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Comparison of Japanese Seismic Isolation Design Code with Overseas Codes

Contents

1 Introduction

In October 2022, "ISO 23618:2022 Bases for design of structures - General principles for seismically isolated structures" was published. Detailed design procedures of Japan (MLIT Notification No. 2009), China (GB/T 51408-2021), USA (ASCE 7-16) and Eurocode (EC8) are compared to propose a common design procedure for engineering practice.

Seismic isolation design codes are introduced first. Seismic load, analysis methods, major load combinations and device testing methods are compared. A 7-story RC building model is used to demonstrate the design procedures. Response results of response spectrum analysis method for equivalent linear system and response history analysis method are summarized at last.

2 Seismic Isolation Design Codes

The seismic load, analysis methods and test methods for seismic isolation devices of Japan, China, the United States of America and the Eurocode are summarized in Table 1.

Table 1 — Concept of the seismic isolation design Codes

Contents		Japan	China	USA	EC8
Seismic load	Hor. spectrum	defined			
	Ver. spectrum	0.3g	0.2 - 0.4g	defined	
Analysis method	Lateral force	N/A	○	N/A	○
	ELM	○	N/A	○	○
	Spectrum	N/A	○	○	○
	THA	○	○	○	○
Major load combinations	Gravity	D+L	1.3D+1.5L	1.2D+1.6L 1.4D	1.35D+1.5L
	Seismic	D+L±E	$1.0D+0.5L+1.0E_h+0.4E_V$	1.2D+0.5L+1.0E	1.0D+0.3L±1.0E
Devices testing method	Prototype	Factory	○	○	Factory
	Production	○	○	○	○

D: dead load; L: live load; $E_{h,V}$: horizontal or vertical seismic load

In each Code, the horizontal design spectrum is defined as the seismic load. The vertical design spectrum is defined in the USA and Eurocodes, while in Japanese and Chinese Codes, the vertical response coefficient is defined. For the analysis methods, the static method (lateral force or equivalent linearization method) and the dynamic method (response spectrum analysis or response history analysis method) are defined.

The limit state design method is adopted in China, USA and EC8, while the allowable stress design method is adopted in Japanese code. The load combinations usually give impacts to the design of isolation devices. In Chinese and USA Codes, the vertical compression and tension load combinations are different, where the tension load design may be critical than other Codes. There are many mechanical tension-resistant devices applied in China and USA, while there are few applications in Japan.

The quality control of the isolation devices is very important. Strict prototype test method is stipulated in all Codes. In Japanese code and EN 15129, factory surveillance is conducted periodically. For the production control, 100% products are tested in Japan and USA, while a percentage is allowed in Chian and EN 15129.

ULS seismic load and response of the super-structure defined in the Codes are summarized in Table 2. In Japanese Code, seismic loads corresponding 500-year return period are used. Drift value is limited to 1/300 in ELM corresponding with 1st stage design of seismic design and about 1/150 or less in THA. In Chinese Code, 475-year load is used for the design of the super-structure and substructure, while 2475-year load is used to check both the super-structure and isolation devices. In addition, a maximum 10,000-year load is also defined to check both the super-structure and isolation devices in some cases. In USA, from ASCE 7-16, a MCE event having 1% probability of building collapse in 50 years is used to design both the super-structure and isolation system. The EC8 uses 475-year load and there is no requirement for drift response of the super-structure. In USA and EC8, response modification coefficient is adopted so that the model of the super-structure is usually treated as elastic. Except Chinese Code, the bound properties of the isolation system are introduced to obtain the response results. The response deformation of rubber bearings is usually limited to about 250% shear strain in practice.

Table 2 — ULS seismic load and response of the super-structure defined in the Codes

Contents		Japan	China	USA	EC8
Return period (year)	ULS	500[a]	475 1600~2475	2475[a]	475
Model of super-structure		Non-linear	Non-linear	Linear Response mod.coef. R_I	Linear behaviour factor q
Bound properties		○	N/A	○	○
Deformation of RB (%)	ULS	267[b]	min(300,0.55D)	250[b]	250[b]
Drift (RC frame)		1/150-1/300[b]	1/400 1/100	1/67	N/A

a: estimated; b: in engineering practice

3 Design Examples

3.1 Analysis model

The 7-story RC building model presented by Saito (2011) is used to demonstrate the design procedures. The super-structure is slightly modified as shown in Feng (2022), where the fundamental periods of the fixed-base model are Tx = 0.564, 0.190, 0.107s (frame direction) and Ty = 0.238, 0.105, 0.087s (shear wall direction), respectively.

LRB devices are selected as they have appropriate restoring force and damping capacity. Diameters from 650 to 750mm were used in Japan, China and EC8 design model. Diameter of 900mm was used in USA design model due to the large value of the MCER seismic load. The nominal design properties of the isolation system are summarized in Table 3. In USA design model, large number of dampers was needed to restrain the deformation of the isolation system.

Table 3 — Nominal design properties of the isolation system

Item	Symbol	Unit	Japan, China, EC8	USA
Mass	M	Ton	3,555	
Yielding load of lead plug	Q_d	kN	1,092	2,780
Ratio	Qd/W	%	3.1	8.0
Initial stiffness	K_1	kN/m	137,806	199,068
Post-elastic stiffness	K_2	kN/m	10,600	15,313
Vertical stiffness	K_V	kN/mm	34,502	49,536

3.2 Seismic load

To consider the seismic region coefficients, the target construction sites are assumed to be in Tokyo, Beijing, San Fransisco and Reggio Calabria respectively. A fixed soil profile is assumed in all cases, where the average shear wave velocity within the top 30m is about 209 m/s (Feng, 2006). Typically, seismically isolated buildings should be located on relatively stiff ground. In the Japanese code, an iterative procedure was used to calculate the site amplification coefficient, rather than using the amplification coefficients defined in the Code.

The 5% code acceleration spectra and pseudo velocity spectra were calculated to compare the seismic load level at each location shown in Figure 1. Typically, a seismically isolated building usually has about 20% critical damping in ULS earthquakes shown in Figure 2. USA code gave the largest spectra, almost 1.5 times larger than Japan. The pseudo velocity spectra increased with the period in Chinese code while the pseudo velocity spectra remained constant or decreased in other Codes.

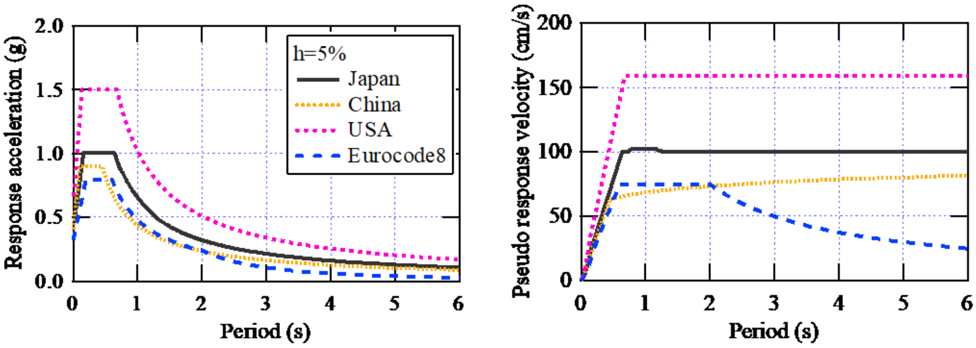


Figure 1 — 5% damping acceleration (left) and pseudo velocity (right) response spectra

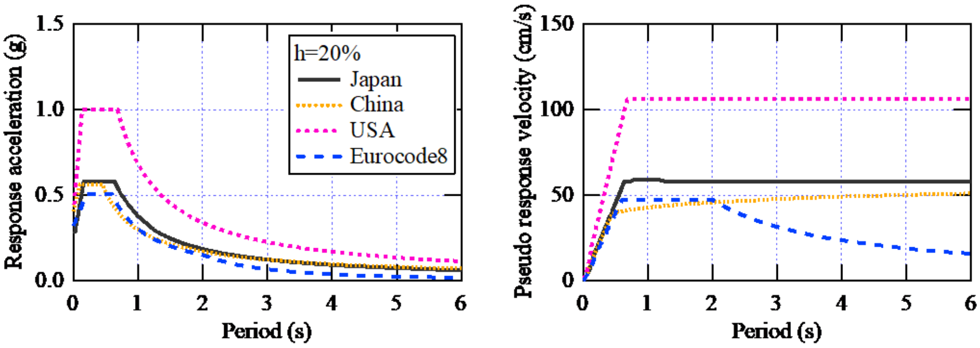


Figure 2 — 20% damping acceleration (left) and pseudo velocity (right) response spectra

3.3 Response analysis results

3.3.1 Response spectrum analysis method for equivalent linear system

The analysis results by the equivalent linear method (ELM) are summarized in Table 4. Although an equivalent linear analysis based on a single-degree-of-freedom (SDOF) system is defined in all codes, there are different limitations on the applicability of the method as summarized by Feng (2006, 2022). Bound properties of the isolation system were determined considering variability and uncertainty in production, temperature and ageing properties etc. In Chinese code, response results by both 475 and 2475-year seismic load were calculated without considering boundary properties. An equivalent mass of 85% is introduced in Chinese Code.

The convergence procedure shown by Feng (2006) was used to obtain the response results. The shear strain of LRB and the equivalent damping ratio obtained by LBDP were 278%, 11% in Japanese Code and 270%, 14% in USA Code, respectively. The base shear force coefficient of the super-structure obtained by UBDP was 0.149 in Japanese Code and 0.194 in USA Code. The vertical distributions of the shear force are shown in Figure 3 comparing with the response results based on THA. In Japanese, USA and EC8 Code, the vertical response was obtained as 0.3g, 0.2SMS=0.3g and $a_{vg}(3\tau)$=0.75g respectively. The moat/seismic gap was obtained considering eccentricity of the isolation system and safety factor etc., which was 0.688m in Japanese Code and 0.633m in USA Code. In EC8, combination of two horizontal direction was considered to obtain the response results. Due to the limitation of the paper, the restrictive requirements check of ELM can be found in Feng (2022).

3.3.2 Response history analysis method

Response history analysis method (THA) is mostly used in all Codes. In Japanese code, the maximum response values from six pairs ground motions were adopted, while in the other codes, the average response values from ten pairs ground motions were adopted. All ground motions were compatible with the 5% design spectra shown in Figure 1. In USA and EC8 Code, combination of two horizontal direction was considered. In Japanese, USA and EC8, vertical spectra were calculated, which were used in the vertical response analysis based on the response spectrum analysis (RSA).

A 3D frame model was used in this study for both RSA and THA. In the horizontal response history response analysis, the super-structure was assumed as non-linear in Japanese and Chinese Codes, while elastic in USA and EC8 Codes. LRB devices were idealized as a bilinear model. In the horizontal response analysis, the structural damping was set to Rayleigh type, the damping ratio of the seismic isolation system was set to 0, and the damping ratio corresponding to the 1st and 2nd natural periods of the super-structure was set to 3%. The THA analysis tool used was SERA3D Ver10.8 by Saito (2021). RSA was conducted for Chinese Code by PKPM which is the 1st commercial program with the convergency procedure. In the vertical response analysis, RSA was used. Since the vertical rigidity of the seismic isolation system is hard, the vibration mode of the beam was remarkable. In the vertical response analysis, the structural damping was set to Rayleigh type too. The damping ratios corresponding to the 1st and 2nd vertical natural periods were both set to 3%. ETABS V18 was used as the analysis tool.

In Figure 3, response results based on THA compared with ELM, RSA and seismic design are shown together. Deformation of the isolation system are shown in Table 4. Shear force coefficient comparing with the seismic design and drift comparing with the Code limitation are shown in Figure 3.

Table 4 — Response results by ELM (equivalent linear method)

Item	Symb.	Unit	Japan		China		USA		EC8	
			UBDP	LBDP	475 yr	2475 yr	UBDP	LBDP	UBDP	LBDP
Effective mass	M	Ton	3,555		3,022		3,555		3,555	
Initial stiffness	K_1	kN/m	173,084	120,305	137,806		282,417	175,533	184,887	114,643
Post-elastic stiffness	K_2	kN/m	13,314	9,254	10,600		21,724	13,503	14,222	8,819
Yielding load of lead	Q_d	kN	1,411	891	1,092		4,688	2,157	1,575	810
Response disp. of IS	δ_r	m	0.283	$\boxed{0.444}$	0.080	$\boxed{0.268}$	0.310	$\boxed{0.541}$	0.133	$\boxed{0.140}$
Response disp. THA	δ_r	m		0.378		0.194		0.270		0.144
Shear strain		%		278		167		270		88
Equivalent period	T_e	s	2.769	3.531	2.215	2.851	1.952	2.833	2.322	3.101
Eqiv. damping ratio	ξ		0.168	0.111	0.320	0.171	0.246	0.142	0.269	0.238
Spec. reduct. coef.	F_h		0.640	0.793	0.550	0.658	0.628	0.755	0.560	0.589
Resp. at top of sub-structure	V_b	kN	5,179		1,928	3,934	11,424		3,624	
Resp. at bottom superstructure		kN					10,722			
Response mod. coef.	R_I, q						R_I=1.875		q=1	
Design base shear f.	$V_s=V_{st}/R_I$	kN	5,179		1,926	3,934	5,719		3, 624	
Shear coef. of IS	C_{r0}		$\boxed{0.149}$		$\boxed{0.055}$	$\boxed{0.113}$	$\boxed{0.328}$		$\boxed{0.104}$	
Shear coef. of SS	C_{r1}		**0.153**		**0.064**	**0.130**	**0.194**		**0.104**	
Vertical response		g	0.3		-	-	0.3		0.75	
Eccentricity coef.				1.1				1.17		1.012
Safety factor				(+0.2m)		1.2				1.2
Seismic gap		m		**0.688**		**0.322**		**0.633**		**0.170**

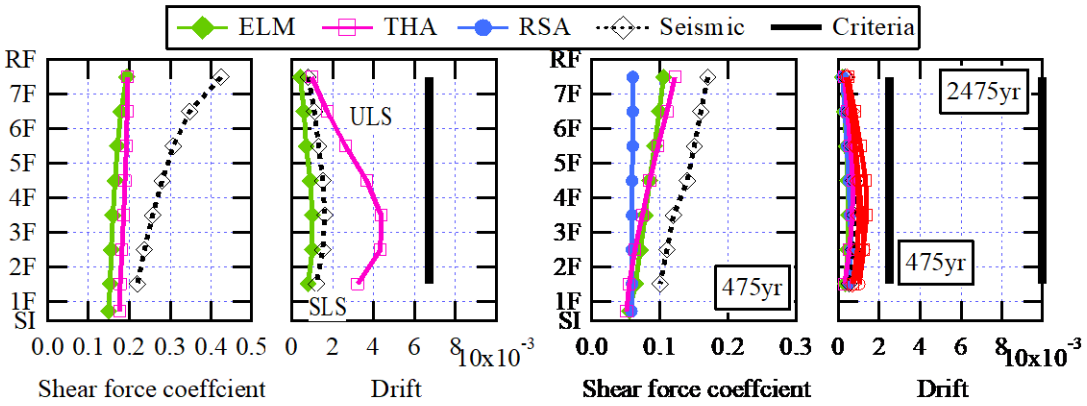
3.3.3 Main findings

In the results of Japanese Code, the drift of the seismic isolation design by ULS was larger than the drift of seismic design by SLS.

In Japan, ELM and THA can be selected independently. In practice, the ratio between ELM and THA is about 20%:80%. In this design case, shear force due to KOBE NS phase (near filed ground motion) were the maximum and larger than ELM. The deformation of isolation system based on ELM was larger.

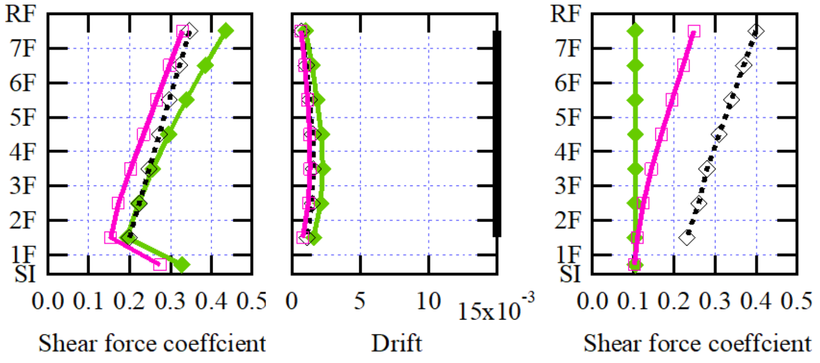
In China, the 475-year seismic load is used to design the super-structure based on RSA. Since the drift of the super-structure due to 2475-year seismic load has to be checked, THA is used together with the spectrum method. The maximum response values between RSA and THA are taken as design load.

In USA, the response results based on THA has a limitation from the ELM. The shear force based on ELM was slightly larger than the seismic design, which is only case in this study. Different response reduction coefficients (R_I=1.875 for SI, R=5 for normal seismic design) were main reason.



(a) Japan

(b) China



(c) USA

(d) EC8

Figure 3 — Response results based on THA compared with ELM, RSA and seismic design

4 Conclusions

Detailed design procedures of seismically isolated buildings were compared to propose a common one based on Japanese, Chinese, USA and EC8 Codes. The seismic load, analysis methods and test methods for seismic isolation devices were summarized first. A 7-story RC building model was used to demonstrate the design procedures. Response results based on the equivalent linear method and response history analysis method were compared.

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