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Research Note

Evaluation of Iranian Seismic Guidelines: Case Study of Special Steel Moment Frames

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The purpose of this paper is to evaluate performance-based procedures in the Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings, which is currently being used for the vulnerability assessment of existing buildings in Iran. For this evaluation, two construction programs are studied for buildings: 1) The displacement coefficient method and 2) The Iranian seismic code (Standard 2800). In this study, several special steel moment-resisting frames are designed, according to Standard 2800 requirements, and their vulnerability is assessed. Analytical results show that some columns do not satisfy life safety requirements at the design hazard level. Moreover, the target displacement estimated by the displacement coefficient method is larger than the maximum displacement calculated by nonlinear dynamic analysis.

INTRODUCTION

Based on multiple coefficients, the design criteria in the Standard 2800 code were supported, as more of the ground motion and response phenomena became known. Most of these coefficients are based on good engineering judgment and rely on physical concepts and equations. In most aspects, the designs were force-based and required the provision of adequate strength to all elements of the lateral load resisting system. Nowadays, the Standard 2800 code is used for the seismic design of new buildings in Iran [1] and the Iranian Guideline for the Seismic Rehabilitation of Existing Buildings is used for the vulnerability assessment of existing buildings [2]. This guideline recommends four analytical procedures to estimate seismic demand. The first is the linear static procedure and the second is the linear dynamic procedure. These two methods are force-based. The third method is the nonlinear static procedure. This procedure uses the displacement coefficient method, in which the modeled structure is displaced with a target displacement by means of a pushover analysis. The fourth method is the nonlinear dynamic procedure. The third and fourth methods are displacement-based.

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In this paper, the performance-based procedures in the Iranian Guideline for the Seismic Rehabilitation of Existing Buildings are assessed. For this assessment, the Iranian seismic code is used as a benchmark.

DESCRIPTION OF BUILDINGS

The sample buildings are of 1 to 20 stories high. These buildings have special steel moment frames as the lateral resisting system. The sample buildings are designed according to the Standard 2800 code provisions. For the design of frames, the linear static analysis is used for all sample buildings, except for 15 and 20 story buildings, for which the linear static analysis is not adequate. In these cases, a linear dynamic analysis should be used to specify and distribute the seismic design forces.

ANALYSIS PROCEDURES

A vulnerability assessment objective shall be selected for the building. In the Standard 2800 code, the goal of the design is the life safety performance under a design earthquake. Therefore, the basic safety objective is adopted for the vulnerability assessment of the sample buildings. The basic safety objective is defined as the life safety building performance level for earthquake hazard level 1.

The Iranian Guideline for the Seismic Rehabilitation of Existing Buildings suggests four analytical procedures to estimate seismic demand. Of these four methods, linear and nonlinear dynamic procedures and the nonlinear static procedure are used in this study.

Linear Dynamic Analysis

In the linear dynamic procedure, the design seismic forces, their distribution over the height of the building and the corresponding internal forces and system displacements are determined, using a linearly elastic dynamic analysis, in compliance with the requirements of the Iranian Guideline for the Seismic Rehabilitation of Existing Buildings. This procedure includes the response spectrum method and the time history method. The response spectrum method uses peak modal responses calculated from the dynamic analysis for a mathematical model. Only those modes contributing significantly to the response need to be considered. Modal responses are combined, using rational methods, to estimate total building response quantities. The time-history method involves a time-step-by-time-step computation of building response, using recorded or synthetic earthquake records as the base motion input. However, the response spectrum method is used for the linear dynamic procedure. In this method, the value of the usage ratio is calculated as follows [2]:

a. *Beam*: The value of the usage ratio is defined as the ratio of the DCR_m to m-factor.

$$\text{Usage ratio} = \frac{M_U}{m \times M_{CE}} = \frac{DCR_m}{m}, \quad (1)$$

where DCR_m is defined as the ratio of internal force to the strength of beam; m is partial ductility coefficient (m-factor). This parameter is given in Table 5.2 in the Iranian Guideline [2] for the Seismic Rehabilitation of Existing Buildings; M_U is the bending moment in the member, calculated in accordance with the linear analysis; M_{CE} is the expected flexural strength of beam components and shall be determined using equations for design strength, given in AISC (1997) Seismic Provisions, except that the reduction factor of the strength, ϕ, shall be taken as 1.0 and $1.1F_y$ shall be substituted for the yield stress (F_y is the lower-bound strength).

b. *Column:* For steel columns under combined axial compression and bending stress, where the axial column load is less than 50% of the lower-bound axial column strength, P_{CL}, the column shall be considered as deformation controlled for flexural behavior and force controlled for compressive behavior. In this case, the value of the usage ratio shall be evaluated by Equations 5.12 to 5.14 in the Iranian Guideline for the Seismic Rehabilitation of Existing Buildings [2].

However, steel columns with axial compressive forces exceeding 50% of the lower-bound axial compressive strength, P_{CL}, shall be considered as force controlled for both axial load and flexure and the value of the usage ratio shall be evaluated using Equations 5.15 and 5.16 in the Iranian Guideline for the Seismic Rehabilitation of Existing Buildings [2].

This ratio was calculated for beams and columns, based on the results of linear dynamic analyses, which will be shown in the following sections.

Nonlinear Static Analysis

In the nonlinear static method, the internal forces and deformations are evaluated for the corresponding target displacement. The target displacement intends to represent the maximum displacement that the structure can reach during the design earthquake.

The displacement coefficient method is the primary nonlinear static procedure presented in FEMA356 and is used in the Iranian Guideline. This approach modifies the linear elastic response of an equivalent SDOF system, by multiplying it by a series of coefficients, from C_0 to C_3, to estimate the maximum global displacement of the building, which is termed the target displacement [3]. Target displacements are calculated for all sample buildings and are shown in Table 1.

In the nonlinear static method, the value of the usage ratio is defined as the ratio of deformation demand to deformation capacity [2]:

$$\text{Usage ratio} = \frac{\theta}{\theta_{LS}}, \quad (2)$$

where θ is the deformation demand; this parameter is obtained from the nonlinear static analysis; θ_{LS} is the deformation capacity for life safety performance; this parameter is calculated by addition of the yield rotation to the value of Table 5.3 in the Iranian Guideline for the Seismic Rehabilitation of Existing Buildings [2].

This ratio was calculated for beams and columns, based on the results of nonlinear static analysis, which will be shown in the following sections.

Table 1. Target displacement.

	Target Displacement (m)
1-Story	0.10
2-Story	0.15
3-Story	0.20
5-Story	0.28
10-Story	0.55
15-Story	0.88
20-Story	1.16

Nonlinear Dynamic Analysis

For the development of time-histories, the Abhar, Zanjan and Lahijan earthquake records are used. These real time-histories were recorded on soil type III.

The selected time-histories should be modified to be closer to the design ground motion conditions. The scaling of motion in the Iranian Guideline is different from that of FEMA356. The requirements in the Iranian Guideline are, as follows:

> "The time-history analysis shall be performed with pairs of appropriate horizontal ground-motion time history components, which shall be selected and scaled from not less than three recorded events. The motions shall be scaled, such that the values of the response spectrum of the earthquake partly match the 5 percent-damped spectrum of the design-based earthquake, for periods from 0.1 T to 3 T seconds (T is the fundamental period of the building). The parameter of interest shall be calculated for each time history analysis. If three time-history analyses are performed, then, the maximum response of the parameter of interest shall be used for the design. If seven or more time-history analyses are performed, then, the average value of the response parameter of interest may be used for the design [2]."

In this study, the motions are scaled by the Iranian Guideline requirements. The scale factors for the Abhar, Zanjan and Lahijan earthquakes are shown in Table 2.

All sample buildings are analyzed for any three records and the maximum displacement on the roof of the buildings is extracted. For any building, the maximum of the three values that have been calculated is written in Table 3.

Table 2. Scale factor.

	Scale Factor
Abhar	3.69
Zanjan	3.96
Lahijan	5.54

Table 3. Maximum displacement.

	Maximum Displacement (m)
1-Story	0.11
2-Story	0.15
3-Story	0.17
5-Story	0.25
10-Story	0.31
15-Story	0.50
20-Story	0.60

In the nonlinear dynamic method, the calculation of the usage ratio is the same as in the previous method. This ratio was calculated for beams and columns, based on the results of nonlinear dynamic analysis and will be shown in the following sections.

RESULT AND DISCUSSIONS

The usage ratios of columns and beams (inside and outside) in a 15-story building are shown in Figures 1 to 3. These ratios demonstrate that some lower columns of the building do not satisfy the life safety performance at the design hazard level, while all the beams of the buildings do satisfy this performance. This result is discussed in the following sections.

Linear Dynamic Analysis

In this section, the linear dynamic analysis of the Iranian Guideline is evaluated. For this evaluation, the linear static and spectral analyses of the Standard 2800 code are used. This is done by comparison of the curves presented in Figure 1. In this figure, the horizontal axis is the number of stories and the vertical axis is the usage ratio. ST2800 and GSREB are used for representing the Standard 2800 code and the Iranian

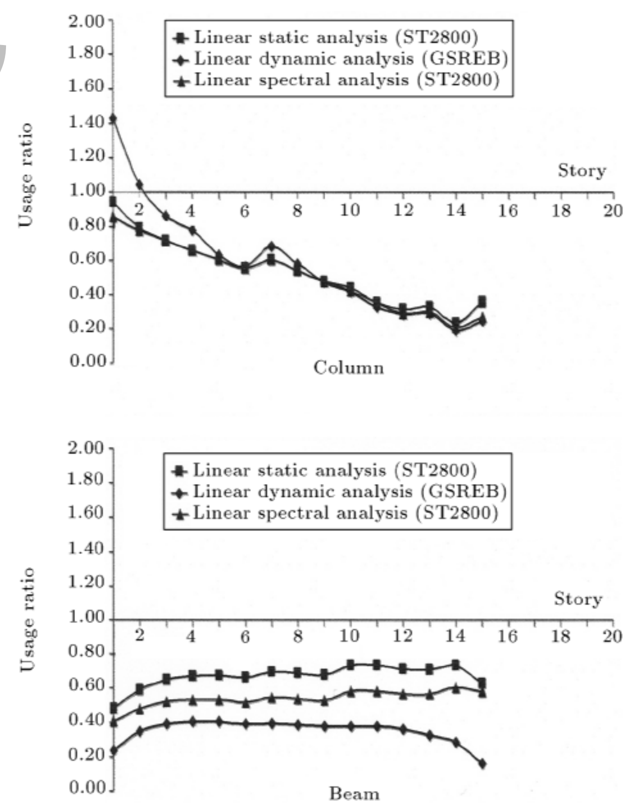

Figure 1. Usage ratio of a 15-story building (linear dynamic analysis).

Guideline for the Seismic Rehabilitation of Existing Buildings, respectively.

For example, Figure 1 includes two graphs (outside/inside beam and column). Each of these graphs includes three curves, entitled "linear static analysis (ST2800)", "linear spectral analysis (ST2800)" and "linear dynamic analysis (GSREB)".

As seen in this figure:

a). In the lower columns of the frames, the Standard 2800 (the curves entitled "linear static analysis (ST2800)" and "linear spectral analysis (ST2800)") is located below the GSREB (the curve entitled "linear dynamic analysis (GSREB)");

b). In the upper columns of the frames, the Standard 2800 code (the curves entitled "linear static analysis (ST2800)" and "linear spectral analysis (ST2800)") is appropriately matched to the GSREB (the curve entitled "linear dynamic analysis (GSREB)").

This result arises from a difference in the concepts of the two codes (Standard 2800 and GSREB). The Standard 2800 code uses the behavior coefficient, R, to bring the nonlinear behavior into analysis. While the Iranian Guideline uses the partial ductility coefficient (m-factor) for this purpose.

The behavior coefficient is constant for all members of an individual building. But the m-factor depends on the axial forces of the members [2] as follows:

$$m = 8\left(1 \quad 1.7\frac{P}{P_{CL}}\right), \tag{3}$$

where P is the axial force in the member, calculated in accordance with linear analysis, and P_{CL} is the effective design strength or the lower-bound axial compressive strength of the column components, which is calculated in accordance with AISC (1997) Seismic Provisions, taking $\phi = 1.0$ and using the lower-bound strength, F_y, for the yield strength.

Therefore, in the lower columns of the frames, where the amounts of axial force are high, the m-factor is low and, consequently, the Standard 2800 code is located below the Iranian Guideline.

Nonlinear Static Analysis

In this section, the nonlinear static analysis of the Iranian Guideline is evaluated. For this evaluation, the linear spectral analysis of the Standard 2800 code is used. As seen in Figure 2:

a). In the lower columns of the frames, the Standard 2800 code (the curves entitled "linear spectral analysis (ST2800)") is located below the GSREB (the curves entitled "nonlinear static analysis (GSREB)");

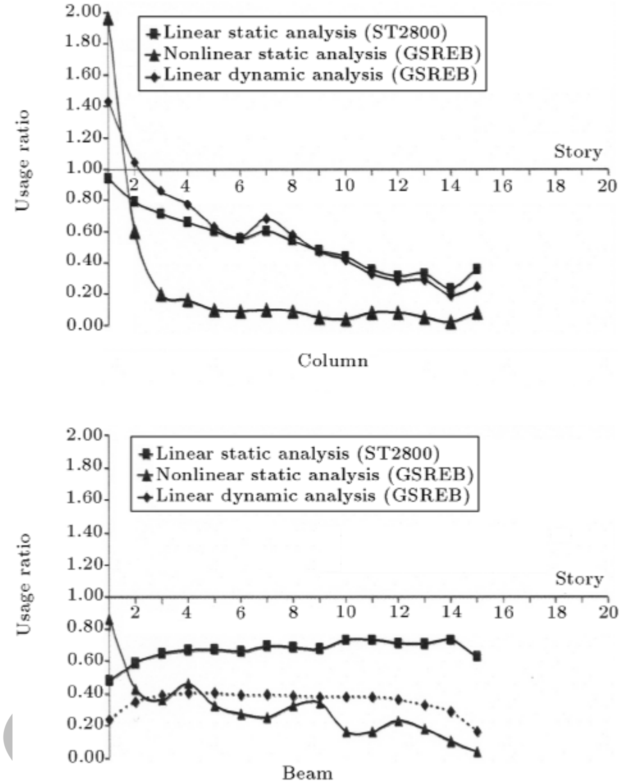

Figure 2. Usage ratio of a 15-story building (nonlinear static analysis).

b). In the upper columns of the frames, the Standard 2800 code (the curves entitled "linear spectral analysis (ST2800)") is located above the GSREB (the curves entitled "nonlinear static analysis (GSREB)").

As stated before, the behavior coefficient is constant for all members of an individual building. However, the capacity of the nonlinear behavior depends on the axial forces of the members (Equation 4) [2]:

$$\theta_P = 7\left(1 \quad 1.7\frac{P}{P_{CL}}\right)\theta_y, \tag{4}$$

where θ_y is yield rotation of the member and θ_P is the plastic rotation capacity of the member.

Therefore, in the lower columns of the frames, where the amounts of axial force are high, the plastic rotation capacity is low and, consequently, the Standard 2800 code is located below the Iranian Guideline.

Nonlinear Dynamic Analysis

In this section, the nonlinear dynamic analysis of the Iranian Guideline is evaluated. For this evaluation, the linear spectral analysis of the Standard 2800 code is used. The result of this section (as seen in Figure 3) is the same as that in the previous section.

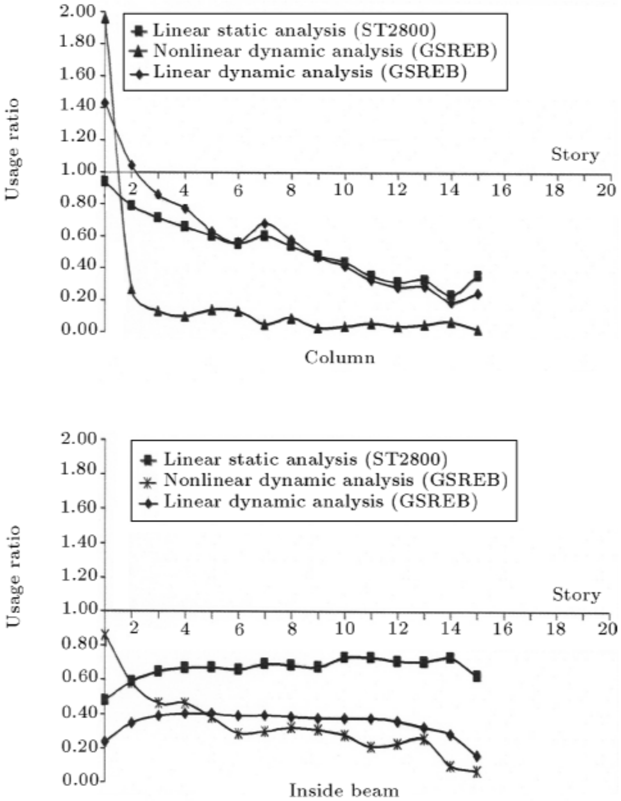

Figure 3. Usage ratio of a 15-story building (nonlinear dynamic analysis).

EVALUATION OF TARGET DISPLACEMENT

There are two options in using nonlinear static procedures. These are: The capacity-spectrum method, which is documented in ATC-40 and the displacement coefficient method, which is presented in FEMA 356. Both approaches use nonlinear static analysis to estimate the lateral force deformation characteristics of the structure.

The FEMA 440 [3] is the principal product of the ATC-55 project. This report evaluates both current procedures by a series of nonlinear single-degree-of-freedom oscillators of varying period, strength and hysteretic behavior. These oscillators are subjected to ground motion representing different site soil conditions. The resulting database of, approximately, 180,000 predictions of maximum displacement, was used as a benchmark to judge the accuracy of the approximate nonlinear static procedures. This was accomplished by comparing the estimates for each oscillator from both nonlinear static procedures to the results of the nonlinear response history analyses. The differences in the two estimates were compiled and compared in a statistical study.

FEMA 440 [3] summarizes the results of studies to assess the ability of the displacement coefficient method in estimating the maximum displacement of inelastic structural models.

For example, Figure 4 presents mean errors calculated from the ratio of the displacements computed using C_1 and C_2, as determined from FEMA 356, to maximum displacements, computed using nonlinear response history analyses, for stiffness and strength degrading systems. The results, in this case, correspond to site class C. This figure shows that the target displacement is overestimated when the period is longer than 0.5 seconds [3].

In this paper, buildings with special steel moment frames have been studied. For these buildings, the ratio of target displacement (values in Table 1) to maximum displacement (values in Table 3) is calculated and shown in Figure 5. This figure demonstrates that the nonlinear static procedure introduced in the Iranian Guideline overestimates the target displacement for buildings that have long and medium periods.

CONCLUSIONS

The results of this study show that few lower columns of the selected frames satisfy the life safety perfor-

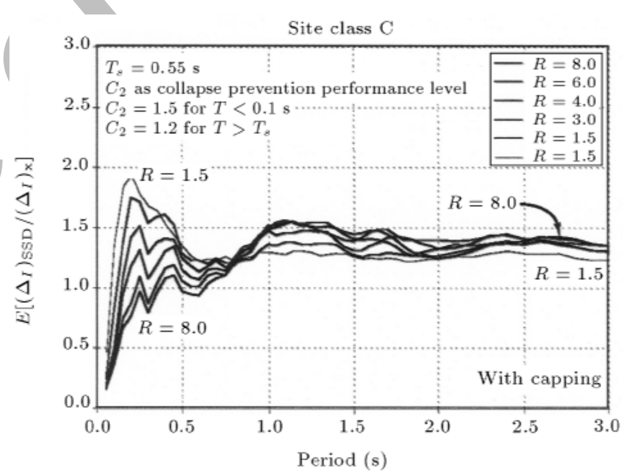

Figure 4. The mean error statistics associated with C_1 and C_2, assuming a collapse prevention performance level in accordance with FEMA 356 for stiffness and strength degrading systems [3].

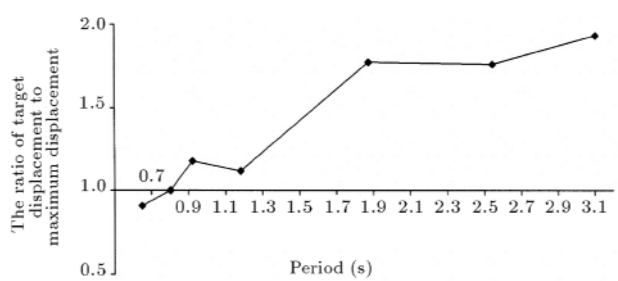

Figure 5. The ratio of target displacement to maximum displacement in the roofs of buildings.

mance at the design hazard level. Therefore, the Standard 2800 code does not match the Iranian Guideline in life safety performance at the design hazard level.

This result is important for buildings designed using the Standard 2800 code. According to this result, the buildings which are being established now should be rehabilitated. A comparison between nonlinear and linear analysis shows that the results of these two analyses are completely different. So, linear analyses are not reliable for the vulnerability assessment of building with moment resisting frames. Moreover, the results of nonlinear static and dynamic analyses show that the displacement coefficient method overestimates the target displacement. This result is also mentioned in FEMA 440. But all analyses used in the FEMA 440 are obtained from one degree freedom models [3].

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