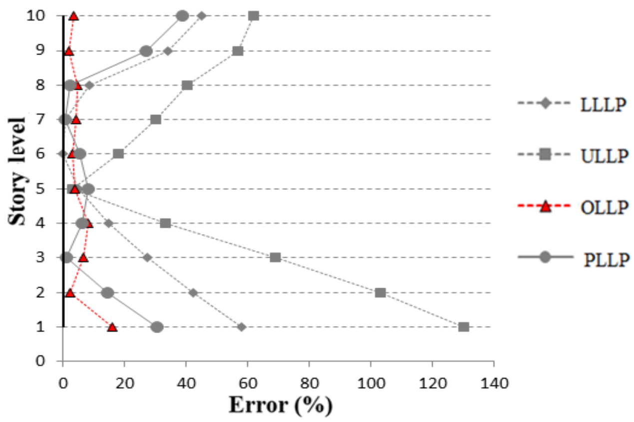

Fig. 16 The percentage of error of LLLP, ULLP, OLLP, PLLP for 10-story frame

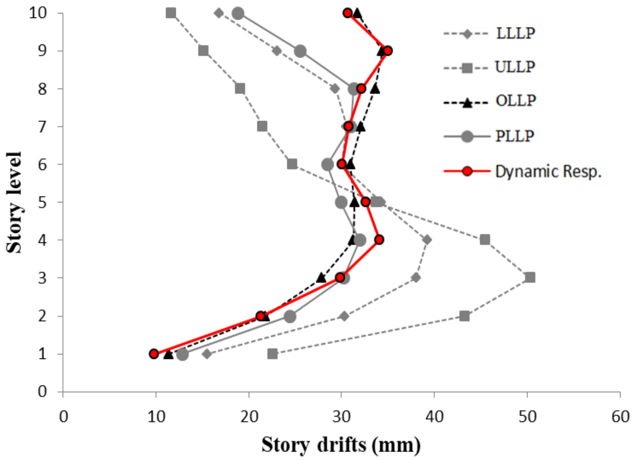

Fig. 15 Comparing the story drifts of LLLP, ULLP, OLLP, PLLP with dynamic ones for 10-story frame

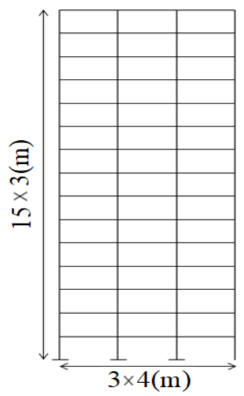

Fig. 17 15-story, 3-bay frame

generations, it is almost zero. It is important that the optimization method is converged after the certain number of generations and it is not capable to improve the results after some generations that indicates that the proposed optimization method has found the global optimization point. In Fig. 15, the lateral displacement of pushover analysis under optimal, uniform, linear and parabolic lateral load patterns are depicted. The percentage error of pushover analyses comparing to NDA is presented in Fig. 16.

For this example, just like the previous one, ULLP overestimates drifts of lower stories and underestimates the drifts of higher stories. PLLP presents proper outcomes in middle stories and the peak of its errors is around 40 percent. The distribution of errors for LLLP is the same with parabolic pattern. The maximum error of this pattern is almost 60 percent. Although errors of the optimal pattern are lower than 10 percent in 2^{nd} to 10^{th} floors, the error of the first floor is around 18 percent.

Table 4 Section properties for 5-story, 2-bay frame

Story \ Element type	Edge columns	Middle column	All beams
Story 15	IPE240	2IPE140	IPE220
Story 14	IPE240	2IPE180	IPE240
Story 13	IPE270	2IPE220	IPE270
Story 12	IPE300	2IPE240	IPE300
Story 11	IPE300	2IPE270	IPE300
Story 10	2IPE240	2IPE270	IPE300
Story 9	2IPE270	2IPE300	IPE300
Story 8	2IPE270	2IPE300	IPE300
Story 7	2IPE300	2IPE330	IPE300
Story 6	2IPE300	2IPE330	IPE300
Story 5	2IPE330	2IPE360	IPE300
Story 4	2IPE330	2IPE360	IPE300
Story 3	2IPE330	2IPE360	IPE300
Story 2	2IPE360	2IPE400	IPE300
Story 1	2IPE360	2IPE450	IPE300

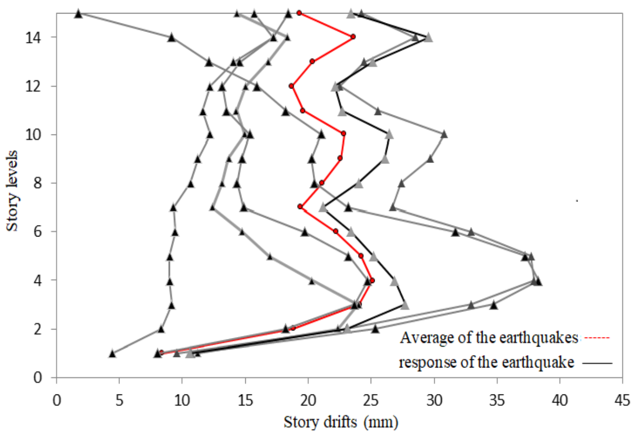

Fig. 18 Story drifts of each floor level in selected earthquakes and the average of them for 15-story frame

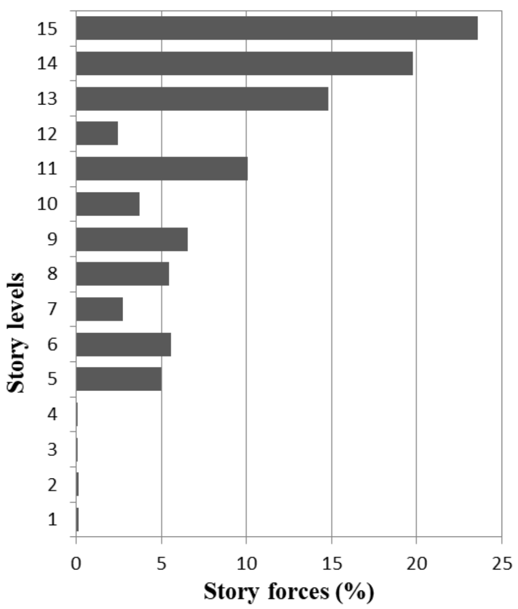

Fig. 19 The optimal lateral load distribution for the 15-story frame

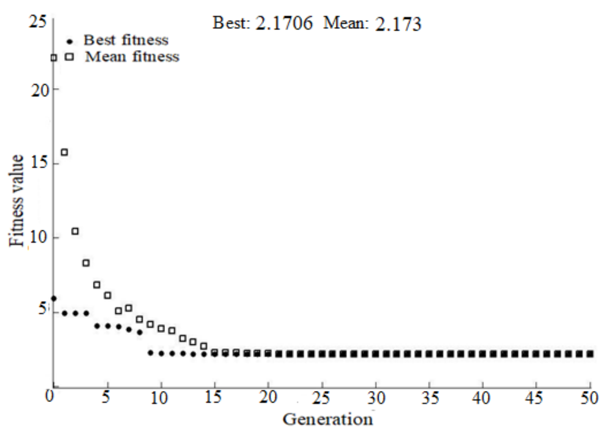

Fig. 20 The fitness value for each generation for the 15-story frame

4.3 Example 3

The third example is 15-story, 3-bay frame (Fig. 17). The designed sections of this frame are tabulated in Table 4. The main period of this frame is 1.79 second.

The average of dynamic response and drifts of each earthquake in peak displacement of the roof is displayed in Fig. 18.

As it is shown in Fig. 18, the difference between drifts of the first and second stories as well as the last and fourteenth stories are significant. The optimal lateral load forces for this frame are demonstrated in Fig. 19.

For this frame, as observed in Fig. 19, the lateral loads for the first to fourth stories are approximately zero. The convergence proceeds throughout the optimization process are shown in Fig. 20. The lateral displacement of pushover analysis under different kinds of lateral load patterns and the errors rather than dynamic analysis are presented in Figs. 21 and 22.

For this example, the least error belongs to OLLP (20 percent) and the larger corresponds to uniform one (98 percent), It seems, because of higher mode effects, LLLP does not appropriate results (the maximum error is 49 percent), The outcomes of PLLP are more accurate than uniform and linear ones. One of the most outstanding

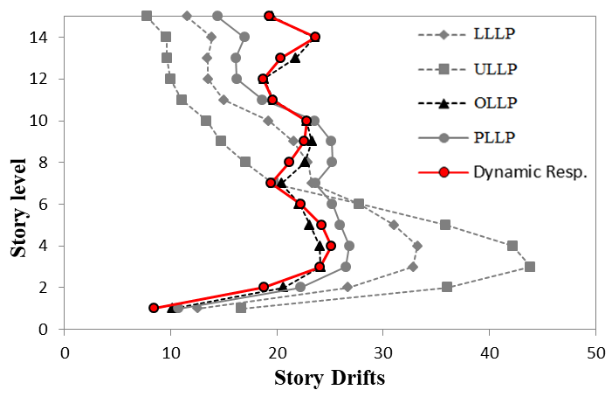

Fig. 21 Comparing the story drifts of LLLP, ULLP, OLLP, PLLP with dynamic ones for 15-story frame

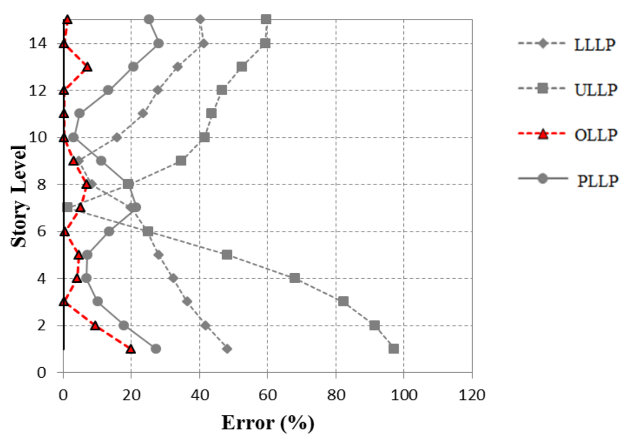

Fig. 22 The percentage of error of LLLP, ULLP, OLLP, PLLP for 15-story frame

features of the OLLP is uniform distribution and a little swing of errors.

5. Conclusions

Since conventional pushover methods have two main drawbacks comprising neglecting the higher mode effects and the progressive changes of dynamic characters along the analysis, in this study, a new methodology to acquire the lateral load pattern in pushover analysis is proposed in which applying optimization procedure, an optimal lateral load pattern with the best compatibility to nonlinear dynamic analysis is achieved. In the presented procedure, due to applying the reverse engineering approach, the influences of higher modes and changes of the modal properties along the analysis are considered. To confirm the accuracy of the proposed method, three special moment resisting steel frames are designed and their optimal lateral load distributions are achieved. Then the lateral floor displacements of these frames subjected to obtained optimal, uniform, linear and parabolic load patterns are compared with NDA. The results prove the validity of the suggested procedure. It is shown that pushover analysis of all the structures applying the optimal load pattern leads to more accurate results than existing load patterns e.g., uniform, linear and parabolic. In comparison, the highest error belongs to uniform lateral load pattern and the presented optimal lateral load pattern accounts for the lowest error.

References

Akbas, B., Tugsal, Ü.M. and Kara, F.İ. (2009), “An evaluation of energy response and cumulative plastic rotation demand in steel moment-resisting frames through dynamic/static pushover analyses”, *Struct. Des. Tall Special Build.*, **18**(4), 405-426. https://doi.org/10.1002/tal.442

Amini, M.A. and Poursha, M. (2018), “Adaptive Force-Based Multimode Pushover Analysis for Seismic Evaluation of Midrise Buildings”, *J. Struct. Eng.*, **144**(8), p.04018093. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002070

Antoniou, S. and Pinho, R. (2004a), “Advantages and limitations of adaptive and non-adaptive force-based pushover procedures”, *J. Earthq. Eng.*, **8**(4), 497-522.

Antoniou, S. and Pinho, R. (2004b), “Development and verification of a displacement-based adaptive pushover procedure”, *J. Eng.*, **8**(5), 643-661.

ATC–40 Report, (1996), Seismic evaluation and retrofit of concrete buildings; Applied Technology Council, Redwood City, CA, USA.

Attard, T. and Fafitis, A. (2005), “Modeling of higher-mode effects using an optimal multi-modal pushover analysis”, *WIT Transact. Built Environ.*, **81**.

Chen, Z., Chui, Y.H., Ni, C., Doudak, G. and Mohammad, M. (2014), “Load distribution in timber structures consisting of multiple lateral load resisting elements with different stiffnesses”, *J. Perform. Constr. Facil.*, **28**(6), A4014011. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000587

Chopra, A.K. and Goel, R. (2001), “Modal pushover analysis of SAC building”, *Proceedings of SEAOC Convention*, San Diego, CA, USA.

Chopra, A.K., Goel, R.K. and Chinatana-pakdee, C. (2004), “Evaluation of a modified MPA procedure assuming higher modes as elastic to estimate seismic demands”, *Earthq. Spectra*, **20**(3), 757-778. https://doi.org/10.1193/1.1775237

Costa, R., Providencia, P. and Ferreira, M. (2017), “Influence of joint modelling on the pushover analysis of a RC frame”, *Struct. Eng. Mech., Int. J.*, **64**(5), 641-652. https://doi.org/10.12989/sem.2017.64.5.641

Eldin, M.N., Kim, J. and Kim, J. (2018), “Optimum distribution of steel slit-friction hybrid dampers based on life cycle cost”, *Steel Compos. Struct.*, **27**(5), 633-646. https://doi.org/10.12989/scs.2018.27.5.633

Elnashai, A.S. (2001) “Advanced inelastic static (pushover) analysis for earthquake applications”, *Struct. Eng. Mech., Int. J.*, **12**(1), 51-69. http://dx.doi.org/10.12989/sem.2001.12.1.051

Endo, Y., Pelà, L. and Roca, P. (2017), “Review of different pushover analysis methods applied to masonry buildings and comparison with nonlinear dynamic analysis”, *J. Earthq. Eng.*, **21**(8), 1234-1255. https://doi.org/10.1080/13632469.2016.1210055

Etedali, S. and Irandegani, M.A. (2015), “A proposed lateral load pattern for pushover analysis of structures subjected to earthquake excitations”, *J. Vibroeng.*, **17**(3), 1363-1371.

Fakhraddini, A., Fadaee, M.J. and Saffari, H. (2018), “A lateral load pattern based on energy evaluation for eccentrically braced frames”, *Steel Compos. Struct., Int. J.*, **27**(5), 623-632. https://doi.org/10.12989/scs.2018.27.5.623

Ganjavi, B., Hajirasouliha, I. and Bolourchi, A. (2016), “Optimum lateral load distribution for seismic design of nonlinear shear-buildings considering soil-structure interaction”, *Soil Dyn. Earthq. Eng.*, **88**, 356-368. https://doi.org/10.1016/j.soildyn.2016.07.003

Ghanoonibagha, M., Gol, M.R.A. and Ranjbar, M.R. (2016), “Study of higher mode effects and lateral load patterns in pushover analysis of steel frames with steel shear wall”, *Adv. Sci. Technol. Res. J.*, **10**(29), 13-27.

Gulkan, P. and Sozen, M.A. (1974), “Inelastic responses of reinforced concrete structures to earthquake motions”, *J. Am. Concrete Inst.*, **71**(12), 604-610.

Gupta, B. and Kunnath, S.K. (2000), “Adaptive spectra-based pushover procedure for seismic evaluation of structures”, *Earthq. Spectra*, **16**(2), 367-391. https://doi.org/10.1193/1.1586117

Habibi, A. and Bidmeshki, S. (2018), “A dual approach to perform geometrically nonlinear analysis of plane truss structures”, *Steel Compos. Struct., Int. J.*, **27**(1), 13-25.

Izadpanah, M. and Habibi, A. (2015), “Evaluating the spread plasticity model of IDARC for inelastic analysis of reinforced concrete frames”, *Struct. Eng. Mech., Int. J.*, **56**(2), 169-188. http://dx.doi.org/10.12989/sem.2015.56.2.169

Izadpanah, M. and Habibi, A.R. (2018), “New Spread Plasticity Model for Reinforced Concrete Structural Elements Accounting for Both Gravity and Lateral Load Effects”, *J. Struct. Eng.*, **144**(5), p.04018028. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002016

Jan, T.S., Liu, M.W. and Kao, Y.C. (2004), “An upper-bound pushover analysis procedure for estimating the seismic demands of high-rise buildings”, *Eng. Struct.*, **26**(1), 117-128. https://doi.org/10.1016/j.engstruct.2003.09.003

Kalkan, E. and Kunnath, S.K. (2006), “Adaptive modal combination procedure for nonlinear static analysis of building structures”, *J. Struct. Eng., ASCE*, **132**(11), 1721-1731. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:11(1721)

Kim, S.P. and Kurama, Y.C. (2008), “An alternative pushover analysis procedure to estimate seismic displacement demands”, *Eng. Struct.*, **30**(12), 3793-3807. https://doi.org/10.1016/j.engstruct.2008.07.008

Kim, J., Kim, M. and Eldin, M.N. (2017), “Optimal distribution of steel plate slit dampers for seismic retrofit of structures", *Steel Compos. Struct., Int. J.*, **25**(4), 473-484. https://doi.org/10.12989/scs.2017.25.4.473

Krawinkler, H. (1995), "New trends in seismic design methodology", *Proceedings of European Conference on earthquake Engineering*, Duma, Russia, pp. 821-830.

Lawson, R.S., Vance, V. and Krawinkler, H. (1994), "Nonlinear static pushover analysis—why, when and how?", *Proceedings of the 5th U.S. Conference on Earthquake Engineering*, **1**, 283-292.

López-Menjivar, M.A. (2004), "Verification of a displacement-based Adaptive Pushover method for assessment of 2-D Reinforced Concrete Buildings", Ph.D. Thesis; European School for Advances Studies in Reduction of Seismic Risk (ROSE School), University of Pavia, Italy.

Mansouri, I., Soori, S., Amraie, H., Hu, J.W. and Shahbazi, S.H. (2018), "Performance based design optimum of CBFs using bee colony algorithm", *Steel Compos. Struct., Int. J.*, **27**(5), 613-622. https://doi.org/10.12989/scs.2018.27.5.613

Mao, J., Zhai, C. and Xie, L. (2008), "An improved modal pushover analysis procedure for estimating seismic demands of structures", *Earthq. Eng. Eng. Vib.*, **7**(1), 25-31. https://doi.org/10.1007/s11803-008-0786-y

Ozgenoglu, M. and Arıcı, Y. (2017), "Comparison of ASCE/SEI Standard and modal pushover-based ground motion scaling procedures for pre-tensioned concrete bridges", *Struct. Infrastruct. Eng.*, **13**(12), 1609-1623. https://doi.org/10.1080/15732479.2017.1310258

Papanikolaou, V.K. and Elnashai, A.S. (2005), "Evaluation of conventional and adaptive pushover analysis I: Methodology", *J. Earthq. Eng.*, **9**(6), 923-941.

Papanikolaou, V.K., Elnashai, A.S. and Pareja, J.F. (2006), "Evaluation of conventional and adaptive pushover analysis II: Comparative results", *J. Earthq. Eng.*, **10**(1), 127-151.

Paret, T.F., Sasaki, K.K., Eilbeck, D.H. and Freeman, S.A. (1996), "Approximate inelastic procedures to identify failure mechanisms from higher mode effects", *Proceedings of the Eleventh World Conference on Earthquake Engineering* (Vol. 2).

Qiao, S., Han, X., Zhou, K. and Li, W. (2017), "Conceptual configuration and seismic performance of high-rise steel braced frame", *Steel Compos. Struct., Int. J.*, **23**(2), 173-186. https://doi.org/10.12989/scs.2017.23.2.173

Quintero-Duran, M., Candelo, J.E. and Sousa, V. (2017), "Recent trends of the most used metaheuristic techniques for distribution network reconfiguration", *J. Eng. Sci. Technol. Rev.*, **10**(5).

Reinhorn, A.M., Roh, H., Sivaselvan, M., Kunnath, S., Valles, R., Madan, A., Li, C., Lobo, R. and Park, Y. (2009), IDARC 2D version 7.0: A program for the inelastic damage analysis of buildings, Buffalo, NY, USA.

Saiidi, M. and Sozen, M.A. (1981), "Simple nonlinear seismic analysis of R/C structures", *J. Struct. Div., ASCE*, **107**(ST5), 937-951.

Sarkar, P., Prasad, A.M. and Menon, D. (2016), "Seismic evaluation of RC stepped building frames using improved pushover analysis", *Earthq. Struct.*, **10**(4), 913-938. http://dx.doi.org/10.12989/eas.2016.10.4.913

Shakeri, K., Shayanfar, M.A. and Kabeyasawa, T. (2010), "A story shear-based adaptive pushover procedure for estimating seismic demands of buildings", *Eng. Struct.*, **32**(1), 174-183. https://doi.org/10.1016/j.engstruct.2009.09.004

Shayanfar, M.A., Ashoory, M., Bakhshpoori, T. and Farhadi, B. (2013), "Optimization of modal load pattern for pushover analysis of building structures", *Struct. Eng. Mech., Int. J.*, **47**(1), 119-129. http://dx.doi.org/10.12989/sem.2013.47.1.119

Tiana, L. and Qiu, C. (2018), "Modal pushover analysis of self-centering concentrically braced frames", *Struct. Eng. Mech., Int. J.*, **65**(3), 251-261. https://doi.org/10.12989/sem.2018.65.3.251

Uniform Building Code (UBC) (1997), International Conference of Building Officials, Vol. 2.

Zhang, Z., Pan, J., Fu, J., Singh, H.K., Pi, Y.L., Wu, J. and Rao, R. (2017), "Optimization of long span portal frames using spatially distributed surrogates", *Steel Compos. Struct., Int. J.*, **24**(2), 227-237. https://doi.org/10.12989/scs.2017.24.2.227

CC