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Comparison of seismic design for steel moment frames in Europe, the United States, Japan and China

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ABSTRACT

Seismic provisions to guide the design of steel moment frames in Europe, the United States, Japan and China are comprehensively examined. Seismic hazard levels and performance requirements, ground type classification, magnitude and shape of elastic response spectra, seismic design force and distribution of required story shear strength, local ductility requirements, and reduction factors are compared. The results show that the no-collapse requirements in Eurocode and Japanese code correspond to a lower level of ground motion than the other two codes. The unreduced elastic response spectra given in four codes are quite different in recognition of different ground types and seismicity, in particular, Japanese code generally specifies much larger elastic spectrum than other codes. Although local ductility requirements are quite similar, U.S. code specifies higher reduction factors than Eurocode and Japanese code, while Chinese code stipulates a constant reduction factor with a relatively small value regardless of the ductility level of structures. As a result of such over-conservatism, Chinese code designed steel moment frames exhibit 20% to 150% larger lateral stiffness and resistance than Eurocode and U.S. code in most cases, while the significant even larger lateral stiffness and resistance predicted by Japanese code than that by Chinese code is mainly due to the larger seismic force from elastic response spectrum.

1. Introduction

Steel moment frames were widely used for seismic design around the world due to their highly regarded seismic performance under earthquakes and relatively simple construction in practice. However, such steel frames suffered much damage or even collapsed in the 1994 Northridge [1,2] and 1995 Kobe earthquakes [3,4], which highlighted the need to thoroughly investigate seismic behavior of steel framed structures. Since then, researchers and engineers have contributed to giving a better understanding of those approaches in seismic design and thus improving the provisions in seismic codes. Those efforts have led to various improved seismic design practices for steel buildings, such as the innovative series of research by SAC to identify better seismic details in beam-to-column connections [5], re-calibration of seismic force reduction factor correlated with the expected ductility [6] and new capacity design criteria to ensure a global plastic mechanism [7]. It is notable that although current seismic codes in various countries are based on similar fundamental seismic design principles, the actual design procedures, detail strength and ductility requirements, and consequently, the global seismic resistance and behavior exhibited by steel structures can be quite different. It is therefore imperative that design concepts and detailing rules in various seismic codes are appraised and compared. Such information is deemed useful for researchers and engineers to understand better the seismic design practices in various countries. Some differences in the comparison may be attributed to the engineering history, culture and economy, but others may come from a lack of understanding or knowledge in the engineering philosophy for seismic design, even the recognition and experience of practical earthquake damages. Thus, such a comparison can also reveal the potential opportunities to calibrate and re-evaluate the respective design provisions in different seismic codes.

To this end, this paper focuses on assessing and comparing the seismic provisions adopted in Europe, the United States, Japan and China, with emphasis on the seismic design approaches of steel moment frames, since this structural system is the most basic seismic force resisting system (SFRS). Some detailed assessment and comparison of differences among the seismic codes in Europe, the United States and Japan have been conducted by Uang [8], Mazzolani et al. [9], Nakashima et al. [10], Tada et al. [11], Marino et al. [12] and Elghazouli [13,14]. However, as the seismic codes are constantly revised in light of recent research findings and substantial developments, the previous comparison studies did not include seismic codes in Europe, the United States and Japan simultaneously, and are not comprehensive, e.g. structural performance requirement under different seismic hazard levels (Section 2 below) and conversion relationships between the response spectral parameters in different seismic codes (Section 3.2 below) are not included. Moreover, there hasn't been any comparison including the seismic code in China, which suffered much from several recent severe earthquakes including the 2008 Wenchuan earthquake, the 2010

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Yushu earthquake, the 2013 Ya'an earthquake and the 2014 Ludian earthquake. Therefore, the study in this paper provides a valuable overview and attempts to bridge differences of the design philosophy in seismic codes in Europe, the United States, Japan and China.

A systematic and comprehensive comparison requires full characterizations of the whole seismic design process, including the basic performance requirements, seismic action for different limit states, required strength, seismic force reduction factor and the corresponding ductility requirements, and finally, drift limits. Currently, Eurocode 8 [15] (referred to as Eurocode hereinafter) and GB 50011-2010 [16] (referred to as Chinese code hereinafter) are the seismic codes applied in Europe and China respectively, while in the United States, seismic design requirements of steel moment frames are included in ANSI/AISC 341-10 [17] and ASCE/SEI 7-10 [18] or IBC-2012 [19] (all referred to as U.S. code hereinafter). Japan has a seismic design code adopted in 1981, which is called Building Standard Law [20], then the provisions have been expanded to include limit state concepts and some revisions have been made since then [21–24] (referred to as Japanese code hereinafter). It should be stressed that the comparison is conducted on steel moment frames located in a benchmark site of China, but designed per different codes. Thus the difference in geography or geology of different countries and its influence on design results can be excluded, leaving behind only the difference in seismic design procedures or guidelines. The ultimate goal of the presented study is to provide an insight into the design philosophy in current seismic codes, in particular, the trade-off between required strength and ductility, which is quite beneficial for evaluating the strength and ductility capacity of steel moment frames using high strength steels (especially in columns) and proposing rational design alternatives for such steel frames that are both safe and economical [25–27].

2. Performance requirements

Eurocode specifies two levels of ground motion. One is the reference ground motion associated with a reference probability of exceedance equal to 10% in 50 years or a return period of 475 years, under which no local or global collapse of a structure is permitted (i.e. no-collapse requirement which refers to ultimate limit state); the other one has a probability of exceedance equal to 10% in 10 years or a return period of 95 years and structures are designed to have sufficient resistance and stiffness to maintain the function of vital services, without the occurrence of damage and the associated limitations of use (i.e. damage-limitation requirement which refers to serviceability limit state).

U.S. code defines only one explicit level of seismic action based on a recommended probability of exceedance of 2% in 50 years or a return period of 2475 years, namely maximum considered earthquake (MCE) ground motion, and stipulates that structures are designed to provide an approximately uniform margin against collapse under such level of ground motion throughout the United States [28]. The so-called seismic margin is set at 1.5; consequently, the design level ground motion is defined as 2/3 of MCE and is used to formulate the design response spectrum. Such design approach leads to a uniform margin against collapse but not a uniform probability of the ground motion for seismic design in different regions, which is quite different from Chinese code and Eurocode employing the same level of design ground motion (i.e. probability of exceedance of 10% in 50 years) in any region. For example, the deign level ground motion in most regions of low-to-moderate seismicity in the central and eastern United States corresponds to a probability of exceedance of about 2% to 5% in 50 years, while in the western United States of high seismicity (e.g. Los Angeles and San Francisco, California) the value of probability of exceedance is around 10% [29].

Japanese code explicitly considers two levels of ground motion. The probability of exceedance of the Level 1 ground motion is equal to 50% in 30 years (the return period is 43 years), while the probability of exceedance of the Level 2 ground motion is equal to 10% in 50 years (the return period is 475 years). The former one is for serviceability requirement and structural damage should be limited under this level of ground motion. The latter one is for safety and no collapse of a structure is required.

Chinese code basically defines three-level seismic performance requirements, i.e. “operational”, “damage-repairable” and “collapse-prevention”, which essentially refer to serviceability, damageability and survivability limit states respectively under seismic loading. The operational and collapse-prevention requirement correspond to ground motion based on a recommended probability of exceedance of 63% and 2%–3% in 50 years or a return period of 50 and 1600–2400 years respectively; whilst the values associated with the damage-repairable level relate to a recommended probability of exceedance of 10% in 50 years or a return period of 475 years. To satisfy those requirements, a two-phase design approach is employed. Phase 1 design is accomplished by performing an elastic analysis with the 63% in 50 years ground motion and by assuring that critical structural elements are below yield levels and the elastic inter-story drift should be within the limiting values. Phase 2 design is required for some irregular or special structures to ensure the inelastic inter-story drift under the 2%–3% in 50 years ground motion within the limiting value. Generally nonlinear static (i.e. pushover analysis) or dynamic (i.e. time history analysis) analysis is performed.

Those performance requirements by Eurocode, U.S., Japanese and Chinese codes are compared in Fig. 1. It is clear that Chinese code is the only one that defines an explicit three-level performance requirement; no-collapse requirement in Eurocode and Japanese code is less stringent than that in the other codes, whilst the serviceability limit state in Eurocode corresponds to a higher level of ground motion than Chinese and Japanese codes. U.S. code doesn't consider any performance requirement under frequent earthquakes.

3. Seismic action

In seismic design, an elastic pseudo-acceleration response spectrum is developed to represent the ground motion, and such a spectrum is correlated with the nature of supporting ground, i.e. different ground types ranging from hard to soft soil result in different elastic response spectra defined in each code. In order to compare seismic action levels stipulated in different codes, correspondence among ground types is established first; subsequently, elastic response spectra corresponding to the equivalent ground type and the same level of ground motion are compared.

3.1. Ground types

Although the descriptions of stratigraphic profile for various ground types are more or less different, a common parameter which is used to quantitatively classify ground conditions is the average shear wave velocity V_s, which is computed as follows,

$$V_s = \frac{d}{\sum_{i=1}^{n} \frac{h_i}{V_i}} \tag{1}$$

where n is the number of soil layers, h_i and V_i denote respectively the thickness and shear wave velocity of the i-th soil layer, and d represents the total depth of considered soil layers. In Chinese code, d is taken as the thickness of overburden soil layer or 20 m, whichever is less, and five ground types named I_0, I_1, II, III, and IV are specified on the basis of V_s; while in Eurocode, d equals to 30 m, then ground types A, B, C and D are classified according to V_s, while ground type E corresponds to a particular kind of ground stratigraphy in which a soft surface layer (type C or D) is placed over a hard soil (type A), and there are another two ground types S_1 and S_2 representing deposits or highly liquefiable or sensitive soils. U.S. code also sets d as 30 m when