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Equivalent Damping Factor of Composite RCS Frames

by H. Kuramoto and I. Nishiyama

Synopsis: The building standard law of Japan was largely revised in June 1998. With the revision, the adoption of the capacity spectrum method (CSM) for the seismic design procedure is being considered toward the enforcement in June 2000. In the CSM, the estimation of the demand spectrum is one of important issues, because the damping properties of a building should be appropriately considered. The equivalent damping factor of composite RCS buildings consisting of steel beams and reinforced concrete columns is investigated in this paper. The relations between the equivalent damping factor and story drift of RCS joints and frames, which have different joint detail and failure mode, are examined using the existing test results including those obtained in the US-Japan cooperative research program on composite and hybrid structures. It is indicated that the influence of the hysteretic damping of beam-column joints can not be ignored for estimating the equivalent damping factor of composite RCS buildings particularly when the strength and stiffness of joints are relatively small.

Keywords: beam-column joint; capacity spectrum method; composite RCS building; equivalent damping factor; evaluation; failure mode; frame; seismic design

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INTRODUCTION

The building standard law of Japan was largely revised in June 1998 after an interval of about 50 years. The adoption of new seismic design procedures, which will be enforced by June 2000, is being considered with the revision. The most likely procedure for the adoption is the capacity spectrum method [1-3] that is one of nonlinear static analysis procedures. In this method, as shown in Fig. 1, through superposition of the capacity curve obtained from the pushover analysis of a building and a reduced response spectrum (the demand spectrum), the maximum earthquake response of the building can be approximated. The estimation of the demand spectrum is one of important issues in the capacity spectrum method, because the damping properties of a building including the effect of interaction between the building and foundation should be appropriately considered. The hysteretic damping of a building is usually of structural members such as beams, columns and shear walls. However, the influence of the hysteretic damping of beam-column joints can not be ignored particularly when the structural performance of the joints affects that of the building.

Composite RCS buildings consisting of steel beams and reinforced concrete columns are often part of structures of this kind. The equivalent damping factor of beam-column joints in composite RCS buildings is discussed in this paper. The relation between the damping factor and displacement ductility level of RCS joints and the effect of the detailing and failure modes of the joints on the equivalent damping factors are examined to find appropriate values of the damping factor for applying to the capacity spectrum method.

EQUIVALENT DAMPING FACTOR OF BUILDINGS

Considering a beam-column subassemblage subjected to horizontal load as shown in Fig.2, the relative story drift, δ_J, is composed of the story drifts due to the deformation of adjacent beams, adjacent columns and the joint panel, δ_b,

δ_c and δ_p. The energy absorption of the beam-column joint is also composed of that of the beams, columns and joint panel, as illustrated in Fig.3. Therefore, the equivalent damping factor of a beam-column joint, ζ_{eqJ}, can be expressed by the following equation:

$$\zeta_{eqJ} = \frac{\zeta_{eqb} \cdot \delta_b + \zeta_{eqc} \cdot \delta_c + \zeta_{eqp} \cdot \delta_p}{\delta_J} \tag{1}$$

where ζ_{eqb}, ζ_{eqc} and ζ_{eqp} are the equivalent damping factors of the beams, columns and joint panel, respectively. However, note that these are different from the equivalent damping factors of the beams, columns and joint panel themselves and are defined as follows (see Fig. 3):

$$\zeta_{eqb} = \frac{1}{2\pi} \cdot \frac{\Delta W_b}{Q_J \cdot \delta_b} \tag{2}$$

$$\zeta_{eqc} = \frac{1}{2\pi} \cdot \frac{\Delta W_c}{Q_J \cdot \delta_c} \tag{3}$$

$$\zeta_{eqp} = \frac{1}{2\pi} \cdot \frac{\Delta W_p}{Q_J \cdot \delta_p} \tag{4}$$

Assuming that the total energy absorption of a building during a earthquake is nearly equal to the energy absorption of the equivalently converted single degree of freedom (SDOF) system shown in Fig. 4, the equivalent damping factor of the building, ζ_{eqF}, is given by the following equation:

$$\zeta_{eqF} = \frac{1}{4\pi} \cdot \frac{\Delta W_{SD}}{W_{SD}} = \frac{1}{2\pi} \cdot \frac{\sum_{i=1}^{n} \Delta W_{J,i}}{Q_B \cdot {}_1\delta} \tag{5}$$

where, Q_B = base shear
${}_1\delta$ = horizontal displacement in SDOF system
W_{SD} = potential energy in SDOF system ($= Q_B \cdot {}_1\delta/2$)
ΔW_{SD} = energy absorption of SDOF system
$\Delta W_{J,i}$ = energy absorption in the i-th beam-column joint
n = the number of joints including column bases in a building

Using the equivalent damping factor, $\zeta_{eqJ,i}$, the average story shear, $Q_{J,i}$, and the story drift, $\delta_{J,i}$, of the i-th beam-column joint, the energy absorption, $\Delta W_{J,i}$, in Eq. (5) can then be written as the following:

$$\Delta W_{J,i} = 2\pi \cdot \zeta_{eqJ,i} \cdot \delta_{J,i} \cdot Q_{J,i} \tag{6}$$

Substituting Eqs. (1) and (6) for Eq. (5), the following expression on the equivalent damping factor of the building, ζ_{eqF}, is obtained:

$$\zeta_{eqF} = \frac{\sum_{i=1}^{n} \zeta_{eqJ,i} \cdot \delta_{J,i} \cdot Q_{J,i}}{Q_B \cdot {}_1\delta} = \frac{\sum_{i=1}^{n} \left(\zeta_{eqb,i} \cdot \delta_{b,i} + \zeta_{eqc,i} \cdot \delta_{c,i} + \zeta_{eqp,i} \cdot \delta_{p,i}\right) \cdot Q_{J,i}}{Q_B \cdot {}_1\delta} \tag{7}$$

Thus the equivalent damping factor of a building can be related to those of the beams, columns and joints. As illustrated in Fig. 5, if the equivalent damping factors of the beams, columns and joints are individually given with relation to their displacement ductility levels, the damping factor of a building can be obtained by Eq. (7) and the results of a pushover analysis considering the joint panel distortion. Incidentally, the information of parameters except the equivalent damping factors in Eq. (7) can be obtained through the pushover analysis.

EQUIVALENT DAMPING FACTOR OF *RCS* BEAM-COLUMN JOINTS

For composite RCS beam-column joints failing in joint shear and that with the distinct yielding of beams, the equivalent damping factors were calculated to investigate the progress of those with an increase of the displacement ductility levels.

For beam-column joints failing in joint shear, four specimens of the through column type which had been tested by the authors [4,5] as a part of the US-Japan cooperative earthquake research program "Composite and Hybrid Structures" were used to calculate. The specimens are Specimens BRI2 and BRI3 reinforced by cover plates, horizontal stiffeners and extended face bearing plates (FBP) and Specimens BRI5 and BRI6 with transverse stiffeners and extended FBP. Figure 6 shows story shear versus story drift relations and the progress of the equivalent damping factors of a joint panel with an increase of the story drift for each specimen.

In the calculations, Takeda model [6] was used for the hysteresis rule of reinforced concrete columns, and steel beams were assumed to be elastic, namely the equivalent damping factors of beams must be zero. Using the story shear and story drift corresponding to the distortion of a joint panel in each loading step, the equivalent damping factor of the joint panel was calculated. The story drift used was obtained by subtracting the story drifts corresponding to the deformation of beams and columns from the whole drift.

In the specimens with cover plates, the equivalent damping factors of the joint panel increase with the story drift gaining before the relative member rotation angle corresponding to the story drift of a beam-column subassemblage, *R*, reaches 0.015 radian. After that, however, the equivalent damping factors tend to be constant, of which the values are about 20% regardless of the thickness of cover plates or the number of loading cycles. In the specimens with transverse stiffeners, on the other hand, the equivalent damping factors tend to be constant regardless of the member rotation angle though the tendency of the first cycle is slightly different from that of the second cycle. The value ranges from 12 to 15% in the loading cycles after *R* of 0.02 radian.

Figure 7 shows story shear versus story drift relations and the progress of the equivalent damping factors with an increase of the story drift for a specimen of the beam yielding type tested by Kanno [7]. In this case, the calculations of the equivalent damping factors were carried out under assumptions that the hysteresis loops of reinforced concrete columns can be simulated by Takeda model and the behavior of a joint panel was elastic. In the same way as cases of joints failing in joint shear, using the story drift which subtracts the story drifts corresponding to the deformation of a joint panel and columns from the whole drift, the equivalent damping factors of beams were calculated.

The equivalent damping factors of beams are about 10% just after beams yield, at *R* of about 0.02 radian. After that, the equivalent damping factors increase suddenly with the story drift gaining and are about 40% at *R* of 0.05 radian. These results imply that quite a bit of damping effect can be expected for composite RCS frames in which the capacities of columns and joints are much larger than those of beams.

EQUIVALENT DAMPING FACTOR OF COMPOSITE *RCS* FRAMES

The equivalent damping factors of two composite RCS frame specimens consisting of 2-story and 2-bay tested by Iizuka, et al. [8] were calculated. The difference of the specimens is only joint details which are the through beam type with FBP for Specimen TB and the through column type with transverse stiffeners and extended FBP for Specimen TC. The configuration and joint details of the specimens are shown in Fig. 8.

Figure 9 shows base shear versus average story drift angle relations for each frame, in which the average story drift angle are given by dividing the total height of a frame into the relative roof displacement. Circles and squares on the hysteresis loops in the figure show the points of yielding at column bases and beam-ends of the 2nd floor, respectively. In Fig. 10, the progress of the equivalent damping factors of each frame with story drift gaining is plotted.

As seen in Fig. 9, the restoring characteristic of RCS frames extremely changes due to only the difference of joint details. The distinguished difference of damping properties between both frames is observed in loading cycles after the drift angle of 0.01 radian, as shown in Fig. 10. As made clear through the difference of the drift angles occurring the yielding of beams at the 2nd floor shown in Fig. 9 (square marks), the capacity ratios among beams, columns and joints affect the damping properties of the frames. In other words, the results imply that the strength and stiffness of beam-column joints in Specimen TC are higher than those in Specimen TB and are enough to form a weak beam-strong column mechanism in the frame.

CONCLUSIONS

For composite RCS buildings, high damping properties and forming a weak beam-strong column mechanism can be expected when the strengths of columns and joints are relatively larger than that of beams. However, composite RCS systems are usually applied to long span frames in order to make the most of the merit. As a result, designing frames that form a weak beam-strong column mechanism is not so easy because the shape and dimension of steel beams tend to be governed by the design for not seismic load effects but vertical load effects. In such buildings, the beam-column joints suffer more damage before the beams yield. Consequently, in the verification of the seismic performance of composite RCS buildings using the capacity spectrum method, appropriate estimation for the equivalent damping factors of not only beams and columns but also joints is necessary.

Incidentally, the maximum value of the equivalent damping factors of RCS beam-column joints failing in joint shear of the through column type tested by the authors were about 20% for joints with cover plates and about 15% for joints with transverse stiffeners, respectively. For a RCS beam-column joint with the distinct yielding of beams, the damping factor significantly increased with an increase of the story drift after the beams yielding, and was about 40% at the story drift angle of 0.05 radian.

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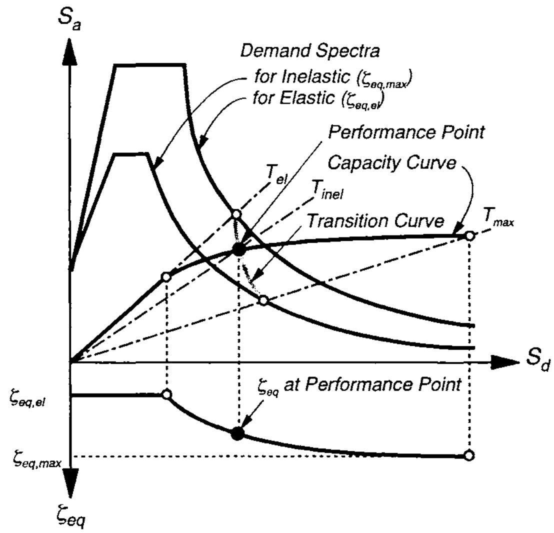


Fig. 1 Relationship among Capacity Curve, Demand Spectra and Equivalent Damping Factor

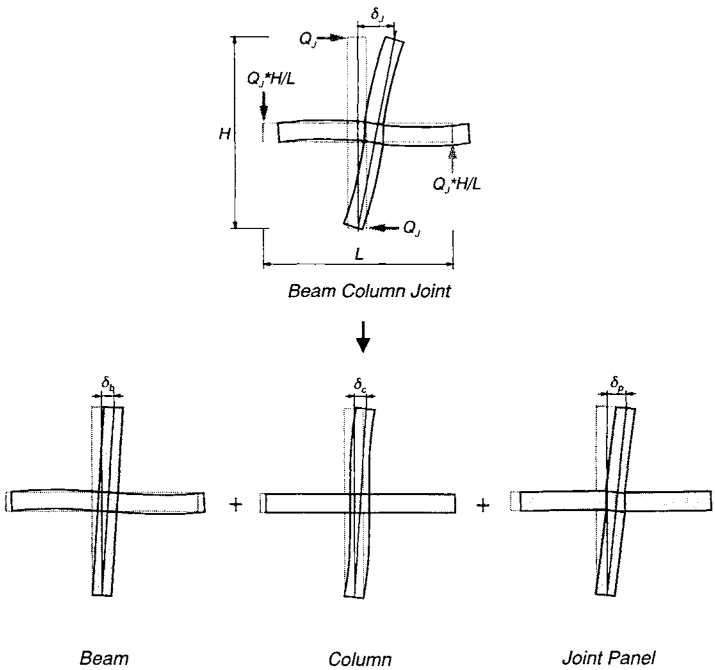


Fig. 2 Deformation Components in Beam-Column Joint Assembly

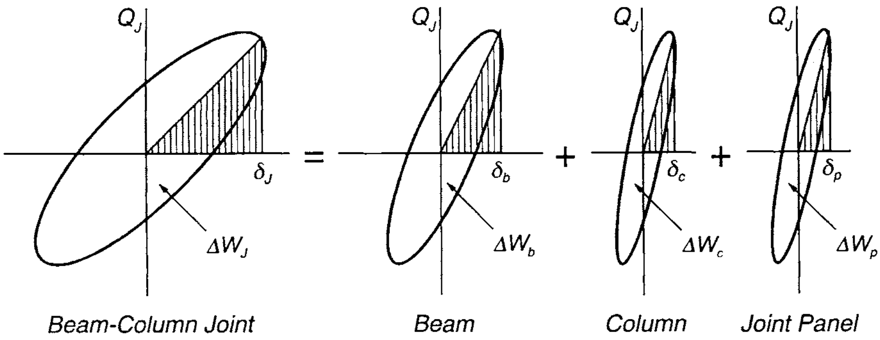


Fig. 3 Equivalent Damping Factor of Beam-Column Joint and its components

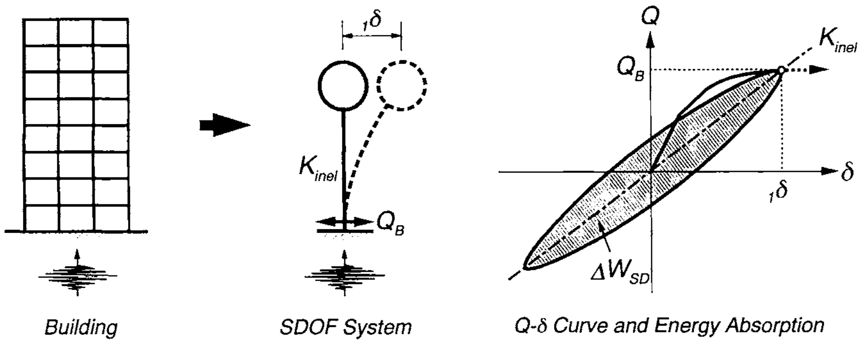


Fig. 4 Equivalent Single Degree of Freedom System

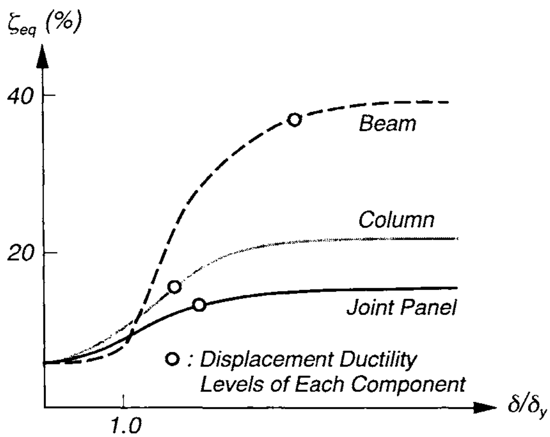
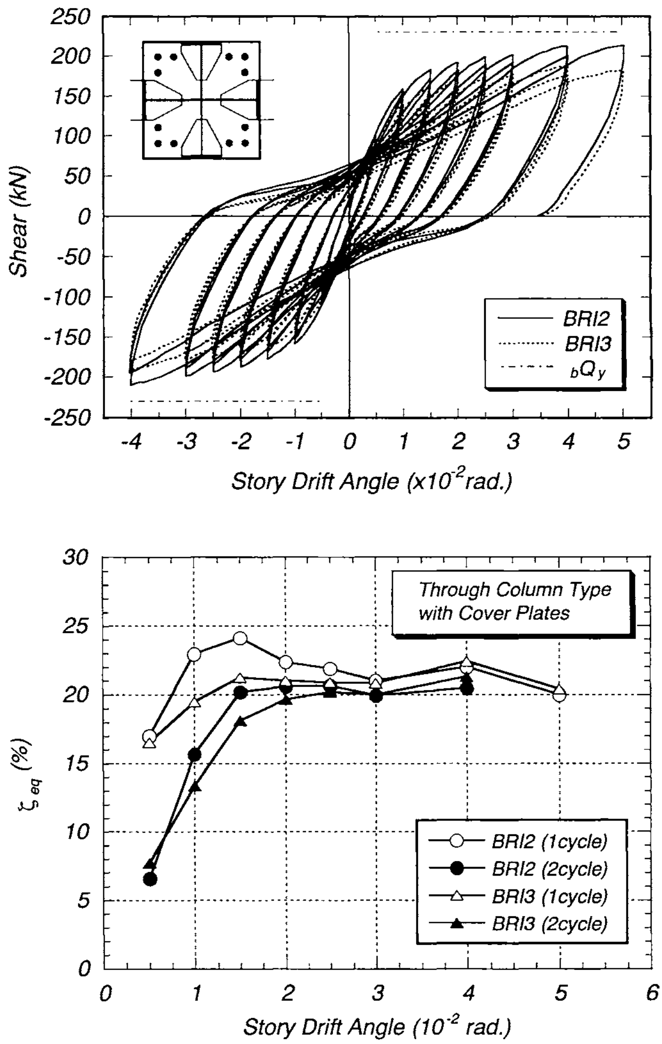


Fig. 5 Idealized Relationships between Equivalent Damping Factors of Each Component and the Ductility Levels at the Maximum Response of a Building



(a) Cover Plate Type

Fig. 6 Hysteresis loops and Progress of Equivalent Damping Factors of Joint Panel with an Increase of Story Drift for RCS Beam-Column Joints Failing in Joint Shear [4,5]