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A COMPARISON STUDY OF STEEL STRUCTURES DESIGN METHOD BASED ON CHINESE AND JAPANESE BUILDING CODES

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Abstract

In both Chinese and Japanese building codes, a two-stage design philosophy, damage limitation (small earthquake) and life safety (extreme large earthquake), is adopted. The two building codes use different design methods to achieve same performance target. Japanese code adopts the allowable stress design method, while Chinese code uses the probabilistic limit state design method.

In this paper, the target buildings are limited to small or moderate height, less than 60m for easy understanding. The design load combinations and material strength are compared first in the small earthquake. Load value and steel material's strength are compared at the condition where the dead load, live load and seismic load are assumed as same. Although the two codes use totally different design method, the ratio between design strength with load value diffs few.

The design formulas to calculated stress of structural members under axial load, shear load, bending moment and the mixes are compared then. The formulas are almost same, except in Chinese code a ductility factor is introduced to give smaller stress. The stability of column is checked separately in Chinese code, while the stability is considered by decreasing the design strength in Japanese code. A column and a beam are selected from a steel moment-resisting frame designed according Japanese code, to demonstrate the design process. The load condition and stress results are checked step by step to be understood clearly.

Keywords: building code, steel structure, material strength, load stress

1. Introduction

The steel structures are more popular than reinforced concrete structures in Japan, whose share is about 40%, over two times of the RC structures, estimated by construction floor area in 2015[1]. However in China, over 90% structures are reinforced concrete, although China is the No.1 country to produce raw steel material. This comparison study of steel structures design method based on Chinese and Japanese building codes hopes to accelerate the development of steel structures in China.

Seismic design method based on Chinese and Japanese building codes are compared first, which have been widely reviewed [2-3]. For easy understanding the target buildings are limited to small or moderate height, less than 60m. Design method, response spectra and drift limits are summarized. In the next comparison section, are compared load combinations of gravity load and seismic load, shear, compression and bending stress calculation formulas of structural members and popular steel materials' strength definitions. In the test design comparison section, column and beam design procedure are demonstrated.

2. Seismic Design Method based on Chinese and Japanese Building Codes

In both Chinese [4] and Japanese [5] building codes, a two-stage design philosophy, damage limitation (small earthquake) and life safety (extreme large earthquake), is adopted. In the damage limitation stage, the structural safety performance should be preserved. In the life safety stage, the building should not collapse to assure the safety of human life. The two building codes use different design methods to achieve same performance target. Japanese code adopts the allowable stress design method, while Chinese code uses the probabilistic limit state design method.

Chinese and Japanese building codes are summarized in Table 1. The target buildings are limited to small or moderate height, less than 60m for easy understanding. The return period of level 1 earthquake load in both Chinese and Japanese code is about 50 years. In Japanese code, the analysis methods are elastic in level 1 and inelastic in level 2, respectively. However, In the Chinese code, the elastic analysis is conducted in level 1 and a specification check is performed in level 2 in most cases. In the following sections, the Chinese and Japanese codes are shown in detail.

Table 1 – Design method and earthquake load corresponding with each building code

	Level	**Japan**	**China**
Design method		allowable stress	probabilistic limit state
Return period (Years)	Level 1	50*	50
	Level 2	500*	1600-2500
Drift limits	Level 1	1/200	1/250
	Level 2	1/75**	1/50
Analysis method	Level 1	elastic	elastic
	Level 2	inelastic	specification

*: estimated; **: engineering practice

2.1 Chinese building code [4]

In the probabilistic limit state design method, both load stress and material strength are determined by considering factors probabilistically as shown in Eq. (1).

$$S=\gamma_G\cdot S_{GE}+\gamma_{Eh}\cdot S_{Ehk}+\gamma_{Ev}\cdot S_{Evk}+\psi_w\cdot\gamma_w\cdot S_{wk}\le R/\gamma_{RE} \quad (1)$$

For simple structure with moderate height less than 40m, the shear force F due to the seismic load can be obtained by lateral seismic load method expressed by Eq. (2). If the height is larger than 40m, response spectrum analysis method has to be used, which is more commonly used in engineering practice. There are four segments in the design response spectrum which are combined functions of the zone factor, the site class and the response reduction factor, shown in Eq. (3), Eq. (4) and Fig. 1. Seismic design category is also stipulated in Chinese code.

$$\begin{aligned} F_{eq} &= \alpha_1 G_{eq} \\ F_i &= \frac{G_i H_i}{\sum_{j=1}^{n} G_j H_j}(1-\delta_n)F_{eq} \end{aligned} \quad (2)$$

Where,

F_{eq}: equivalent seismic load; α_1: acceleration response spectrum at T_1, which is shown in Eq. (3).

G_{eq}: effective weight; F_i: shear force in each floor; H_i: height of each floor.

$$\alpha(g) = \begin{cases} (0.45 + \dfrac{\eta_2 - 0.45}{0.1} T)\alpha_{\max} & T \le 0.1 \\ \eta_2 \alpha_{\max} & 0.1 < T \le T_g \\ (\dfrac{T_g}{T})^{\gamma} \eta_2 \alpha_{\max} & T_g < T \le 5T_g \\ [\eta_2 0.2^{\lambda} - \eta_1 (T - 5T_g)]\alpha_{\max} & 5T_g < T \le 6.0 \end{cases} \quad (3)$$

Where α_{max} is the zone factor defined in Table 2, relating with the macro-seismic intensity 9, 8, 7 and 6. η_1 and γ are the shape coefficients, η_2 is the response reduction factor defined in Eq. (4). T_g is the characteristic period related to the site soil profile, and ζ is the effective damping. There are four site classes which are classified by characteristic period T_g shown in Table 3.

$$\begin{aligned} \gamma &= 0.9 + \frac{0.05 - \zeta}{0.3 + 6\zeta} \\ \eta_1 &= 0.02 + \frac{0.05 - \zeta}{4 + 32\zeta} \qquad \eta_1 \ge 0 \\ \eta_2 &= 1 + \frac{0.05 - \zeta}{0.08 + 1.6\zeta} \qquad \eta_2 \ge 0.55 \end{aligned} \quad (4)$$

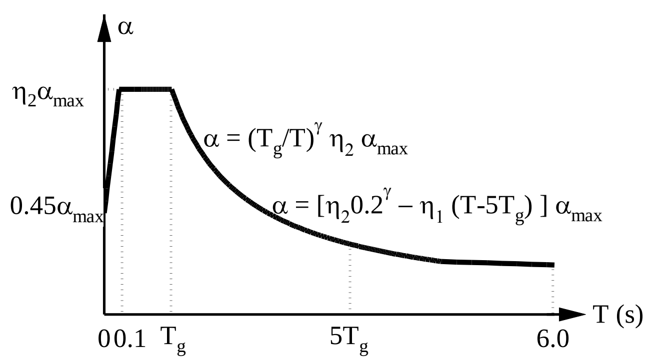


Fig. 1 – Design response spectrum (China)

Table 2 – Zone factor α_{max} based on Seismic Intensity (g)

	Intensity 6	Intensity 7	Intensity 8	Intensity 9
Level 1	0.04	0.08 (0.12)	0.16 (0.24)	0.32
Level 2		0.50 (0.72)	0.90 (1.20)	1.40

( ): regions where the amplitude of design basic acceleration is 0.15g or 0.30g.

Table 3 – Characteristic period T_g related to site class (s)

	Site I	Site II	Site III	Site IV
Zone 1	0.25	0.35	0.45	0.65
Zone 2	0.30	0.40	0.55	0.75
Zone 3	0.35	0.45	0.65	0.90

As pointed by Feng [3], in Chinese code, the spectrum in the constant velocity portion is additionally increased to ensure the safety of structures having long natural periods, such as high-rise buildings or seismically isolated buildings. The response reduction factor η_2 decreases fewer at long natural period, too.

2.2 Japanese building code [5]

In the allowable stress design method, the load stress is directly compared with the material strength to verify the safety condition as shown in Eq. (5)

$$S \le R \tag{5}$$

The shear force due to the seismic load is shown in Eq. (6). The earthquake response factor R_t is shown in Eq. (7) and in Fig. 2. If the building is higher than 60m or using special system, such as seismic isolation technology, the building has to be analyzed by time history analysis method where the response spectrum will be used to generate synthetic ground motions [3]. The analysis method is not compatible for building crossing the 60m height since the response spectrum is different with earthquake response factor R_t. Seismic design category is not stipulated in Japanese code.

$$\begin{aligned} Q_i &= C_i \times \sum W_i \\ C_i &= Z \cdot R_t \cdot A_i \cdot C_0 \\ T &= h(0.02 + 0.01\alpha) \\ A_i &= 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i\right) \times \frac{2T}{1+3T} \\ \alpha_i &= \frac{\sum W_i}{W} \end{aligned} \tag{6}$$

$$R_t = \begin{cases} 1.0 & T < T_c \\ 1 - 0.2\left(\frac{T}{T_c} - 1\right)^2 & T_c \le T \le 2T_c \\ 1.6\frac{T_c}{T} & 2T_c < T \end{cases} \tag{7}$$

Where,

Q_i: shear force in each floor.
Z: zoning factor, 0.7-1.0. At nearly all highly populated areas Z=1.0.
R_t: earthquake response factor shown in Eq. (7).
A_i: the shear force distribution factor over the height.
C_0: 0.2 in level 1; 1.0 in level 2.
h: total height in meters.
T_c: corner period. 0.4s for firm, 0.6s for soft, 0.8s for very soft soil.

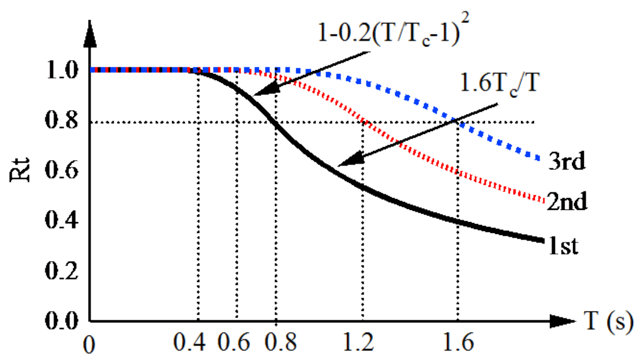


Fig. 2 – Earthquake response factor R_t (Japan)

2.3 Comparison of response acceleration

The 5% acceleration response spectrum in Chinese code is compared with the base shear coefficient $C_1= R_t*C_0$ in Japanese code, both at site class II, shown in Fig.3. Intensity 8 (0.30g), T_g=0.40s parameters were used in Chinese code. If the building height is limited to less than 60m, the period will be small than 1.8 sec. (=0.03*60) in Japanese code. The response acceleration in Chinese code was larger before 0.5 second, but become significantly smaller over 0.5 second.

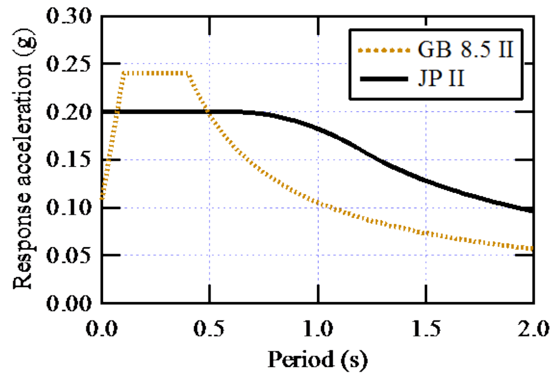


Fig. 3 – The 5% acceleration response spectrum in Chinese code compared with the base shear coefficient $C_1= R_t*C_0$ in Japanese code

3. Load Combinations, Design Formulas and Steel Material's Strength Comparison Study

The load combinations of gravity load and seismic load are compared first shown in Table 4. The load factors in Japanese code are very simple, while there are dozens cases in Chinese code. The typical combinations are shown in Table 4. In both load combinations, the load value in Chinese code is much larger than that in Japanese code.

Table 4 – Load factors in Chinese and Japanese codes

	China	Japan
Gravity load combinations	$1.35D+0.7\text{x}1.4L$ $1.2D+1.4L$ … maximum value	$D+L$
Seismic load combinations	$1.2(D+\gamma_{EG}L)+1.3S_{Ehk}$	$D+L+E$

D: dead load; L: live load; S_{Ehk},E: seismic load

Formulas to calculate response stress of structural members in Chinese [6] and Japanese [7] codes are shown in Table 5, which are almost same. There is a plastic progress coefficient γ stipulated in Chinese code to give smaller stress. For the calculation of shear stress, Japanese code uses a simplified formulation in engineering practice to obtain maximum response value easily. The stability of a column is checked separately in Chinese code, while the stability is considered by decreasing the design strength σ_c in Japanese code.

Then, the popular materials' strength definition is compared in Table 6(a) for Chinese code, Table 6(b) for Japanese code. The design strength becomes stronger in Chinese 2014 draft [6] than 2003 code, due to the good quality of the steel material. In both codes, design shear strength is taken as $1/\sqrt{3}$ of the design tensile strength.

But even the yield strength of the material is same, the design strength is different in two codes. For example, for a steel plate with thickness of 45mm in Chinese code, material Q345, and 35mm in Japanese code, material SN490, the yield strength is 325 N/mm^2 in both codes. But the design strength in Chinese code is 290

N/mm^2 and 216.6 N/mm^2 in Japanese code, respectively. The design strength somehow corresponds with the load value summarized in Table 4. In the seismic load combinations, the design strength in Chinese code is amplified by $1/\gamma_{re}$ (1/0.75=1.33), while amplified by 1.5 in Japanese code.

Table 5(a) – Stress calculation of structural members in Chinese and Japanese codes

	China	Japan
Bending	$\frac{M}{\gamma W} \le f$	$\frac{M}{Z} \le f_b$
Shear	$\tau = \frac{V \cdot S}{I \cdot t_w} \le f_v$	$\tau = \frac{Q}{h \cdot t_w} \le f_s$
Axial, bending	$\frac{N}{A_n} \pm \frac{M_x}{\gamma_x W_{nx}} \pm \frac{M_y}{\gamma_x W_{ny}} \le f$	$\frac{\sigma_c}{f_c} + \frac{{}_c\sigma_b}{f_b} \le 1$ $\frac{{}_t\sigma_b - \sigma_c}{f_t} \le 1$
Combination of shear and bending	$\sqrt{\sigma^2 + \sigma_c{}^2 - \sigma\sigma_c + 3\tau^2} \le \beta_1 f$	$\sqrt{\sigma^2 + 3\tau^2} \le f_b$

Table 5(b) – Stability check of compression members in Chinese and Japanese codes

	China	Japan
Stability	In-plane $\frac{N}{\varphi_x A} + \frac{\beta_{mx} M_x}{\gamma_x W_{1x}\left(1 - 0.8\frac{N}{N'_{Ex}}\right)} \le f$ Out-plane $\frac{N}{\varphi_y A} + \eta \frac{\beta_{tx} M_x}{\varphi_b W_{1x}} \le f$	$f_c = \frac{\left\{1 - 0.4\left(\frac{\lambda}{\Lambda}\right)^2\right\} F}{\nu}, \lambda \le \Lambda$ $f_c = \frac{0.277F}{\left(\frac{\lambda}{\Lambda}\right)^2}, \lambda > \Lambda$

Table 6(a) – Popular steels' strength definition in Chinese code [6]

Name	Thickness (mm)	Yield strength (f_y) N/mm^2	Gravity load combinations		Seismic load combinations	
			Tension, compression, bending (f)	Shear (f_v)	Tension, compression, bending	Shear
Q235	～16	235	215	125	f/γ_{re} γ_{re}=0.75	f_v/γ_{re} γ_{re}=0.75
	16～40	225	205	120		
	40～100	215	200	115		
Q345	～16	345	300	175		
	16～40	335	295	170		
	40～63	325	290	165		
	63～80	315	280	160		

Table 6(b) – Popular steels' strength definition in Japanese code [7]

Name	Thickness (mm)	Yield strength (F) N/mm^2	Gravity load combinations		Seismic load combinations	
			Tension, compression, bending (f_b)	shear (f_v)	Tension, compression, bending (f_b)	shear (f_v)
SS400 SM400 SN400	～40	235	F/1.5 (=156.6)	F/1.5/√3 (=90.4)	F	F/√3 (=135.6)
	40～100	215	F/1.5 (=143.3)	F/1.5/√3 (=82.7)	F	F/√3 (=124.1)
SM490 SN490	～40	325	F/1.5 (=216.6)	F/1.5/√3 (=125.0)	F	F/√3 (=187.6)
	40～100	295	F/1.5 (=196.6)	F/1.5/√3 (=82.7)	F	F/√3 (=124.1)

We use same load values (dead, live seismic) to compare the difference of load values at the load combinations shown in Table 7. We selected a steel plate with thickness of 45mm in Chinese code, material Q345, and 35mm in Japanese code, material SN490. The yield strength is 325 N/mm^2 in both codes. In the gravity load combinations condition, the ratio between China and Japan was about 1.26 but the material's design strength was about 1.34. Japanese code may require slightly larger member section at such condition. However, in the seismic load combinations condition, the situation became reverse.

Table 7 **–** Comparison of load value and material's design strength

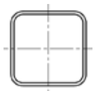
Load \ Material's strength		China Q345*	Japan SN490	China/Japan
Gravity load combinations	Load	1.2 D + 1.4 L 1.35 D + 0.98 L	D+L	1.26
	f (N/mm^2)	290	217	1.34
	f_v (N/mm^2)	165	125	
Seismic load combinations	Load	1.2(D+0.5 L)±1.3E	D+L+E	1.27
	f (N/mm^2)	387=290/0.75	325	1.19
	f_v (N/mm^2)	220=165/0.75	187	

D=127.1, L=51.9, E=1662
Q345*: values of thickness > 40 used just for comparison

4. Test Design Comparison

We designed a six story steel moment-resisting frame structure based on Japanese code. The 1st natural period was 0.769 sec. We picked up a column and a main beam in 3rd story for comparison study. The column, expressed by □-700x700x28, with height of 3.7m was designed as coldly press-formed rectangular steel column, whose material was BCP325 (=SN490). The beam, expressed by H-900x300x16x28, with span of 8.5m was designed as H-shape beam, whose material was SN490B. These materials corresponded with Q345 in Chinese code. The design strength followed both codes strictly based on the plate thickness. The size, shape and load values (dead, live, seismic) were assumed as same, summarized in Table 8. The seismic load at X direction only was compared. From Fig.3, it can be seen, at the period of 0.769s, the seismic load in Japanese code was 1.48 times of that in Chinese code. The test design case may be very rare case in Chinese code.

Table 8 – Column and beam size and load values designed based on Japanese code

	Size	Shape	Load values			
				D	L	E_x
Column	☐-700 x700x28 H=3.7m		Mx (kN m)	13.5	5.5	1708
			My (kN m)	88.0	36.0	
			N (kN)	3445.6	1407.4	108
			Qx (kN)	6.4	2.6	1120
Beam	H-900x300 x16x28 Span: 8.5m		M (kN m)	127.1	51.9	1662
			Q (kN)	76.7	31.3	426

Characteristics of the column and the beam are shown in Table 9, which can be found in a handbook easily. In Japanese engineering practice, to design the beam, the bending moment is considered to be borne by the flange plats, and the shear force borne by the web plate. Same parameters were used to calculate member's stress values in both codes.

Table 9 – Characteristics of the column and the beam

	Size	A	A_w	Z	i	I	S
		cm^2	cm^2	cm^3	cm	cm^4	cm^3
Column	☐-700 x700x28	712.3	356.1	14800	27	518000	9490
Beam	H-900x300 x16x28		*135.0***	*7099**		399600	5080

A: cross-sectional area; A_w: shear area; Z: section modulus;
i: radius of gyration; I: second moments of area; S: first moment of area
*: only the flange plates; **: only the web plate

Table 10 – Stress checks according Japanese code

Load combinations / Members		Gravity load			Seismic load		
		Load	Axial, bending	Shear (τ)	Load	Axial, bending	Shear (τ)
(f_b =216.6, f_s=125)			*1.0*	*125*		*1.0*	*187*
Column	Mx (kN m)	19.0	0.37		1727.0	0.61	
	My (kN m)	124.0			124.0		
	N (kN)	4853.0			4961.0		
	Qx (kN)	9.0		0.25	1129.0		31.7
Beam	M (kN m)	179.0	0.12		1841.0	0.80	
	Q (kN)	108.0		8.0	534.0		39.5

Stress check results according Japanese code shown in Table 5, are summarized in Table 10. The design strength of column was decreased from f_b=216.6 to f_c=208 N/mm^2, by considering the stability property (λ=22) (table 5(b))

Stress check results according Chinese code shown in Table 5, are summarized in Table 11. (1.2D+1.4L) combination gave larger values. The design strength values of column and beam are different due to the thickness according Chinese code. To check the shear stress of the beam, design strength with thickness equal to 16mm, f_v=175 N/mm^2, was used.

The load values of seismic load combination case were larger in all cases. The safety margin values (σ/f) are compared in Table 12. The bending moment gave most severe result in both codes. Comparing with the results shown in Table 7, the two safety margin values were miraculously same.

Table 11 – Stress checks according Chinese code

Members \ Load combinations		Gravity load			Seismic load		
		Load	Axial, bending (σ)	Shear (τ)	Load	Axial, bending (σ)	Shear (τ)
Column	(f, f_v)		*295*	*170*		*393.3*	*226.7*
	Mx (kN m)	23.9	97.29		2239.9	224.20	
	My (kN m)	156.0			127.2		
	N (kN)	6105.1			5119.6		
	Qx (kN)	11.3		0.37	1465.2		47.94
Beam	f_v for Q			*175*			*233.3*
	M (kN m)	225.2	30.2		2344.3	314.5	
	Q (kN)	135.9		10.8	664.6		52.8

Table 12 – The safety margins comparison for both codes

Country \ Load combinations		Gravity load		Seismic load	
		Axial, bending (σ/f)	Shear (τ/f$_s$)	Axial, bending (σ/f)	Shear (τ/f$_s$)
China	Column	0.33	0.002	0.57	0.211
	Beam	0.10	0.062	0.80	0.226
Japan	Column	0.37	0.002	0.61	0.170
	Beam	0.12	0.064	0.80	0.211

5. Conclusions

Seismic design method based on Chinese and Japanese building codes were compared first. The target buildings are limited to small or moderate height, less than 60m for easy understanding. The two building codes use different design methods to achieve same performance target. Japanese code adopts the allowable stress design method, while Chinese code uses the probabilistic limit state design method.

The design load combinations and material strength were compared then. Although the two codes use totally different design method, the ratio between design strength with load value diffs few.

In the test design comparison section, design procedures of a column and a beam were demonstrated using same load values and same member sections to give a clear understanding. The safety margin values (σ/f) of the beam due to bending moment, which were most severe case, were miraculously same.

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