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Seismic evaluation of multi-storey moment-resisting steel frames with stiffness irregularities using standard and advanced pushover methods

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Abstract

The nonlinear static procedure, based on pushover analysis, has become an important tool to characterize the seismic demand and the performance of structures. The standard pushover procedure is restricted to single-mode response, a valid supposition for symmetrical or low-rise buildings, where the response is dominated by the fundamental vibration mode. The standard pushover procedures become misleading when the response of the structure is influenced by higher vibration modes. This is the case of tall or non-symmetrical buildings. Several pushover procedures, able to take into account the effects of higher vibration modes, have been lately developed to overcome this drawback. This paper presents a comparison between standard, advanced pushover analyses and the exact results obtained by nonlinear time history analysis. The analyses have been conducted on a series of moment-resisting steel frames with stiffness irregularities, with different number of stories, designed according to EC8 and the Romanian Seismic Design Code for Romania's Vrancea Seismic Area.

Keywords: advanced pushover, nonlinear inelastic time history, moment-resisting steel frames, stiffness irregularity, seismic demand.

1. Introduction

Although elastic analysis gives a good estimate of the elastic capacity of the structure and identifies the first yield point, it is not capable to foresee the collapse mechanism and to take into account the redistribution of forces as the plastic hinges are developing in the structure's elements. Nonlinear analysis gives an image of the behavior of the structure in case of strong earthquakes, when it is supposed that the elastic capacity of it will be exceeded. Consequently design engineers have the convenience of noticing the collapse modes, the potential of

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progressive collapse or to detect possible errors in the design of the structure. Nonlinear inelastic time history analysis is the most accurate method of determining the response of the structure, but due to the necessity of complex input data (accelerograms, hysteretic behavior of the materials and so on) nonlinear static analysis seems to be a more adequate method for the practicing engineers. In a nonlinear static procedure, based on pushover analysis, a mathematical model directly incorporating the nonlinear load-deformation characteristics of individual components and elements of the building is subjected to monotonically increasing lateral loads, representing inertia forces in an earthquake, until a target displacement is exceeded. The target displacement is intended to represent the maximum displacement likely to be experienced during the design earthquake [3-4].

Nomenclature

$F_{i,j}$	the force at *i*-th story in the *j*-th mode
α_j	modification factor, that can assume positive or negative values (herein 1 or -1)
ϕ_j	the mode shape vector corresponding to mode *j*
Sa_j	the spectral acceleration coresponding to the *j*-th mode
$\Delta_{i,j}$	the interstorey drift at *i*-th story in the *j*-th mode
m_i	the mass of the *i*-th story
Γ_j	the modal participation factor for the *j*-th mode
$\bar{F}$	normalized distribution of forces
$\bar{D}$	normalized distribution of displacements
U	pushover analysis with a uniform distribution of vertical forces
M1	pushover analysis with a vertical distribution after the first vibration mode
FAP	force-based scaling adaptive pushover with earthquake specific spectrum amplification
DAP	interstorey drift-based scaling adaptive pushover with earthquake specific spectrum amplification
MMC	method of modal combination for pushover analysis

2. Pushover analysis

There are three key concepts in pushover analysis: capacity, demand and performance. The first concept is delineated by the capacity curve, which shows the structures capacity to withstand an incremental lateral loading. Demand is symbolized by the target displacement, representing the maximum displacement expected to be experienced by the structure during a considered earthquake. Having the capacity and the demand for a certain building, its performance can be determined on basis of global and component accepted deformations.

In a classical pushover method there is a fixed distribution of the lateral forces subjected in an incremental way to the mathematical model of the building. These loads should be applied to the structural model in proportion to the distribution of the inertia forces in the plane of each floor diaphragm. A pattern can be selected from: a uniform distribution consisting of lateral forces at each level proportional to the total mass at each level, a vertical distribution proportional to the distribution found in the seismic codes for elastic design, a vertical distribution proportional to the shape of the fundamental mode or a vertical distribution proportional to the story shear distribution calculated from a response spectrum analysis of the building [3]. Studies have shown that these classical pushover methods with fixed distributions are not able to predict with sufficient accuracy the seismic response of tall or irregular structures, where higher vibration mode effects might play an important role in the dynamic response [4]. In order to improve the method, a series of advanced pushover methods have been proposed. The modal procedures, Modal Pushover Analysis [5], Method of Modal Combinations [6], are able to consider the effects of higher vibration modes in different manners, keeping a fixed distribution of the vertical forces. The latest approach and the one considered to give the best results in terms of structural response is the adaptive pushover method [7]. In this method, the vertical distribution of forces is updated at each increment, during the analysis, in order to detect the changes in the structure's stiffness and its dynamic properties as it is pushed beyond the elastic limit.

2.1. Method of modal combinations for pushover analysis

In this procedure, the vertical variation of applied forces is determined from:

$$F_{i,j} = \sum \alpha_j \Gamma_j m_i \phi_j Sa_j \left(\zeta_j, T_j\right) \tag{1}$$

$$\Gamma_j = \left(\left[\phi_j\right]^T [m]\{i\} / M_j \text{ in which } M_j = \left[\phi_j\right]^T [m]\left[\phi_j\right]\right) \tag{2}$$

Therefore, the procedure requires multiple pushover analyses wherein several combinations of modal load patterns are applied. Afterwards, it is necessary to consider peak demands at each story level and then establish an envelope of demand values.

2.2. Adaptive pushover

In the adaptive pushover approach, the lateral load distribution is updated at each step of the analysis, according to the modal shapes and participation factors derived by eigenvalue analysis. This method is multi-modal and accounts for the softening of the structure and the modification of inertia forces due to spectral amplification. The structure can be loaded with a force distribution, as in the case of classical pushover method, or it can employ deformation profiles. The effect of spectral amplification can be taken into account through the choice of using a design spectrum given by the seismic code or by using the response spectrum derived from a certain seismic accelerogram. Obviously, there is the option of no spectral amplification.

Force-based scaling adaptive pushover vertical force distribution is computed at each step of the analysis as follows:

$$F_{i,j} = \Gamma_j \phi_{i,j} Sa_j m_i , \quad F_i = \sqrt{\sum_{j=1}^{n} F_{i,j}^2} \Leftrightarrow F_i = \sqrt{\sum_{j=1}^{n} \left(\Gamma_j \phi_{i,j} Sa_j m_i\right)^2}, \quad \bar{F}_i = \frac{F_i}{\max\left(F_i\right)} \tag{3}$$

Interstorey drift-based scaling adaptive pushover vertical displacement distribution is computed at each step of the analysis as follows:

$$D_i = \sum_{k=1}^{i} \Delta_k, \quad \Delta_i = \sqrt{\sum_{j=1}^{n} \Delta_{i,j}^2} = \sqrt{\sum_{j=1}^{n} \left[\Gamma_j \left(\phi_{i,j} - \phi_{i-1,j}\right)\right]^2}, \quad \bar{D}_i = \frac{D_i}{\max\left(D_i\right)} \tag{4}$$

3. Structural models

Two moment-resisting steel frames situated in the town of Bucharest, Romania, consisting of 8 and 12 stories (Fig. 1.), have been designed and analyzed. Each frame consists of three bays of 6 m. The first level has the height of 4.5 m and the rest of the levels have 3.5 m. The structures have been designed according to the codes: EUROCODE 3, EUROCODE 8 and P100/2006. Permanent (24 kN/m) and live (12 kN/m) loads have been considered to be uniformly distributed on the beams. The seismic response spectrum used is the one given by the Romanian code P100/2006 for the Bucharest area. The design ground acceleration is 0.24g. In order to create a soft story, the original structures have been modified. According to 2000 NEHRP provisions, a soft story is one in which the lateral stiffness is less than 70 percent of that in the story above or less than 80 percent of the average stiffness of the three stories above. The 3-rd story columns have been changed at the 8-story frame (HEB450 to HEB360). The result is a reduction of the lateral stiffness of 45 percent compared to the story above. The 4-th story columns have been changed at the 12-story frame (HEB600 to HEB500), resulting in a lateral stiffness reduction of 40 percent compared with the story above.

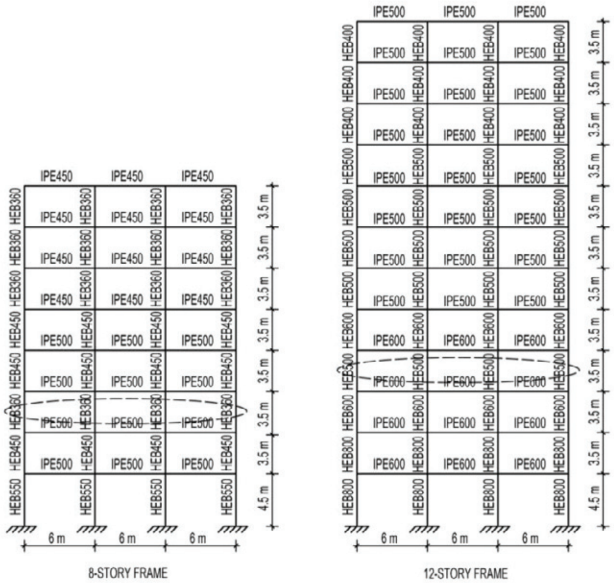

Fig. 1. (a) 8-story frame; (b) 12-story frame

4. Nonlinear analyses

A mathematical model of the structures with lumped plastic hinges at both ends of each element has been used for the nonlinear static and dynamic analyses. Geometric and material nonlinear properties have been included. The pushover and time history analyses have been performed with the SeismoStruct software [2]. The time history analyses are considered the benchmarks. Three earthquakes were considered (Vrancea 1977, Vrancea 1986 and Vrancea 1990) and scaled at three different peak ground accelerations (0.16g, 0.24g and 0.32g). A total of nine earthquakes were taken into account for each structure. Two classical non-adaptive pushover analyses with a uniform distribution (U) and a distribution after the first vibration mode (M1), a forced-based scaling adaptive pushover (FAP), an interstorey drift-based scaling adaptive pushover (DAP) and a method of modal combinations for pushover analysis (MMC) have been the nonlinear analyses of which capacity to approximate the structural response was determined. The adaptive pushover methods have been scaled using earthquake specific spectrum, derived from the earthquake's accelerogram; an acceleration response spectrum for the force-based scaling and a displacement response spectrum for the interstorey drift-based scaling. The displacement of the control node (top of the structure), computed through nonlinear time history analysis, has been imposed as top displacement (target displacement) for the pushover analyses.

The aim of the study is to determine if the advanced pushover methods are capable of better structural response predictions than the classic pushover methods. The interstory drifts are the structural responses to be compared. A comparison was made between the nonlinear inelastic dynamic time history analysis (NTH), considered to give the "exact" results and the pushover methods. The medium (Emed) and maximum (Emax) errors have been computed and compared. The medium error is the arithmetic mean of the errors computed in respect to the value given by the benchmark analysis (NTH) at every story of the structure. The maximum error is the maximum absolute value of the errors resulted.

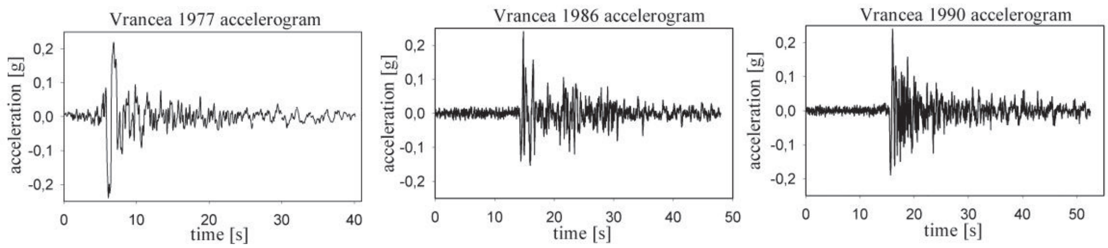

Fig. 2. (a) Vrancea 77 earthquake accelerogram; (b) Vrancea 86 earthquake accelerogram; (c) Vrancea 90 earthquake accelerogram

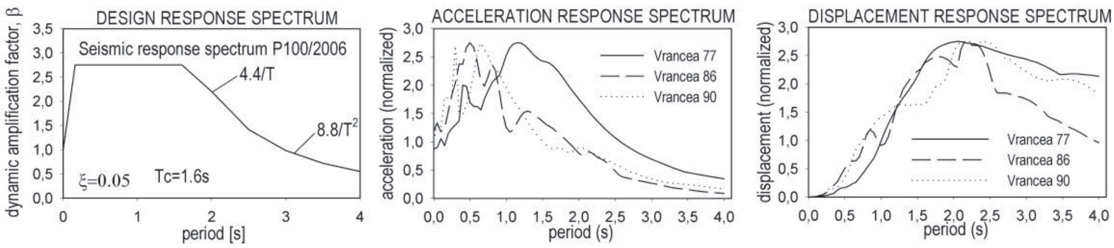

Fig. 3. (a) Design response spectrum; (b) Acceleration response spectrum; (c) Displacement response spectrum

Table 1. Inter-story drift errors for the 8-story frame (Emed-medium error; Emax-maximum error)

		U	**M1**	**FAP**	**DAP**	**MMC**	**U**	**M1**	**FAP**	**DAP**	**MMC**	**U**	**M1**	**FAP**	**DAP**	**MMC**
		0,16g					0,24g					0,32g				
Vrancea 77	Emed	34	20	21	13	12	39	30	31	24	9	37	32	31	20	13
	Emax	50	29	36	22	26	61	44	50	33	22	61	45	50	31	30
Vrancea 86	Emed	20	14	16	13	6	22	11	12	10	6	29	10	15	9	16
	Emax	50	38	38	25	13	45	27	27	18	14	48	31	38	19	35
Vrancea 90	Emed	19	5	8	7	15	41	12	22	10	20	54	24	34	14	29
	Emax	38	13	15	13	31	89	25	39	22	56	122	35	70	39	87

Table 2. Inter-story drift errors for the 12-story frame (Emed-medium error; Emax-maximum error)

		U	M1	FAP	DAP	MMC	U	M1	FAP	DAP	MMC	U	M1	FAP	DAP	MMC
		0,16g					0,24g					0,32g				
Vrancea 77	Emed	62	11	15	9	65	61	23	18	12	72	57	28	16	14	61
	Emax	159	22	28	17	152	135	39	40	25	139	109	46	47	34	120
Vrancea 86	Emed	25	15	17	12	25	36	21	19	16	34	35	32	31	32	33
	Emax	50	42	42	33	50	76	44	49	38	65	69	58	62	55	71
Vrancea 90	Emed	27	16	20	14	27	41	18	25	13	40	71	27	52	19	71
	Emax	53	41	41	30	47	100	37	44	32	85	243	42	157	35	214

5. Conclusions

The results show that the adaptive pushover methods give the best approximation in terms of medium and maximum errors of the interstorey drifts. As the considered earthquakes grow in intensity and the structures are being pushed further in the post elastic domain the error grows significantly. The intersorey drift-based scaling adaptive pushover is more accurate than the force-based scaling adaptive method, being the only method that gives superior approximation than does the classical non-adaptive pushover method with a vertical distribution after the first vibration mode. The method of modal combinations for pushover analysis seems to lose its capacity to predict the structural response as the seismic intensity grows and the structure gets taller.

Another aspect of the problem is that the spread of the errors does not seem to fall into a pattern. Further comparative analyses need to be done and different structural configurations to be taken into account in order to have an image of the performance of these static nonlinear methods based on pushover analysis for the Romania's Vrancea seismic area.

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