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ORIGINAL ARTICLE

Seismic performance of steel frames designed using different allowable story drift limits

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Abstract The design of Moment Resisting Steel Frames (MRSFs) is usually governed by drift limits rather than strength because of their high flexibility. The purpose of this study is to evaluate the seismic performance of a 6-story MRSF designed according to the Egyptian code with three different levels of allowable story drift limits: 0.5%, 0.75% and 1.0%. Seismic evaluation in this study has been carried out by static pushover analysis and time history earthquake analysis. Ten ground motions with different PGA levels are used in the analysis. The mean plus one standard deviation values of the roof-drift ratio, the maximum story drift ratio and the maximum beam- and column-strain responses are used as the basis for the seismic performance evaluations.

The results obtained indicated that the strength and the initial stiffness of the designed frames decrease as the allowed story drift limit of the frame increases. Two of the designed frames exhibit maximum story drifts that are higher than the allowed limits specified by the code. The maximum story drift and beam-strain responses of the designed frames under the earthquake loading increase with the increase in the allowable story drift limits.

1. Introduction

The main objective of seismic codes including the recent Egyptian code (ECP-201) [1] is to achieve satisfactory performance of structural systems when subjected to earthquake loading. However, seismic design of building structures is usually conducted by approximate procedures that rely on using elastic static analysis instead of the actual inelastic dynamic one. This highlights the importance of evaluating the actual dynamic inelastic performance of the code designed structures under the effect of real earthquake records. Such evaluation is essential to provide information on the level of protection afforded to the code designed structures against seismic loading.

The Egyptian code provisions for the seismic design of MRSFs have been evaluated through parametric and comparative investigations using different analysis procedures and numerical models. The analysis has been conducted at either the structure-level or the beam-to-column connection level. Shehata et al. [2] analyzed MRSFs designed according to the Egyptian code with strong and weak-joint approaches. The global and local performance parameters of the frames are evaluated under lateral loading conditions. The results indicated satisfactory performance of both the design approaches.

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Serror et al. [3] investigated how to define the boundary between special moment resisting frame and ordinary moment resisting frame in the ECP-201. The seismic provisions of ECP-201 have been compared with those of the Euro-Code 8 and the Uniform Building Code with regard to ductility classes and their impact on the response modification factor. They suggested specifying a structure as special moment resisting frame means that its members should adhere to class 1 (compact width-to-thickness ratio) requirements; while specifying a structure as ordinary moment resisting frame means that using members of class 2 (non-compact/slender width-to-thickness ratio) is permitted.

Finite element modeling of MRSF connections has been conducted by Mashaly et al. [4,5]. The software package ANSYS is used to model the joint under the effect of lateral loading. The results confirmed that the chosen parameters such as material and section geometry of the joint, played effective roles on the energy dissipation of the connection under seismic loading.

El-Shaer [6] evaluated the effect of earthquake on steel frames with partial rigid connection. The analysis was based on the nonlinear dynamic analysis considering both geometrical and material nonlinearities. The analysis demonstrated that the calculated displacement responses are close to those proposed by different seismic codes. Abdel Raheem [7] evaluated the Egyptian code provisions for the seismic design of moment-resistant frame multi-story building through using nonlinear time history analysis, equivalent static load and response spectrum analysis methods. He found that diaphragm flexibility caused an increase in the fundamental period and in floor displacements compared with the case of rigid diaphragms of equivalent buildings. He concluded that the code empirical methods under-predict the fundamental period of structures with flexible diaphragms. He also concluded that the equivalent static force approach of the ECP-201 is not accurate as it overestimates the base shear. Serror and Abdel-moneam [8] evaluated the performance of MRSFs designed according to the Egyptian code. The focus of their study was on the effect of beam slenderness limit on the anticipated ductility of MRSFs. They proposed guidelines to estimate the appropriate force reduction factor, R-factor, based on the beam slenderness limit.

Most recent seismic codes, including the Egyptian code for calculating loads (ECP-201) are developed with two performance levels. One, with the intent of limiting damage during frequent moderate earthquakes namely the serviceability limit state and the other is for ensuring collapse prevention during a major earthquake namely the ultimate limit state [9]. Displacement parameters often offer better evaluation of damage effects than force parameters when assessing structures to a serviceability limit state [10]. Therefore limiting displacement is a requirement for controlling the seismic damage.

In order to estimate the actual inelastic displacement that develops in strong earthquakes, ECP-201 specifies that the computed displacement from the reduced lateral forces is amplified by a factor that is equal to $0.7 \times$ R-factor. The R-factor is the force reduction factor that accounts for the ductile inelastic behavior of the structural system. For the case of moderate frequent earthquake, the displacement demand is estimated by reducing the strong-earthquake displacement to account for the difference in return periods between the strong earthquake and the frequent one. ECP-201 uses a displacement reduction factor v for this purpose. The value of the displacement reduction factor v is 0.4 for important structures and 0.5 for ordinary buildings.

Seismic codes specify limits on the lateral displacement demand corresponding to moderate frequent earthquakes to control seismic damage to nonstructural components for serviceability considerations. Traditionally lateral displacement has been defined in terms of story drift which is the relative lateral displacement occurring between two successive floors. Limitations on story drift ratios vary among the codes, generally ranging from 0.25% to 1.5% depending on the type of the non-structural elements. The Egyptian code specifies three levels of allowable story drift limit depending on the type of the non-structural elements and their arrangements into the structure. The code specifies 0.5% allowable story drift ratio for brittle partitions, 0.75% for ductile partitions and 1.0% for structural systems with partitions fully isolated from the structure motion.

The objective of this study is to evaluate the seismic performances of a 6-story MRSF designed according to the Egyptian code with different levels of allowable story drift limits. Three design cases of the 6-story MRSFs, D_1, D_2, and D_3 are considered in this study. These design cases are corresponding to allowable story drift limits of 0.5, 0.75, and 1.0%, respectively. Seismic evaluation in this study has been carried out using static pushover analysis and time history earthquake analysis using the SeismoStruct computer program [11]. Ten ground motions with different PGA levels are used in the analysis. Each of the ground motion records is scaled to different PGA levels to excite the structure well into the inelastic range of deformation. The mean plus one standard deviation values of the roof-drift ratio, the maximum story drift ratio and the maximum beam- and column-strain responses are used as the basis for the seismic performance evaluations.

2. Prototype frames and computer program

The prototype steel building considered in this study is a 6-story office building located in Cairo, Egypt with a design PGA of 0.15 g. The plan of the building, shown in Fig. 1, has a rectangular configuration with 5-bays in the short direction and 7-bays in the long direction. The bay width in both directions is constant and equals to 7.5 m. The story height is 4.5 m for the ground floor and 3.5 m for other floors with the total building height of 22.0 m. The floors consist of 10 cm light weight concrete slab over a composite metal deck. Structural members are selected from the American wide flange sections (W-sections). The usual structural steel specification for W-sections is ASTM A992. The yield strength is 345 MPa, modulus of elasticity is 200 GPa, strain hardening ratio is 0.01, and the shear modulus is 81 GPa.

The building is considered to have MRSFs in the perimeter of the short direction and braced steel frames in the perimeter of the long direction to carry the seismic loads. A typical perimeter MRSF in the short direction is shown in Fig. 2. The dead load is assumed equal to 5 kPa and it includes weights of deck, beams, girders, ceiling, partitions and mechanical and electrical systems. Surface weight of the exterior walls is considered equal to 1.25 kPa. The applied live load considered is taken 3 kPa for office buildings.