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Evaluation of Nonlinear Static Analysis for Special Moment Resisting Frames

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ABSTRACT: In order to prevent extensive devastation and death toll in strong earthquakes, rehabilitation of existing structures was emphasized and after the publication of prestandards such as FEMA 274, ATC 40, FEMA 356, ATC 55, it was time for the code ASCE 41-06 to be published. In FEMA and ASCE 41, nonlinear static analysis method is considered a common approach to assess seismic behavior of structures. Considering widespread acceptance of this method (nonlinear static analysis) the question is put forward to what extent the results obtained from this approximate method are reliable. To answer this question, seven models of special steel moment resisting frames designed according to ASCE 7-05 and AISC 360- 05 and AISC 341-05 were analysed using nonlinear static and dynamic analyses based on FEMA 356 and ASCE 41-06 provisions. Comparing the results obtained from nonlinear static and dynamic analyses gives good results for low-rise buildings. In addition, it results in conservative estimates implying that this method should be considered more carefully when used for taller buildings.
Key words: Nonlinear Static Method, Special Moment Resisting Frame, Seismic Rehabilitation, Performance-Based Design

INTRODUCTION

A structure is expected to go beyond the elastic limit during an earthquake. The most accurate method to assess a structure's seismic demand is nonlinear dynamic analysis, also known as time history analysis. This method can predict forces and demand deformation in all members with high reliability (FEMA274, 1997).

Since time history analysis is complicated and necessitates modelling of nonlinear behavior of all members which is not always feasible, the necessity of existence of a simpler method was felt. Thus nonlinear static analysis, known as Pushover analysis was devised. Pushover analysis, as a practical way of estimating the deformation and damage pattern of a structure, is getting increasingly more attention. The procedure consists of two parts. First, a target displacement for the building is established. The target displacement is an estimation of the roof displacement of the structure when exposed to the design earthquake excitation. Then a pushover analysis is carried out on the building until the roof displacement of the structure reaches the target displacement (Moghaddam, 2000).

Extensive studies have been carried out on pushover analysis by researchers such as Krawinkler and Sereviratna (1999), Mwafy and Elnashai (2001), Chopra and Goel (2001) and Gupta (1999). Due to the fact that this method is approximate, its reliability and efficiency needs to be checked and confirmed.

In this study, nonlinear static analysis has been carried out on steel moment resisting frames and the results obtained are compared with those of nonlinear dynamic.

MATERIAL AND METHODS

Selected structural systems:

In order to carry out the pushover analysis seven two-dimensional special moment resisting frames at different heights, 1 to 5 stories along with 7 and 10 stories were considered. The frames have a span of 4 and story height of 3 meters. Building codes including IBC 2006 and ASCE 7-05 were used for gravity and seismic loading respectively. Furthermore, AISC 360-05 and AISC 341-05 were used for designing purposes and determination of member sections. Since the frames are considered two dimensional, out-plane displacement of frames is restrained and torsion of columns as well as rotation of members about their weak axis as not allowed. Some special moment resisting frames used in this paper are shown in Figure 1.

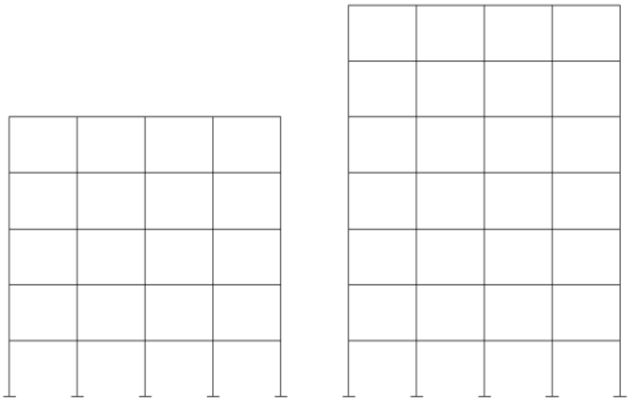

Figure 1. Schematic view of selected moment resisting frames (5 and 7-story frames)

Analysis procedures:

A comparison between results obtained from pushover and nonlinear dynamic analyses is logical only when acceleration response spectrum associated with ground motion record tallies with design response spectra used for nonlinear static analysis. Design response spectra included in all building codes are smoothed spectra. They don't represent the particular acceleration response from a single ground motion time history. But rather they are intended to be more representative of general characteristics for a reasonable range of expected ground motions at a given site. In order to provide the desired response acceleration spectrum, generation of an artificial ground motion record whose acceleration spectrum touches design response spectrum used for nonlinear static analysis is inevitable (Matheu et al., 2005). To do so software Simquake was used. The consistency between spectrum obtained from generated record and design response spectrum is depicted in Figure 2.

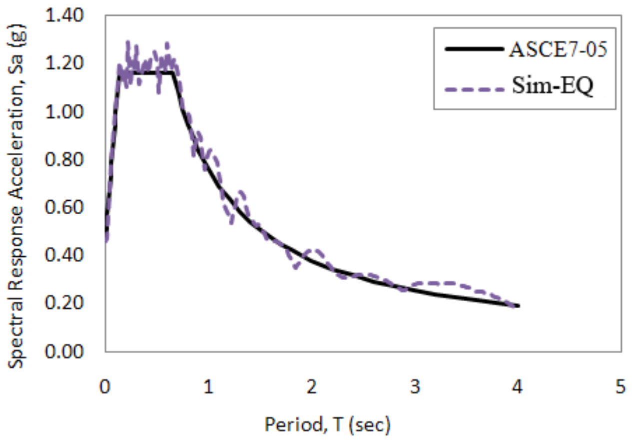

Figure 2. Comparison between generated record spectrum and ASCE design response spectrum

Lateral load distribution in pushover analysis:

Type of lateral load distribution has significant effects on results obtained from nonlinear static analysis. Since analyses conducted in this paper are in accordance with FEMA 356 and ASCE 41-06, types of load distribution presented in these codes are briefly illustrated herein.

First Lateral load distribution pattern in FEMA 356:

As recommended in FEMA 356, inverted triangle lateral load distribution is permitted only when the period of fundamental mode is less than 1 second and more than 75% of total mass participates in the fundamental mode in the direction under consideration. For structures with period of fundamental mode exceeding one second, distribution is proportional to the story shear distribution computed via response spectrum analysis including sufficient modes to capture at least 90% of the total building mass.

$$F_i = \frac{w_i h_i^k}{\Sigma\, w_j h_j^k} V \qquad (1)$$

$$K = \begin{cases} 1 & T < 0.5\text{sec} \\ 0.5T + 0.75 & 0.5 < T < 2.5\text{sec} \\ 2 & T > 2.5\text{sec} \end{cases} \qquad (2)$$

Where W_i is the weight of the i^{th} story, h_i is the height of the i^{th} story from the base, V is the base shear and T is the fundamental period of the structure

Second load distribution pattern in FEMA 356:

As mentioned in FEMA, in order to investigate seismic behavior of structures using pushover analysis, two separate pushover analyses, each under a different lateral load distribution, should be carried out. If the first pattern, inverted triangle, is exerted as the load distribution, it is necessary to apply the second type of lateral load distribution separately. The second pattern, also known as uniform distribution, consists of lateral forces at each level proportional to the total mass at each level.

$$F_i = \frac{m_i}{\Sigma m_j} \qquad (3)$$

Lateral load distribution in ASCE 41-06:

This type of distribution is proportional to the first vibration mode in the direction under study. Figure 3 displays different lateral load distributions for special moment resisting frames. The difference between first pattern recommended in FEMA 356 and that in ASCE is not significant for structures lower than four stories but, as fundamental period of the five story frame and higher exceed one second, distribution pattern of the FEMA 356 will vary and the gap between distribution type 1 in FEMA 356 and that in ASCE widens.

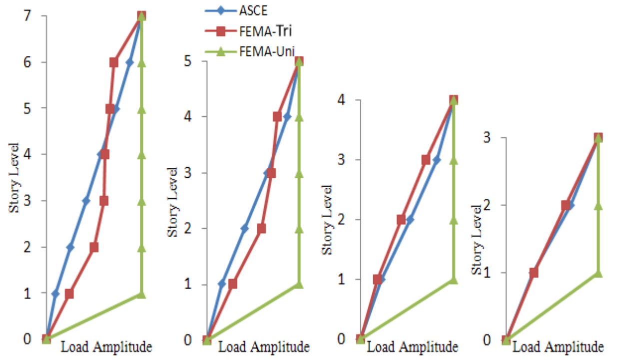

Figure 3. Different lateral load distributions for special moment resisting frames

Target displacement:

This factor plays an important role in results obtained from nonlinear static analysis and can be determined through two acceptable procedures, Capacity Spectrum Method and Coefficient Method. The latter is adapted in this study. Equation 4 is a recommended formula in FEMA 356 to calculate target displacement. After extensive research on calculation method of target displacement, FEMA 440 was published and introduced altered coefficients in the equation 5. Amendments are fully explained in FEMA 440 and ASCE 41 as well.

$$\delta_t = C_0\, C_1\, C_2\, C_3\, S_a \frac{Te^2}{4\pi^2} \qquad (4)$$

$$\delta_t = C_0\, C_1\, C_2\, S_a \frac{Te^2}{4\pi^2} \qquad (5)$$

Coefficients are defined in FEMA 356 and ASCE 41-06

RESULTS

Application of the procedure to the example buildings:

The structural models were subjected to a horizontal artificial ground motion record. In addition pushover analysis was carried out. The inelastic dynamic and static analyses are conducted using the computer program Perform 3D. Pushover curves of models, inter-story drifts, location of plastic hinges, beam rotation angles and structures' target displacements obtained from nonlinear static and dynamic analyses are presented and compared in the following sections.

Pushover curves:

Pushover curve that is actually force-roof displacement of a model is considered a structure's total response. Figure 4 displays the pushover curve of studied frames which is the base shear coefficient versus roof drift obtained from nonlinear static analysis under three lateral load distributions and nonlinear dynamic analyses from artificial ground motion record. It can be observed that the type of lateral load distribution has significant effect on resultant pushover curves. Uniform lateral load distribution gives a capacity curve with a higher initial slope and base shear capacity but less lateral displacement compared to two other distributions.

Considering base shear obtained from nonlinear dynamic analysis, it can be concluded that triangular and modal distributions give a conservative prediction while uniform distribution results in a non-conservative estimate of base shear capacity. This is not true for the ten story model as will be discussed later.

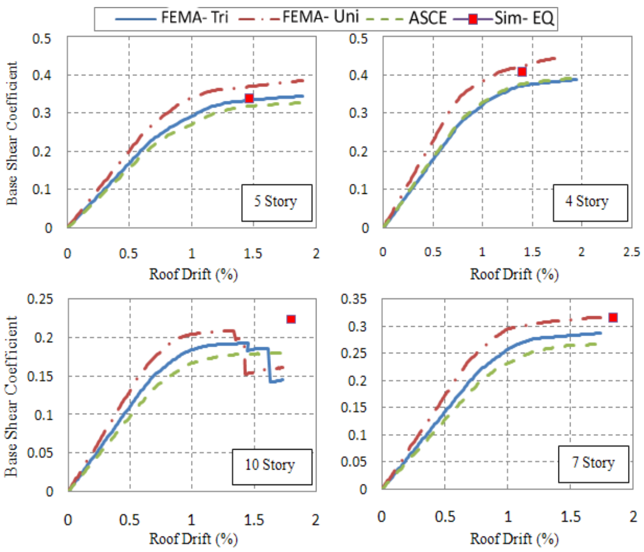

Figure 4. Pushover curves of studied frames

Contradiction in determination of columns' axial forces:

Regarding the provisions provided in FEMA 356 and ASCE 41-06, there is a fundamental difference in the way axial forces of columns can be calculated in nonlinear and dynamic analyses. Capacity of a column in a moment resisting frame is a function of the column's yield rotation angle, θ_y, which is determined as follows:

$$\theta_y = \frac{ZF_{ye}l_c}{6EI_c}\left[1 - \frac{P}{P_{ye}}\right] \qquad (6)$$

Where Z is plastic section modulus, F_{ye} is expected yield strength of the material, l_c is column length, E is modulus of elasticity, I_c is moment of inertia, P is axial force in the member at the target displacement for nonlinear static analyses, or at the instant of computation for nonlinear dynamic analyses $P_{ye} = A_g F_{ye}$ is expected axial yield force of the member. From the above equation it can be seen that θ_y heavily depends on P. The contradiction lies in the axial force determination. As stated in FEMA 356, P is the axial force in the member at the target displacement for nonlinear static analysis while in dynamic analysis it is the member's axial force at the instant of the computation.

As depicted in figure 5 application of lateral load in nonlinear static analysis until the target drift is reached increases the axial force of columns on one side and, according to equation 6, θ_y is greatly reduced resulting in a lower deformation capacity. However, in dynamic analysis P is considered in the presence of only gravity loads giving a higher value of capacity. The difference between the capacities obtained from each analysis method widens as the structure height increases. This justifies the early plunge in the push over curve in the 10-story model (Figure 4).

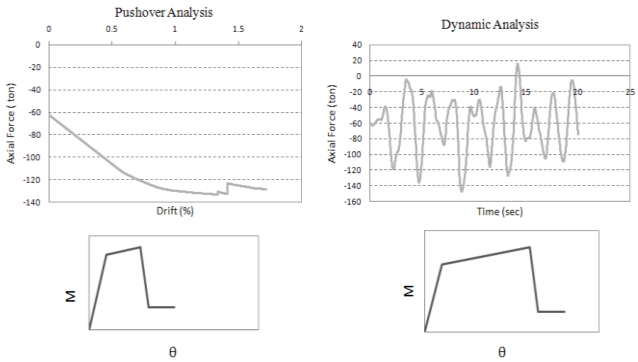

Figure 5. Axial force and Moment-Rotation curves of side columns in the first story of the ten-story frame for nonlinear static and dynamic analyses

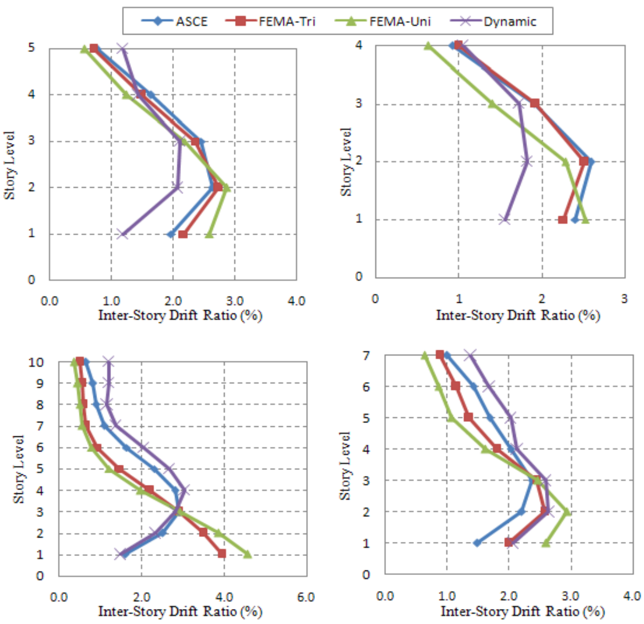

Figure 6. Interstory drift ratios obtained from nonlinear static and dynamic analyses

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Interstory Drift: Calculation of interstory drift and its distribution along the height of the structure is among important considerations in a structure's performance level assessment. That is because the damage to structural and non-structural members during an earthquake has direct relation with interstory drift demands in buildings. So this parameter is known as damage index. Interstory drifts obtained from different analyses are depicted the Figure 6. It is noted that none of the nonlinear static analyses is able to predict accurate value of interstory drifts. Among all three lateral load distributions, modal distribution included in ASCE 41 has the lowest error. Pushover analysis under all types of load distribution overestimates interstory drifts for lower stories and gives a non-conservative estimate on the values of interstory drift of upper stories.

Beam rotation angles: In this section maximum rotation of the right beam in each section has been measured as a benchmark for making comparison between the results of pushover and nonlinear analyses. That is an important parameter because in case all members of moment resisting frame are deformation-controlled, beam rotation is the only factor determining the performance level of the structure. Beam rotations achieved in nonlinear static and dynamic analyses are illustrated in Figure 3.

Comparing Figures 6 and 7, it can be noted that variations of beam rotations along the height of the structures is to a great extent similar to interstory drift at each story. Thus, it could be said that interstory drift at each story along height represents beam rotation of that story. From Figure 7 it is clear that pushover analysis's assessment of beam rotations is non-conservative for lower stories and even FEMA's recommendation to apply at least two distributions of lateral load cannot eliminate the error. Because uniform distribution focuses on lower stories and triangular distribution pattern approaches the uniform distribution as the height increases. Generally it seems that application of the distribution pattern proportional to the first vibration mode shape leads to more accurate results, although in practice and in every day engineering works this type of lateral load distribution is often overlooked.

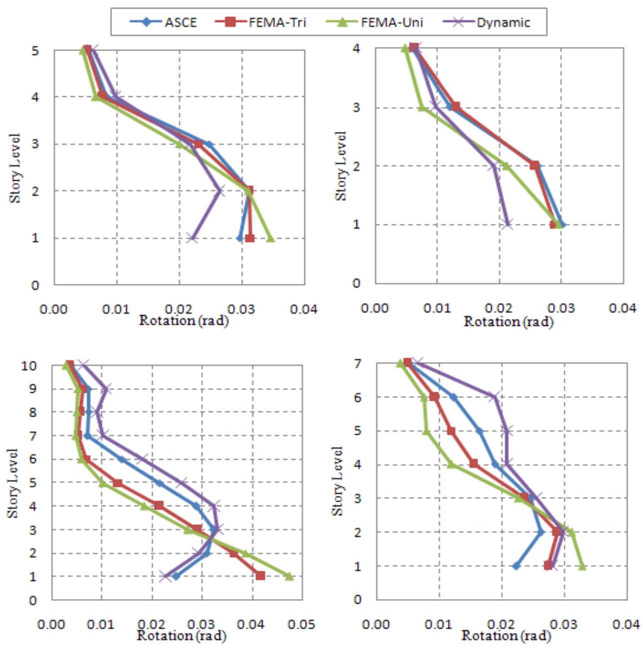

Figure 7. Beam rotations obtained from nonlinear static and dynamic analyses

Location of plastic hinge formation: One of the significant parameters that are expected to be revealed via pushover analysis is the location of plastic hinges that are critical sections where stress reaches the plastic value and failure is more likely to occur. Critical points for plastic hinge formation are marked in the frames shown in Figure 8. It can be observed that as the structure height increases the difference between results obtained from pushover and nonlinear dynamic analyses widens with the ten story frame having the most obvious inconsistencies.

Figure 8 confirms the aforementioned claim that pushover analysis underestimates interstory drifts and beam rotations for upper stories and absence of plastic hinges in upper stories of the ten story frame under different load distributions validates this assertion. Comparing the results of nonlinear static analyses under different load distributions with dynamic analysis, the biggest difference is attributed to pushover analysis under uniform load distribution. Furthermore, FEMA's recommendation on applying two lateral load distribution patterns does not help to make an accurate prediction of the number and location of plastic hinges.

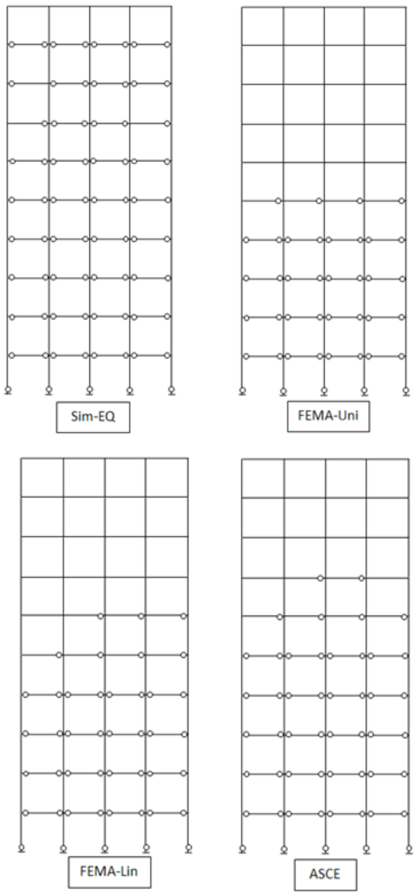

Figure 8. Location of plastic hinges along height in nonlinear static and dynamic analyses

Target displacement: Accurate determination of target displacement of a structure is of considerable importance and can improve the reliability of the obtained results. Figure 9 displays target displacement of structures, obtained in accordance with FEMA 356, ASCE 41-06 and during the artificial earthquake which is defined as the largest displacement of the roof during the dynamic analysis. According to Figure 9, the calculated target displacement directly depends on the applied load

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distribution. Uniform distribution gives the lowest errors compared to other two distribution patterns. Moreover, it is detected that alternations done to ASCE 41 do not improve the results. In order to make sure of accuracy of the calculations done and the results obtained, considering limited number of analyses carried out, result of Goel's study were used. Goel studied five existing concrete buildings whose responses during different earthquakes had been recorded. He stated that amendments to the target displacement method do not necessarily improve the results. The results in this section are consistent with his findings. Finally, as can be seen in Figure 9, rise in building height reduces the difference between results obtained from pushover analyses and dynamic analysis. The reason for this lies in coefficients existing in this method. In other words, that is because coefficients in equations 4 and 5 approach one as the fundamental period of the structure increases. Thus, the number of effective parameters involved in determination of target displacement declines and consequently the error value will decrease.

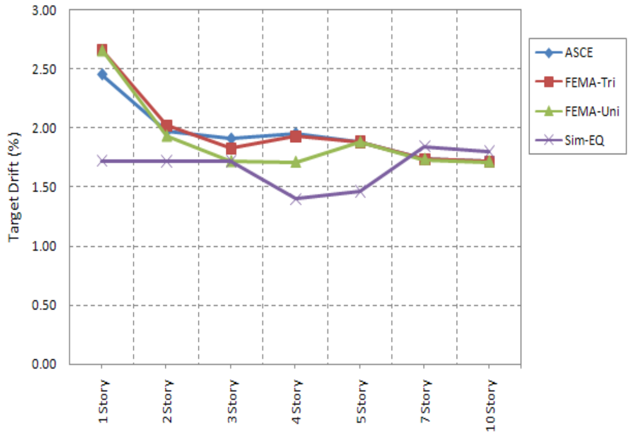

Figure 9. Target displacement of the analysed frames

DISCUSSION

Nonlinear static analyses under different load distribution patterns along with a dynamic analysis were conducted on a total number of seven two-dimensional special moment resisting frames at different heights, 1 to 5 stories along with 7 and 10 stories. Based on the results the following conclusions can be drawn:

Generally, application of two various lateral load distribution patterns leads to two different pushover curves. Pushover analysis under uniform distribution results in a capacity curve with a larger initial stiffness which is the initial slope of the curve and a higher base shear capacity while it gives less lateral displacement compared to two other distributions.

Pushover analyses under triangular and modal distributions give conservative estimates on base shear capacity while uniform distribution leads to a non-conservative of seismic demand. In other words, pushover analysis results obtained from uniform distribution is an upper bound estimate while those obtained from triangular and modal distributions function as lower bound estimate of the structure's seismic response.

Variation of the error values is higher for uniform distribution compared to two other patterns.

Variations in beam rotation values along the structure's height are to a great extent similar to that of interstory drift. Thus, it can be concluded that interstory drift at each story somehow represents the beam rotation value at that story.

The main reason why axial forces of columns in the first story in dynamic analysis differ from those obtained in nonlinear static analyses is the way axial forces of columns are calculated depending the type of analysis.

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