# Comparison of Strength Capacity for Steel Building Structures in the United States and Japan

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#### ABSTRACT

This paper presents a study on U.S. and Japanese seismic design provisions stipulated for steel moment resisting and braced frames. Width-to-thickness requirements, structural classification, seismic force reduction coefficients, and design seismic forces are compared, and differences and similarities are discussed. Unreduced seismic forces are relatively similar between the two countries, but significant differences are present for the seismic force reduction coefficients that allow for system ductility. Expected strength capacity of braced frames is estimated in consideration of seismic force reduction coefficients, strength carried by braces relative to frames, and buckling and post-buckling strengths of braces. Design force requirements are significantly larger for Japanese braced frames than for the corresponding U.S. braced frames, when the frames are arranged with braces of medium lengths.

#### INTRODUCTION

Low- to medium-rise steel buildings suffered much damage, including collapse, in the 1995 Hyogoken-Nanbu (Kobe) earthquake. Most of those buildings were unbraced steel moment frames. Although braces are known to be effective in providing building frames with both strength and stiffness, use of braces has been very limited, particularly in newer construction. There are two primary reasons for this trend. Current architectural requirements place high value on large open spaces, and braces often become obstructions. Second, braced frames are designed for significantly large seismic forces relative to moment resisting frames in Japan primarily due to consideration of deterioration of resistance of buckled braces. In view of the damage revealed in the Kobe earthquake, however, it is felt that braces would have reduced damage to severely damaged unbraced frames.

The ultimate goal of the presented study is to reevaluate the strength and ductility capacity of braced frames, examine the earthquake response behavior of braced frames involving brace buckling, and propose rational design alternatives for braced frames that are safer but more economical. As the first step toward this goal, the U.S. and Japanese seismic design provisions related to steel frames are surveyed, and similarities and differences in these provisions are discussed. The differences of the practice in the steel works were discussed elsewhere [1]. Focus is given to the difference in strength expected from braced frames built in the two countries. Design codes used include the 1997 UBC [2], 1997 AISC seismic provisions [3], 1993 AISC-LRFD specification [4], 1981 BCJ (Building Center of Japan) code [5], 1973 AIJ (Architectural Institute of Japan) design standard [6], and 1998 AIJ limit state design code [7]. In the BCJ code [5], Enforcement Orders of Building Standard Law and Notifications of the Ministry of Land, Infrastructures, and Transportation are collected and published as a handbook.

# SEISMIC FORCES AND EXPECTED DUCTILITY

This paper utilizes the 1997 UBC seismic design forces in the following design comparisons, because this specification is still most commonly used in seismic design. However, U.S. seismic design practice is evolving toward the International Building Code (IBC) [8]. This evolution results in little change in design details but fairly significant changes in the seismic force calculations. The IBC method employs much more complex seismic risk mapping, but it eliminates some of the seismic force adjustments such as the near fault factor used in the UBC method. The net effect of the IBC method may lead to larger seismic design forces for some regions of the U.S. However, the IBC provisions are not widely used to date, and comparison between the IBC provisions and Japanese specifications are less tractable. The seismic design forces obtained with the UBC are still similar to those obtained with the 2000 IBC for most parts of the U.S., and the 1997 UBC is used for comparison in this paper.

In the United States, UBC stipulates the total design base shear (V) by the following formulas:

$$V = \frac{K_t I}{R} W \tag{1}$$

$$K_t = \frac{C_v}{T} \tag{2}$$

where  $C_v$  is the seismic coefficient, *I* is the importance factor, *W* is the total seismic dead load, *R* is a numerical coefficient representative of the inherent overstrength and global ductility capacity of lateral-force-resisting systems, and *T* is the elastic fundamental period of vibration (in seconds). The following upper and lower limits are stipulated for  $K_t$ :

$$K_t \le 2.5 C_a \tag{3a}$$

$$K_t \ge 0.11 \, C_a \, R \tag{3b}$$

In seismic zone 4 such as in California, another lower limit is stipulated as:

$$K_t \ge 0.8 \ ^U Z \ N_v \tag{3c}$$

where  $C_a$  is the seismic coefficient that is stipulated by soil type, seismic zone, and a nearsource factor  $(N_a)$ , <sup>U</sup>Z is the seismic zone factor, and  $N_v$  is the other near-source factor. The total force shall be distributed over the height of the structure in conformance with the following formulas:

$$F_{i} = \frac{(V - F_{i}) w_{i} h_{i}}{\sum_{j=1}^{m} w_{j} h_{j}}$$
(4a)

$$F_t = 0.07 T V$$
 (4b)

where *m* is total number of stories above the base,  $F_t$  is the portion of the base shear, *V*, applied at the top of the structure in addition to  $F_m$ ,  $F_i$  is the design seismic force applied to level *i*, and  $h_i$  is the height above the base to level *i*.

In Japan, BCJ stipulates two levels of design forces. The stress that occurs anywhere in the structure by Level 1 seismic force shall be less than the allowable stress stipulated for the short duration loading. Furthermore, the horizontal strength of the structure calculated by the plastic analysis shall be greater than Level 2 seismic force. Level 1 seismic force is stipulated by the following formulas:

$${}_1Q_i = {}_1C_i \sum_{j=i}^m w_j \tag{5a}$$

$${}_{1}C_{i} = {}^{J}Z R_{t} A_{i-1}C_{0}$$
(5b)

where  ${}_{1}Q_{i}$  is the Level 1 story shear at story i,  ${}_{1}C_{i}$  is the Level 1 story shear coefficient at story i,  $w_{j}$  is the seismic dead load at story level j,  ${}^{J}Z$  is the seismic zone factor,  $R_{t}$  is the vibration characteristic coefficient,  $A_{i}$  is the distribution factor of  $C_{i}$  along the height, and  ${}_{1}C_{0}$  is the standard shear coefficient for Level 1 seismic force, set at 0.2.  $R_{t}$  and  $A_{i}$  are given by the following formulas:

$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i\right) \frac{2T}{1+3T}$$
(6a)

$$\alpha_i = \sum_{j=i}^m \frac{w_j}{W} \tag{6b}$$

• for 
$$T < T_c$$
  
 $R_t = 1$  (7a)

• for 
$$T_c < T < 2 T_c$$
  
 $R_i = 1 - 0.2 \left(\frac{T}{T_c} - 1\right)^2$ 
(7b)

• for 2 
$$T_c < T$$
  

$$R_t = \frac{1.6 T_c}{T}$$
(7c)

where  $T_c$  is determined according to the soil profile type. The value of  $T_c$  is 0.4, 0.6, and 0.8 for Type I, II, and III soil, respectively. The Level 2 seismic force is stipulated by the following formulas:

$${}_{i}Q_{un} = {}_{i}D_{s} {}_{i}F_{es} {}_{2}Q_{i}$$
(8a)

$${}_2Q_i = {}_2C_i \sum_{j=i}^m w_j \tag{8b}$$

$${}_2C_i = {}^JZ R_t A_i {}_2C_0 \tag{8c}$$

where  ${}_{i}Q_{un}$  is the required strength at story *i*,  ${}_{i}D_{s}$  is the structural characteristic factor (seismic force reduction coefficient) at story *i*,  ${}_{i}F_{es}$  is the shape factor at story *i* according to the distribution of the

story stiffness and eccentricity of the plan,  $_2C_i$  is the Level 2 story shear coefficient at story *i*, and  $_2C_0$  is the standard shear coefficient for the Level 2 seismic force, set at 1.0.

Figure 1 shows comparisons of unreduced base shear spectra, namely  $K_t$  in the U.S. and  $R_t$  in Japan. The abscissa is the natural period of the building. The UBC uses near source factors,  $N_v$  and  $N_a$ , to increase seismic design forces for buildings located near active faults in regions of high seismic activity. Without the near-source factors in UBC, the UBC  $S_E$  spectrum and BCJ Type II spectrum (for medium soil, applicable to most coastal regions) are very similar, with the two spectra nearly identical for natural periods not smaller than 1.0 sec. When near-source factors are included, the UBC spectra are significantly larger as shown in Fig. 1(b).

Figure 2 shows the distribution of required story resistance along the height of a ten-story building with uniform mass distribution. Figures 2(a) to 2(c) have natural periods of 0.5, 1.5, and 3.0 sec, respectively. The ordinate is the story number, and the abscissa is the required story resistance divided by the base shear. UBC equation (4) and BCJ equations (6) which stipulate the distribution of design seismic forces along the height look very different, but the



Fig. 1 Unreduced response spectra



Fig. 2 Required story resistance of ten story building with uniform mass distribution

resultant distribution of design story shear forces are nearly identical as shown in Fig. 2.

Figure 3 shows various width-to-thickness requirements stipulated for wide flange crosssections. The ordinate is the normalized widthto-thickness ratio calculated by assuming Young's modulus (*E*) as 29,000ksi in AISC and 2,100tf/cm<sup>2</sup> in BCJ (205,000MPa). The symbols *b*, *d*,  $t_{f5}$ ,  $t_{w}$ , and *F* are the half width of the flange, inner depth of the web, thickness of the flange, thickness of the web, and the yield stress, respectively.  $\Sigma M_{pc}^*$  in the figure is the sum of the column plastic moments at the column-to-beam connection,  $\Sigma M_{pb}^*$  is the sum of the beam plastic moments, and  $n_c$  is the ratio of the axial force of the column to the axial strength defined by

$$n_c = \frac{P_u}{\phi_b \ N_y} \tag{9}$$

where  $P_u$  is required column strength,  $N_y$  is yield axial strength, and  $\phi_b$  is the resistance factor for bending (= 0.90). Limits of width-to-thickness ratios specified for most ductile frames (SMF in AISC and FA frames in BCJ) are very similar for beam and column flanges. The BCJ requirements are somewhat more stringent for beam and column webs.

Figure 4 shows the limits for brace slenderness of AISC and BCJ. The ordinate is the normalized slenderness defined by

$$\overline{\lambda} = \frac{K l}{i \pi} \sqrt{\frac{F}{E}}$$
(10)

where l is length of the brace, i is radius of gyration of the brace, and K is the effective length factor of the brace. In BCJ, braces are classified into three categories in accordance with the slenderness (BA, BB, and BC), and different seismic force reduction factors are applied to braced frames falling into respective brace categories. In AISC, braced frames are classified into two categories in





Fig. 3 Width-to-thickness requirements for flanges and webs of wide flange crosssections

(c) Column Flange



Fig. 4 Slenderness requirements for braces

accordance with the width-to-thickness ratio of braces, the spacing of stitches, and the details of brace-end connections (SCBF and OCBF). As these parameters ensure stable ductile behavior in SCBF, a more relaxed limit is stipulated for brace slenderness in SCBF than in OCBF. The seismic force reduction factor is expressed in BCJ using a term  $D_s$ , which is the inverse of the UBC's *R*. The values of *R* stipulated in UBC are summarized as follows.

- Moment Resisting Frame OMRF: *R* = 4.5, SMRF: *R* = 8.5
- Dual System Combination of OMRF and OCBF: *R* = 4.2 Combination of OMRF and SCBF: *R* = 4.2 Combination of SMRF and OCBF: *R* = 6.5 Combination of SMRF and SCBF: *R* = 7.5
- Building Frame System OCBF: R = 5.6, SCBF: R = 6.4

In BCJ,  $D_s$  is stipulated in accordance with the frame classification, brace classification, and  $\beta$ , defined as the ratio of brace resistance to total (frames and braces) resistance (Table 1). Figure 5 shows comparisons between  $D_s$  and 1/R with respect to  $\beta$ .  $\beta = 0$  corresponds to the moment resisting frame without braces, and  $\beta = 1$  to the braced frame in which all horizontal forces are carried by braces (Building Frame System in UBC). For the Dual System, UBC stipulates that moment resisting frames shall be designed to independently resist at least 25 percent of the design base shear. As this means that the upper limit of  $\beta$  be 1 / (1 + 0.25) = 0.8, 1/R for Dual System is plotted at  $\beta = 0.8$ .

When the most ductile UBC SMRF and BCJ FA frames are compared, the ratio of the seismic

force reduction factors is about 1 to 2. Considering that the unreduced base shear spectra are relatively similar in UBC and BCJ when near-source factors are not included, we may judge that Japanese ductile frames are twice as strong as U.S. ductile frames. This judgment, however, is misleading because of the following reasons. In UBC, elastic analysis is performed (with no force redistribution allowed) with respect to the reduced seismic force, and the estimated member forces are checked against member strengths. In BCJ, plastic analysis (with force redistribution by member plastification permitted) can be applied, and the reduced seismic force is compared with the frame ultimate strength.

# LIMIT OF STORY DRIFT

In UBC, the story drift angle  $\Delta_s$  calculated elastically with respect to the seismic forces [Eqs. (1) ~ (4)] shall conform to the following limit:

$$0.7 R \Delta_s \le \Delta_l \tag{11}$$

where  $\Delta_l$  is 0.025rad for T < 0.7sec, and 0.02rad for T > 0.7sec.

In BCJ, the story drift angle  $\Delta_s$  calculated elastically with respect to Level 1 seismic forces [Eqs. (5) ~ (7)] shall conform to the following limit:

prace classification BA or		BB			BC		
frame classification	$\beta = 0$	$\beta \le 0.3$	$0.3 < \beta \leq 0.7$	$\beta > 0.7$	$\beta \le 0.3$	$0.3 < \beta \le 0.5$	$\beta > 0.5$
FA	0.25	0.25	0.3	0.35	0.3	0.35	0.4
FB	0.3	0.3	0.3	0.35	0.3	0.35	0.4
FC	0.35	0.35	0.35	0.4	0.35	0.4	0.45
FD	0.4	0.4	0.45	0.5	0.4	0.45	0.5
$\begin{array}{c} 0.8 \\ \hline D_{\rm S}, 1/R \\ 0.6 \\ \hline FD \\ \hline FA \\ 0.2 \\ \hline L_{\rm Level 1} \\ 0 \\ 0.2 \\ 0 \\ \hline 0.2 \\ 0 \\ 0.2 \\ 0 \\ 0.3 \\ 0 \\ 0.3 \\ 0 \\ 0.3 \\ 0 \\ 0.3 \\ 0 \\ 0.3 \\ 0 \\ 0 \\ 0.3 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ $		$\begin{array}{c cccc} 0.8 & D_{g}, 1/R & BC, OCBF \\ 0.6 & & FD \\ 0.4 & & FA \\ 0.2 & OMRF & OH \\ 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\ 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\ 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\ 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\ 0.2 & 0.4 & 0.6 & 0.8 & 1.0 \\ 0.3 & 0.6 & 0.8 & 1.0 \\ 0.4 & 0.6 & 0.8 & 1.0 \\ 0.5 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 1.0 \\ 0.6 & 0.6 & 0.8 & 0.8 \\ 0.6 & 0.6 & 0.8 & 0.8 \\ 0.6 & 0.6 & 0.8 & 0.8 \\ 0.6 & 0.6 & 0.8 & 0.8 \\ 0.6 & 0.6 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.8 & 0.8 & 0.8 & 0.8 & 0.8 \\ 0.8 & 0.8 & 0.8 & 0.8 \\ 0.8 & 0.8 & 0.8 & 0.8 & 0.8 $					

Table 1 Structural characteristics factor  $(D_s)$  in BCJ

Fig. 5 Seismic force reduction factors for unbraced and braced frames

$$\Delta_s \le 1/200 \text{rad} \tag{12}$$

Equations (11) and (12) are compared in Fig. 6. In UBC, the story drift limit varies according to the frame ductility, while it is consistent regardless of the frame ductility in BCJ.



Fig. 6 Limit of story drifts

# STRENGTH OF MOMENT RESISTING FRAMES

Design of moment resisting frames is commonly governed by drift requirements. In UBC, the story drift angle  $\Delta_s$  caused by the seismic force [Eqs. (1) ~ (3)], shall be limited by Eq. (11). In BCJ,  $\Delta_s$  caused by Level 1 seismic force [Eqs. (5) ~ (7)] shall be less than 1/200rad. Therefore, the ratio of the story stiffness designed by UBC (<sup>U</sup>K) relative to that by BCJ (<sup>J</sup>K) is expressed as follows:

$$\frac{{}^{U}K}{{}^{J}K} = \frac{0.7 K_{t} I}{200 \Delta_{t} {}^{J}Z R_{t-1}C_{0}}$$
(13)

The story stiffness of moment resisting frames is proportional to the geometrical moment of inertia of members. The story strength is proportional to the plastic section modulus of members. If the shape of members is assumed to be similar, the geometrical moment of inertia is proportional to the fourth power of the member size, whereas the plastic section modulus is proportional to the third power of the member size. Therefore, the ratio of story strength required for the UBC frames  $({}^{U}Q)$  to the strength required for the Japanese frames  $({}^{J}Q)$  may be obtained as follows:

$$\frac{{}^{U}Q}{{}^{J}Q} = \left(\frac{0.7 K_{t} I}{200 \Delta_{t} {}^{J}Z R_{t-1}C_{0}}\right)^{3/4}$$
(14)

Here, short period frames (T < 0.58 sec for Soil  $S_D$  in UBC, and T < 0.60 sec for Type II in BCJ) are considered, with  ${}^JZ = I = 1.0$ . Substituting these values and  $K_t = 2.5 \cdot 0.44 \cdot N_a$  to the above equation leads us to the following equation:

$$\frac{{}^{U}Q}{{}^{J}Q} = \left(\frac{0.7 \cdot 2.5 \cdot 0.44 N_{a}}{200 \cdot 0.025 \cdot 0.2}\right)^{3/4}$$
(15)

The above equation shows that  ${}^{U}Q / {}^{J}Q = 0.82$ when  $N_a = 1.0$ , and  ${}^{U}Q / {}^{J}Q = 1.11$  when  $N_a = 1.5$ . The UBC strength for the moment resisting frame is estimated to be smaller by about 20% (without near-source factors) and larger by about 10% (with near-source factors), respectively, than the corresponding BCJ strength.

## STRENGTH OF BRACED FRAMES

In the U.S., the resistance factored compressive strength  $({}^{U}N_{cr})$  is stipulated in LRFD as follows:

• for 
$$\overline{\lambda} \le 1.5$$
  
 ${}^U N_{cr} = \phi_c \ 0.658^{\overline{\lambda}^2} N_y$  (16a)

for 
$$\overline{\lambda} > 1.5$$
  
 ${}^{U}N_{cr} = \phi_c \, \frac{0.877}{\overline{\lambda}^2} N_y$  (16b)

where  $\phi_c$  is the resistance factor for compression (= 0.85). In Japan, two strength equations, one (allowable strength) for BCJ Level 1 and the other (ultimate strength including the effect of buckling) for BCJ Level 2. The following allowable compressive strength ( $^JN_{cr}$ ) is stipulated for Level 1 in the AIJ's design standard:

$$P \text{ for } \overline{\lambda} \le 1 / \sqrt{0.6}$$

$$^{J}N_{cr} = \frac{1.5 (1 - 0.24 \overline{\lambda}^{2})}{\frac{3}{2} + \frac{2}{3} 0.6 \overline{\lambda}^{2}} N_{y}$$
(17a)

• for 
$$\overline{\lambda} > 1 / \sqrt{0.6}$$
  
 ${}^{J}N_{cr} = \frac{1.5 \cdot 0.277}{0.6 \,\overline{\lambda}^{\,2}} N_{y}$  (17b)

For Level 2, the following post-buckling strength  $({}^{J}N_{u})$  is stipulated in the AIJ's limit state design code.

• for 
$$\overline{\lambda} \le 0.15$$
  
 ${}^{J}N_{u} = N_{y}$  (18a)

• for 
$$0.15 < \overline{\lambda} \le 0.3$$
  
$${}^{J}N_{u} = \frac{1}{11\,\overline{\lambda} - 0.65}N_{y}$$
(18b)

for 
$$\overline{\lambda} > 0.3$$
  
 ${}^{J}N_{u} = \frac{1}{6\,\overline{\lambda} + 0.85}N_{y}$  (18c)

In Fig. 7, the three strength equations  $({}^{U}N_{cr}, {}^{J}N_{cr}, {}^{J}N_{u})$  stipulated by LRFD, AIJ's allowable design, and AIJ's limit state design are drawn with respect to the normalized slenderness ratio  $\overline{\lambda}$ .



Fig. 7 Buckling and post-buckling strength

Considered first is the case in which earthquake forces are carried by the braces only, with the braces arranged in pairs. At the instant when the brace compressive force reaches the LRFD factored compressive strength  ${}^{U}N_{cr}$ , the story shear resisted by the braces is:

$${}^{J}_{3}Q_{cr} = 2n \, {}^{U}N_c \cos\theta \tag{19}$$

In which  $\theta$  is the angle between the brace and beam longitudinal axes; and *n* is the number of brace pair for the concerned story. Similarly, when the brace compressive force reaches the AIJ's allowable strength  ${}^{J}N_{cr}$ , the story shear resisted by the braces is:

$${}^{J}_{B}Q_{cr} = 2n \; {}^{J}N_{er}\cos\theta \tag{20}$$

Here, introduced is a factor,  $k_1$ , defined by:

$$k_1 = \frac{{}_B^J Q_{cr}}{{}_B^U Q_{cr}} = \frac{{}_N^J N_{cr}}{{}_U^U N_{cr}}$$
(21)

Substituting Eqs. (19) and (20) into Eq. (21), we obtain the relationship shown in Fig. 8. This factor,  $k_1$ , indicates the strength estimated by AIJ's allowable design (for Level 1) relative to that estimated by UBC. Figure 8 shows that  $k_1$  is around unity, suggesting that the two strengths are similar.

The story shear  $\binom{J}{B}Q_u$  carried by all the braces at the instant when the brace compressive force reaches the AIJ's post-buckling strength (corresponding to Level 2) is estimated by the following equation. Note that the braces in tension are assumed to yield at the instant.

$${}^{J}_{B}Q_{u} = n\left(N_{y} + {}^{J}N_{u}\right)\cos\theta$$
(22)

Here, another factor,  $k_2$ , is introduced and defined as:

$$k_{2} = \frac{{}_{B}^{J}Q_{u}}{{}_{B}^{U}Q_{cr}} = \frac{N_{y} + {}^{J}N_{u}}{{}^{U}N_{cr}}$$
(23)

This factor indicates the ratio of the strength estimated for Level 2 relative to the strength estimated by UBC. Figure 9 shows the  $k_2$  values, given by inserting Eqs. (16) and (18) into (23). This figure shows that  $k_2$  is greater than unity for larger slenderness. This is because, in the calculation of  ${}_{B}{}^{J}Q_{u}$ , half of the braces (those subjected to tension) are assumed to carry the tensile (yield) strength, whereas in the calculation of  ${}_{B}{}^{U}Q_{cr}$ , all the braces resist the buckling strength.



Fig. 8 Ratio of AIJ to LRFD buckling load



Fig. 9 Ratio of horizontal resistance in postbuckling stage to buckling stage for rairs of compressive and tensile braces

The UBC requires the following strength (in terms of the base shear:  ${}^{U}Q_{D}$ ):

$${}^{U}\mathcal{Q}_{D} = \frac{K_{t} I \rho}{R} W \tag{24}$$

In which  $\rho$  is a factor to allow for structural redundancy, taking a value of 1.0 to 1.5. The BCJ Levels 1 and 2 require the following strengths  $\binom{1}{2}Q_D$  and  $\binom{2}{2}Q_D$ :

$${}^{J}_{1}Q_{D} = {}^{J}Z R_{t} {}_{1}C_{0} W$$
(25a)

$${}_{2}^{J}Q_{D} = {}^{J}Z R_{t} {}_{2}C_{0} D_{s} {}_{1}F_{es} W$$
(25b)

Next, this paper discusses whether UBC or Japanese brace frames require larger strength (more specifically, a larger cross-sectional area)

for the braces. If the design earthquake forces, i.e., the strength demand, stipulated by Eqs. (24) and (25a) or (25b) are identical between UBC and BCJ, the difference in the required brace strength (cross-sectional area) is attributed solely to the difference in the estimate of strength capacity, i.e., Eqs. (21) and (23). On the other hand, if the estimated capacity is identical between UBC and AIJ, the difference in the required brace strength depends on the difference in design earthquake force. Allowing for the two types of differences in combination, we obtain the following relationship (Level 1 and Level 2) for the ratio of the strength required for the UBC braces to the strength required for the Japanese braces:

When BCJ Level 1 controls the design,

$$\frac{{}^{U}Q}{{}^{J}Q} = \frac{{}^{U}Q_{D}}{{}^{J}_{1}Q_{D}} \frac{{}^{J}_{B}Q_{cr}}{{}^{U}_{B}Q_{cr}} = \frac{K_{t} I \rho}{{}^{J}Z R_{t} {}_{1}C_{0} R} k_{1}$$
(26a)

When BCJ Level 2 controls the design,

$$\frac{{}^{U}\mathcal{Q}}{{}^{J}\mathcal{Q}} = \frac{{}^{U}\mathcal{Q}_{D}}{{}^{J}\mathcal{Q}_{D}} \frac{{}^{B}_{B}\mathcal{Q}_{u}}{{}^{U}_{B}\mathcal{Q}_{cr}}$$
$$= \frac{K_{t} I \rho}{{}^{J}Z R_{t} {}_{2}C_{0} D_{s} {}_{1}F_{es} R} k_{2}$$
(26b)

Figure 10 shows the ratios given by Eqs. (26a) and (26b). Here, short frames (T < 0.58sec for Soil  $S_D$  in UBC, and T < 0.60sec for Type II in BCJ) are considered, with R = 6.4,  $K_t = 2.5 \cdot 0.44 \cdot N_a$ , and  $R_t = 1.0$ . In addition, the following values are assumed for other factors.

$${}^{J}Z = {}_{1}F_{es} = I = \rho = 1.0 \tag{27}$$

Figure 10(a) shows the case when the near-source factor  $N_a$  is 1.0, and Fig. 10(b) the case when  $N_a = 1.5$ . The figures show that design of the Japanese frame (resisted only by braces) is governed by Level 1 (allowable design) for long braces ( $\overline{\lambda} > 1.5$ ) and governed by Level 2 (ultimate strength) for medium to short braces ( $\overline{\lambda} < 1.5$ ). The line for Level 2, given by Eq. (26b), is not smooth, because different  $D_s$ 



Fig. 10 Comparison in strength between U.S. and Japanese building frame system

(seismic force reduction coefficient) values are stipulated with respect to the brace slenderness  $\overline{\lambda}$ . When  $N_a = 1.0$ , the strength required for braces is smaller for UBC than for AIJ regardless of the slenderness. This means that UBC requires smaller cross-sections for the braces. When  $N_a = 1.5$ , the UBC strength required for braces is larger for very short braces and for long braces. The ratio,  ${}^UQ / {}^JQ$ , is the smallest for  $\overline{\lambda} = 0.63$ , being 0.36 for  $N_a = 1.0$  and 0.54 for  $N_a = 1.5$ .

#### **STRENGTH OF DUAL FRAMES**

Considered next is the dual system in which both braces and moment frames resist earthquake forces. To this end, a factor,  $\beta$ , is introduced that specifies the ratio of the force resisted by the braces to the total resistance. Let us define  $\beta_{e}$ , the force resisted by the braces to the total resistance in the elastic range. In reference to Eq. (19), the story shear ( ${}^{U}Q_{cr}$ ) at the instant when the braces reach the UBC factored compressive strength  ${}^{U}N_{cr}$  is:

$${}^{U}Q_{cr} = {}^{U}_{B}Q_{cr}/\beta_{e} = 2n \; {}^{U}N_{cr} \cos \theta/\beta_{e}$$
(28)

Similarly, the story shear  $({}^{J}Q_{cr})$  at the instant when the braces reach the AIJ's allowable strength  ${}^{J}N_{cr}$ is:

$${}^{J}Q_{cr} = {}^{J}_{B}Q_{cr}/\beta_{e} = 2n {}^{J}N_{cr}\cos\theta/\beta_{e}$$
(29)

Similar to Eq. (26) (specified for frames that are resisted by braces only), the ratio  $\binom{UQ}{Q} \binom{JQ}{Q}$  of the strength required for the UBC dual system to the strength required for the Japanese dual system (when controlled by Level 1) is given as:

$$\frac{{}^{U}Q}{{}^{J}Q} = \frac{{}^{U}Q_{D}}{{}^{1}Q_{D}} \frac{{}^{J}Q_{cr}}{{}^{U}Q_{cr}} = \frac{{}^{U}Q_{D}}{{}^{1}I_{QD}} \frac{{}^{J}B_{Qcr}/\beta_{e}}{{}^{U}B_{Qcr}/\beta_{e}}$$
$$\frac{{}^{U}Q_{D}}{{}^{1}I_{QD}} \frac{{}^{J}B_{Qcr}/\beta_{e}}{{}^{U}B_{Qcr}/\beta_{e}} = \frac{K_{t} I \rho}{{}^{J}Z R_{t} {}^{1}C_{0} R} k_{1}$$
(30)

Note that the factor  $\beta_e$  has been cancelled out in the above expression, meaning that the ratio is constant regardless of the relative brace resistance. It is also notable that Eq. (30) is identical with Eq. (26a) that gives the strength ratio for frames in which all earthquake forces are resisted by braces only.

When BCJ Level 2 controls the design, postbuckling strengths [ ${}^{\prime}N_{u}$ , defined in Eq. (18)] should be considered in the Japanese design. Introducing another factor  $\beta_u$ , defined as the ultimate resistance carried by the braces (estimated based on the post-buckling strength) relative to the total resistance, we obtain for the AIJ's ultimate strength:

$${}^{J}Q_{u} = {}^{J}_{B}Q_{u} / \beta_{u} = n \left( N_{y} + {}^{J}N_{u} \right) \cos \theta / \beta_{u}$$
(31)

The ratio  $({}^{U}Q / {}^{J}Q)$  of the strength required for the UBC dual system to the strength required for the Japanese dual system (when controlled by Level 2) is given as:

$$\frac{{}^{U}Q}{{}^{J}Q} = \frac{{}^{U}Q_{D}}{{}^{J}Q_{D}} \frac{{}^{J}Q_{u}}{{}^{U}Q_{cr}} = \frac{{}^{U}Q_{D}}{{}^{J}2Q_{D}} \frac{{}^{B}Q_{u}/\beta_{u}}{{}^{B}Q_{cr}/\beta_{e}}$$
$$\frac{{}^{U}Q_{D}}{{}^{J}2Q_{D}} \frac{{}^{B}Q_{u}/\beta_{u}}{{}^{B}Q_{cr}/\beta_{e}} = \frac{K_{t} I \rho}{{}^{J}Z R_{t} {}_{2}C_{0} D_{s} {}_{1}F_{es} R} k_{2} \frac{\beta_{e}}{\beta_{u}} (32)$$

For the estimation of Eq. (32), we need values for both  $\beta_e$  and  $\beta_u$ . The story shear Q versus story drift angle r relationship can be drawn systematically as in Fig. 11 for a braced frame in which both the braces and moment frames contribute to the resistance. Suppose that the story drift angle is  $r_{cr}$  at the instant when the force applied to the braces reaches the UBC factored compressive strength, and the story drift angle is  $r_F$ at the moment frame's yielding, we introduce for the ratio  $\alpha$ :

$$\alpha = r_F / r_{cr} \tag{33}$$

In reference to Fig. 12, we find that the stress  $\sigma_{cr}$  exerted in the brace at the story drift angle of  $r_{cr}$  is given by the following equation:

$$\sigma_{cr} = E r_{cr} \cos \theta \sin \theta \tag{34}$$

The cross-sectional area of the brace is given by  $N_y / F$ , and the axial force applied to the brace at the story drift angle of  $r_{cr}$  is:

$$N_{cr} = \frac{E r_{cr} \cos \theta \sin \theta}{F} N_y$$
(35)

Equating  $N_{cr}$  in the above equation with  ${}^{U}N_{cr}$  (the UBC factored compressive strength) in Eq. (16), and further eliminating  $r_{cr}$  using Eq. (33),  $\alpha$  in Eq. (33) is expressed as:

• for 
$$\bar{\lambda} \le 1.5$$
  

$$\alpha = \frac{r_F E \cos \theta \sin \theta}{F \phi_c \ 0.658^{\bar{\lambda}^2}}$$
(36a)

•for 
$$\lambda > 1.5$$
  

$$\alpha = \frac{r_F \,\overline{\lambda}^2 \, E \, \cos \theta \sin \theta}{0.877 \, F \, \phi_c}$$
(36b)

In view of Fig. 11, the UBC frame resistance  ${}_{F}{}^{U}Q_{cr}$  (at the story drift angle of  $r_{cr}$ ), and the Japanese frame resistance  ${}_{F}{}^{J}Q_{u}$  (at the ultimate state) can be correlated as:

$${}^{U}_{F}Q_{cr} = {}^{J}_{F}Q_{u} / \alpha \tag{37}$$



Fig. 11 Behavior of dual systems



Fig. 12 Axial deformation of brace

The following equations hold from the definitions of  $\beta_e$  and  $\beta_u$ :

$$\beta_e = \frac{{}_B^U Q_{cr}}{{}_B^U Q_{cr} + {}_F^U Q_{cr}}$$
(38a)

$$\beta_u = \frac{{}_B^J Q_u}{{}_B^J Q_u + {}_F^J Q_u}$$
(38b)

Solving Eq. (23) for  ${}_{B}{}^{U}Q_{cr}$  and substituting this and Eq. (37) into (38a), we obtain:

$$\beta_e = \frac{\alpha {}_B^J Q_u}{k_2 {}_F^J Q_u + \alpha {}_B^J Q_u}$$
(39)

Solving Eq. (38b) for  $_{F}{}^{J}Q_{u}$  and substituting it for the above equation [Eq. (39)], we finally find the following relationship between  $\beta_{e}$  (the relative brace resistance in the elastic stage) and  $\beta_{u}$  (the relative brace resistance in the ultimate stage) as:

$$\frac{\beta_u}{\beta_e} = \frac{\alpha - k_2}{\alpha} \beta_u + \frac{k_2}{\alpha}$$
(40)

Once the frame's yield story drift angle  $r_F$ , the yield stress of the material *F*, and the angle of brace inclination  $\theta$  are specified,  $\alpha$  is given uniquely by Eq. (36). Inserting the  $\alpha$  value into Eq. (40), we find  $\beta_u / \beta_e$ , given as a function of  $\overline{\lambda}$  and  $\beta_u$ . Figure 13 shows  $\beta_u / \beta_e$  for three different  $\beta_u$ 's: 0.75, 0.5, and 0.25. In the figure,  $\theta = \pi / 4$  and  $r_F =$ 

0.005 and 0.01. The values of  $\beta_u / \beta_e$  are smaller than unity, because the brace resistance decreases (due to buckling) and the frame resistance increases (due to the attainment of maximum strength) in the ultimate stage relative to in the buckling stage. The values of  $\beta_u / \beta_e$  become smaller for smaller  $\beta_u$ 's (corresponding to larger resistance by the moment frames).

Figure 14 shows either Eq. (30) or (32) (whichever controls the design) with respect to the normalized brace slenderness  $\overline{\lambda}$  for three  $\beta_{\mu}$ 's and  $r_F = 0.0075$  rad. Figure 14(a) is for the nearsource factor  $N_a$  of 1.0 and Fig. 14(b) for  $N_a = 1.5$ . The solid and dotted lines correspond to F =325MPa and 235MPa, respectively. When  $N_a =$ 1.0, the strength required by UBC is smaller than that required by AIJ regardless of the brace slenderness. When  $N_a = 1.5$ , the strength which is greater depends on the brace slenderness. In both Fig. 14(a) and (b), design of the Japanese dual system is controlled by Level 1 (allowable design) when  $\beta_{\mu} = 0.25$ . This is the case of relatively small resistance provided by braces, in which the frame resistance corresponding to the story drift of brace buckling is significantly smaller than the frame's ultimate resistance that can be accounted for in the strength estimation in Level 2. In reference to Eq. (30), the UBC strength requirement relative to the AIJ's allowable strength requirement (for BCJ Level 1) remains the same regardless of the brace resistance ( $\beta_e$ ); hence the comparison between the lines for  $\beta_u = 0.25$  and  $\beta_u =$ 0.5 or 0.75 drawn in Fig. 14 provides information as to whether Level 1 or Level 2 control the Japanese design. According to Fig. 14 and for the material strength of 325MPa, Level 2 controls the design for  $\overline{\lambda} = 0.2$  to 1.1 when  $\beta_u = 0.5$  and for  $\overline{\lambda}$  < 1.4 when  $\beta_{\mu}$  = 0.75. In these ranges of brace slenderness, the strength required by AIJ is generally larger than that required by UBC because of the larger strength required for Level 2 (as a result of relatively small post-buckling strength stipulated) in the Japanese design. The ratio,  ${}^{U}Q$  / <sup>J</sup>Q, takes the smallest for  $\overline{\lambda} = 0.63$ , being 0.38 for  $N_a = 1.0$  and  $\beta_u = 0.75$  and 0.57 for  $N_a = 1.5$  and  $\beta_u$ = 0.75.







(b) Yield strength (F) = 325Mpa

Fig. 13 Comparison in ratio of brace resistance to total resistance between buckling and post-buckling stages



Fig. 14 Comparison in strength between U.S. and Japanese dual system

### **CONCLUDING REMARKS**

The U.S. and Japanese seismic design provisions related to steel frames are compared, focusing on the difference in strength expected for braced frames built in the two countries.

Major conclusions are as follows.

- (1) The unreduced design earthquake force is relatively similar for UBC and BCJ if nearsource factors are not included. UBC unreduced design earthquake force is larger (approximately twice) than that of BCJ if maximum near-source factors are considered.
- (2) Thickness and slenderness requirements stipulated for ensuring large ductility capacity are similar for UBC and BCJ.
- (3) Seismic force reduction factors are smaller (approximately half) in UBC (1/R) than in BCJ ( $D_s$ ). This indicates that a significant conceptual difference may exist in the trade-off between strength and ductility in the two countries.
- (4) Stiffness requirements (interstory drift limits) stipulated in UBC and BCJ are relatively similar. Design of moment resisting frames (unbraced frames) tends to be governed by stiffness requirements rather than by strength requirements; then UBC strength is similar to BCJ strength for moment resisting frames.
- (5) For lightly braced frames, UBC strength is smaller than BCJ strength (by 20 to 30%) if near-source factors are not included, but larger (by 10 to 20%) if these factors are included. For braced frames arranged with many braces of intermediate lengths, UBC strength is smaller (by as much as 40%) than BCJ strength even if near-source factors are included. Large strength required for BCJ reflects a combination of a smaller brace post-buckling strength and a larger seismic force reduction factor.
- (6) A significant difference in strength of braced frames is notable in that both U.S. and Japan consider similar levels of earthquake forces. How brace buckling and resultant strength degradation have been allowed for in the two

countries is a subject worthy of further exploration.

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#### **SYMBOLS**

- $A_i$ : distribution factor of  $C_i$  along height in Japan.
- $C_a$ : seismic coefficient stipulated by soil type, seismic zone, and near-source factor  $(N_a)$  in U.S.
- $C_{\nu}$ : seismic coefficient stipulated by soil type, seismic zone, and near-source factor  $(N_{\nu})$  in U.S.
- ${}_{1}C_{i}$ : design story shear coefficient at story *i* for Level 1 earthquake in Japan.
- $_{2}C_{i}$ : design story shear coefficient at story *i* for Level 2 earthquake in Japan.
- ${}_{1}C_{0}$ : standard coefficient for Level 1 earthquake in Japan.
- $_{2}C_{0}$ : standard coefficient for Level 2 earthquake in Japan.
- $_iD_s$ : structural characteristic factor at story i in Japan.
- E: Young's modulus.
- F : yield stress.
- $F_i$ : design seismic force applied to level *i* in U.S.
- $F_t$ : design seismic force applied at top of structure in addition to  $F_i$  in U.S.
- ${}_{i}F_{es}$ : shape factor at story *i* according to distribution of story stiffness and plan eccentricity in Japan.
- I: importance factor in U.S.
- K: effective length factor of brace.
- $N_a$ : acceleration-related near-source-factor in U.S.

Tada, Fukui, Nakashima, Roeder: Comparison of Strength Capacity for Steel Building Structures in the United States and Japan 49

- $N_{\nu}$ : velocity-related near-source-factor in U.S.
- $N_y$ : yield axial strength of column.
- $^{J}N_{u}$ : post-buckling strength in Japan.
- ${}^{J}N_{cr}$  : allowable compressive strength in Japan.
- $^{U}N_{cr}$ : resistance factored compressive strength in U.S.
- $P_u$ : required column strength in U.S.
- $^{J}Q$ : horizontal strength required in Japan.
- $^{U}Q$ : horizontal strength required in UBC.
- ${}_{1}Q_{i}$ : design story shear at story *i* for Level 1 earthquake in Japan.
- $_{i}Q_{un}$ : required strength at story *i* for Level 2 earthquake in Japan.
- *R* : numerical coefficient representative of inherent overstrength and global ductility capacity of lateral-force-resisting systems in U.S.
- $R_t$ : vibration characteristic coefficient in Japan.
- T : elastic fundamental period of vibration (in seconds).
- $T_c$ : soil period determined according to soil type in Japan (0.4, 0.6, or 0.8 seconds).
- V: total design base shear in U.S.
- W: total seismic dead load.
- $^{U}Z$  : seismic zone factor in U.S.
- $^{J}Z$  : seismic zone factor in Japan.
- $h_i$ : height above base to level *i*.
- *i* : radius of gyration.
- l : length of brace.
- $n_c$ : ratio of column axial force to axial strength in U.S.
- $r_{cr}$ : story drift angle at instant when force applied to the braces reaches UBC factored compressive strength.
- $r_F$  : story drift angle at frame's yielding.
- $w_i$ : seismic dead load at story level *i*.
- $\Delta_l$ : limit story drift angle in U.S (0.025rad for *T* < 0.7sec, and 0.02rad for *T* > 0.7sec).
- $\Delta_s$ : elastic story drift angle with respect to U.S. design seismic force or Japanese Level 1 seismic force.
- $\beta_e$ : force resisted by braces relative to total resistance in elastic range.
- $\beta_u$ : ultimate resistance carried by braces relative to the total resistance in post-buckling stage.

- $\phi_b$ : resistance factor for bending in U.S. (= 0.90).
- $\phi_c$ : resistance factor for compression in U.S. (= 0.85).
- $\overline{\lambda}$  : normalized slenderness of brace.
- $\boldsymbol{\theta}$  : angle between brace and beam longitudinal axes.
- $\rho$ : factor to allow for structural redundancy in U.S. (1.0 to 1.5).

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