A New AIJ standard for Seismic Capacity Calculation: Recent Advances in Beam-Column Joint Design and Seismic Collapse Simulation on Reinforced Concrete Frame Buildings

H. Shiohara[1]

Synopsis: A new concept of joint hinging developed in Japan is presented, which will be implemented in a new draft provision for beam-column joints in the New AIJ (Architectural Institute of Japan) Standard for Seismic Capacity Calculation. This paper discusses the key issues of the new draft provisions, with background, test data verification, theory and analyses with emphasis on why such a concept is necessary. The factors affecting joint hinging failure are discussed for seismic design consideration. Seismic collapse simulation were made by non-linear time history analysis for moment frames with BC joints failing due to joint hinging, to demonstrate the challenge of simulated strength degradation and severe pinching hysteretic behavior inherent to joint hinging. Draft equations to calculate the strength of joint hinging strength of of BC joints are also introduced.

Keywords: Seismic, design, concrete, beam-column joint

INTRODUCTION

Shear failure of reinforced concrete beam-column (BC) joints has been recognized as an undesirable mode of failure, which lowers the seismic resistance of reinforced concrete moment frame structures. Structural collapse due to the instability of BC joints at large story drifts is also a concern. For these reasons shear failure of BC joints is prevented by seismic provisions in major concrete codes, such as ACI, EC8, NZS, and AIJ Guidelines [1]. Historically, the introduction of the BC joint seismic design began in the 1980's and it was coincident with the introduction of Capacity Design. Since then, empirical joint strength equations have been adopted in those codes to preclude BC joint failure, where the joint strength is a function of joint configuration such as interior, exterior or knee joint, dimensions and concrete compressive strength.

Recently a new mechanism designated *joint hinging* was introduced in Japan, and was adopted in new draft provisions of AIJ standard [2], where a new model for *joint hinging strength* is given. This paper summarizes the new AIJ Standard draft provisions for BC joints, with background, test data, theory and analysis with emphasis on why such new concept should be necessary. The *joint hinging failure* discussed here is similar to the type of failure explained in the author's publications [3, 4, 5, 6, 7, 8] and it was experimentally investigated in late 2000's [9, 10, 11, 12]. Joint hinging strength is discussed for seismic design consideration. Collapse simulations were made by non-linear time history analysis for moment frames with BC joints with *joint hinging*, to demonstrate the challenge simulating strength degradation and severe pinching hysteretic behavior inherent to *joint hinging*. Draft equations for the strength degradation caused by *joint hinging* of BC joints are also introduced.

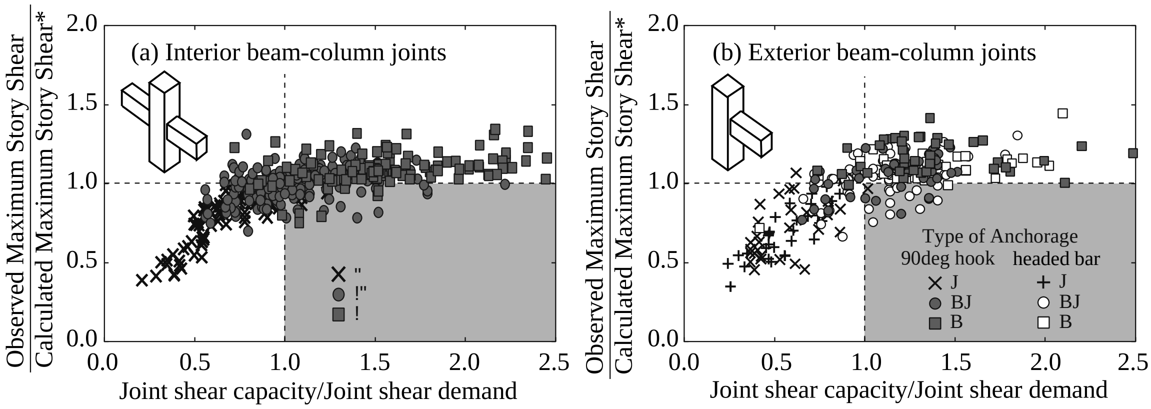
CURRENT BEAM-COLUMN JOINT DESIGN AND ITS CHALLENGE

Capacity Design was introduced in the 1980's. It was one of the crucial developments for the seismic design for high-rise concrete buildings in Japan. The underlying principle of Capacity Design is that the ultimate lateral resistance of a frame structure can be calculated from the moment capacity at the critical section obtained by flexural theory and equilibrium. If the frame is designed to have weak beam-strong column mechanism, then the lateral strength of frame could be calculated based on the flexural strength of

[1] Professor, Dept. Arch. Engineering, the University of Tokyo, Tokyo, Japan

beam sections. To achieve this goal, capacity design does not allow the premature joint shear failure before beam yielding.

Let us reexamine how well the principle is validated by evaluating an experimental database of interior and exterior RC BC joints [13, 14]. In Figure 1, each point represents story shear strength and joint shear strength of a BC joint specimen. The vertical axis is the observed joint shear strength and the horizontal axis is the joint shear demand, where the strengths are normalized by the joint shear capacity in AIJ Guidelines [2] or the calculated story shear by flexural analysis, respectively. Only less than 5% of the BC joint specimens with the joint shear capacity margin larger 1.0 were found to fail due to joint shear (J). A quite a large number of the points with joint shear capacity margin larger than 1.0 were found to have actual strength smaller than the story shear at flexural strength of beam (the area hatched in gray). In some specimens, the strengths fell short by 20%. So joint shear capacity margin is not good index to classify BC joints that have larger strength than predicted by the flexural strength of the beam section.



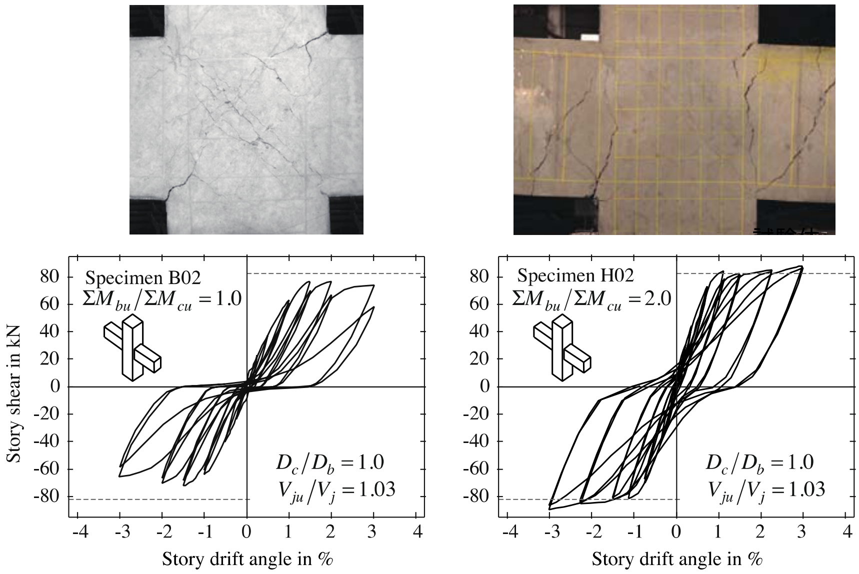
*Story shear at flexural capacity of c ritical section in beam

Figure 1. Database of beam-column joints, with joint shear capacity margin, failure mode and lateral

JOINT HINGING OF BEAM-COLUMN JOINT

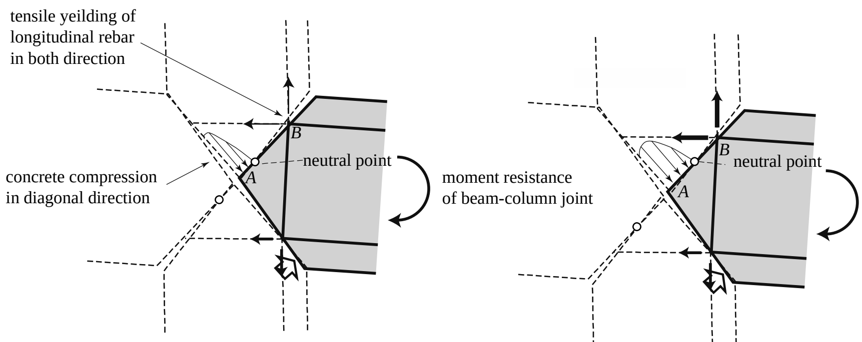
Two BC joint specimens B02 and H02 [8] are compared by photo and load-displacement relationship in Figure 2. There are obvious differences in strength, shape of the hysteresis loops, and location of the hinge, despite both specimens having the same beams. The story shear at calculated flexural strength of beam section is shown by the dotted line. Specimen B02 with joint hinging is quite different from specimen H02 with beam hinging. Sharp contrasts exists in (a) lower strength than predicted by flexural theory and (b) low stiffness after unloading due to pinching and poor capacity in hysteretic energy dissipation, although the two BC joints had the same beam section and beam reinforcement.

A theory was developed to explain why such lightly reinforced RC BC joints as B02 could have lower strength than predicted by the flexural strength of the beams (or columns) [3, 4, 5, 6, 7, 15]. *Joint hinging* was named after the fact that tensile yielding occurs in the longitudinal reinforcement passing through the joint, for both the vertical and the horizontal direction within the BC joint, just beneath the diagonal cracks. The kinematics consists of rotation and separation of triangular concrete segments, as proposed in Figure 3. In a *joint hinging mechanism*, a beam-column joint transfers the moment from the beams to the columns by the pair of the tensile force in the steel and the compressive force in the concrete on the boundary of the segments, as shown in Figure 3(a). The moment capacity of *joint hinging mechanism* is calculated as the maximum moment resisted by the mechanism. The capacity of *joint hinging mechanism* increases with vertical and horizontal reinforcement passing through the joint, and the axial forces in column and beams.



(a) Joint hinging failure (b) Beam hinging failure

Figure 2. Story shear-story drift relationships [8, 9, 10, 11]



(a) joint hinging (b) balanced failure

Figure 3. Mechanical Model for *Joint hinging* and *Balanced failure* [4, 5, 6, 7, 13, 15]

BALANCED FAILURE OF BEAM-COLUMN JOINT

Over reinforced BC joints fail due to so-called joint shear failure. This type of failure is called *balanced failure* of BC joint in the new AIJ standard draft, because its failure mechanism is the same model as the *joint hinging failure* shown in Figure 3(a), where concrete crushing precedes yielding of longitudinal steel in BC joint. The name *Balanced failure* of BC joint is used because the mode of failure is analogous to the balanced failure of RC sections in flexural theory. The most current seismic provisions prevent this type of joint failure through provisions for joint shear strength, but the *joint hinging* is not covered and it is an obvious oversight.

EXPERIMENTAL INVESTIGATION ON JOINT HINGING

Why the joint hinging failure of BC joints has been overlooked in the history of seismic design development? The authors found that tests of lightly reinforced weak beam-strong column BC joints with column-to-beam strength ratio in the range of 1.0 - 1.6 have been rare, because the original Capacity Design provisions for seismic design have very strict column-to-beam strength ratio requirements. But when it was actually adopted in the concrete codes, the minimum column-to-beam strength ratio was not specified in Japan and compromised to be 1.2 in the ACI-318 in the US.

Several experimental projects consisting of more than sixty BC joints were carried out in Japan [10, 11, 12] by a research group including the author in four years starting from FY2008, in which BC joints with interior, exterior and knee joint configurations were tested. Column-to-beam strength ratio (=0.8-2.0) was chosen as a primary test parameter whereas secondary parameters are joint shear strength margin (=0.5-1.5), and column-to-beam depth ratio (=0.5-2.0). Anchorage length of longitudinal bars in BC joint was added to the secondary parameters for exterior and knee joints. Test results were reported at the 15WCEE [8, 9]. It is revealed from those tests that *joint hinging* was observed in a wide range of test parameters. Figure 4 shows some of the typical test results. Strength is smaller than that at the flexural capacity of beam section (or column), when column-to-beam strength ratio is in the range from 0.7 to 1.5. Strength is minimum when column-to-beam strength ratio is 1.0. All the BC joints with column-to-beam strength ratio (0.8-2.0) showed joint hinging. It also revealed that the shape of hysteresis loop is severely pinched. So this type of failure may occur in a BC joint even if it conforms to the current seismic design provisions. It has been also revealed that column-to-beam strength ratio larger than 2.0 and increased horizontal joint reinforcement is necessary to obtain typical beam hinging mechanism with little damage to BC joint as shown in Fig. 2(b). Figure 5 shows the typical story shear-story drift relation for specimens with *joint*

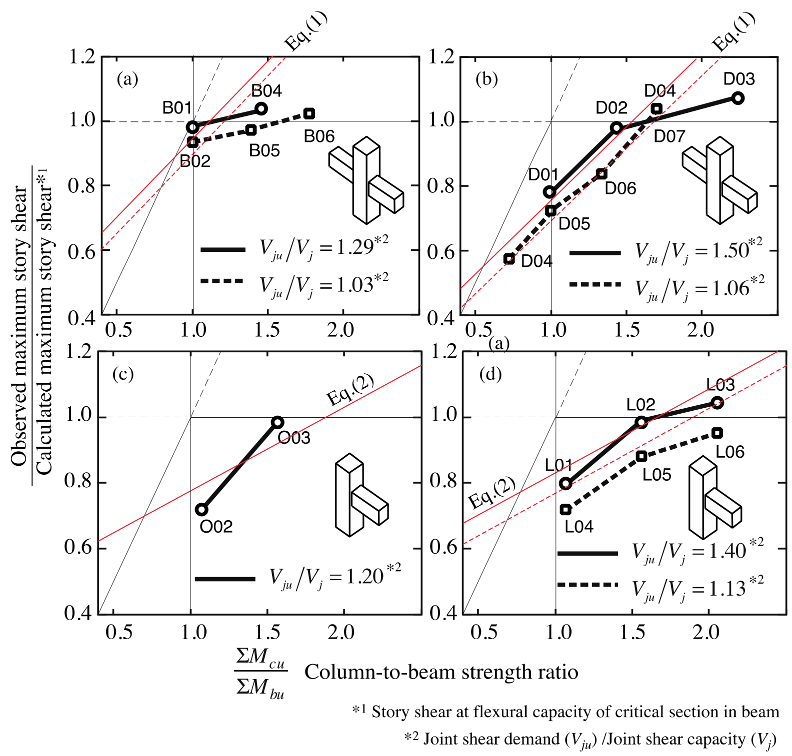


Figure 4. Strength reduction of BC joint with column-to-beam strength ratio near 1.0 [8, 9]

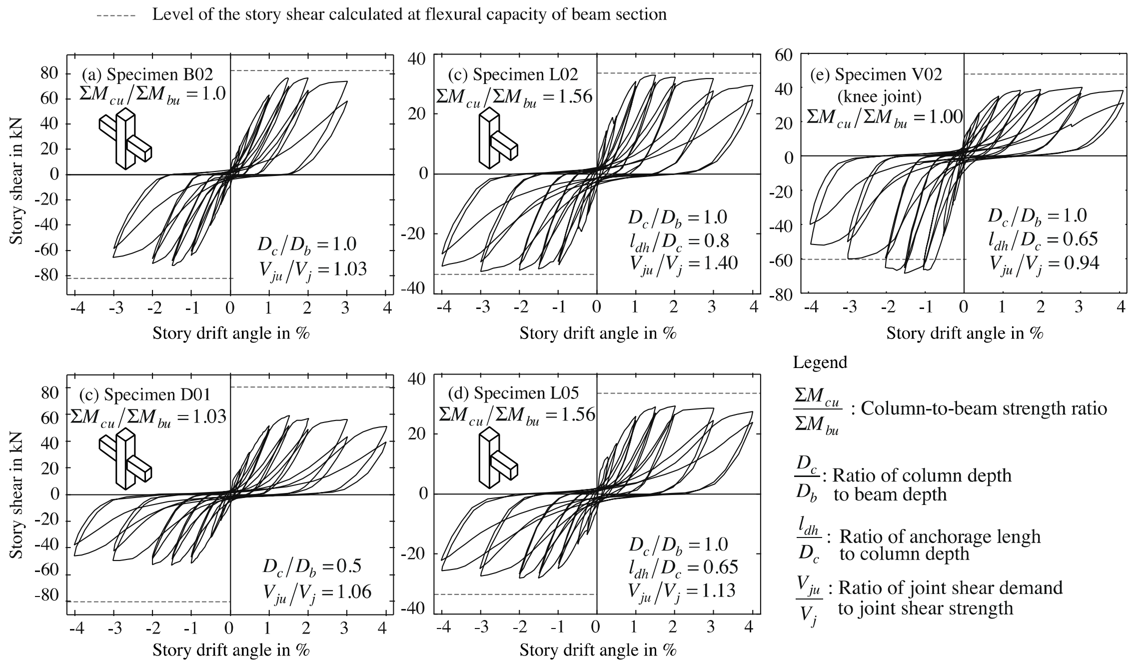


Figure 5. Typical story shear-story drift relation with the joint hinging failure [8, 9]

hinging. The low stiffness after unloading is attributed to the residual diagonal crack in BC joint due to tensile residual strain in longitudinal reinforcements.

DATABASE STUDY

Those specimens in the database in Figure 1 with column-to-beam strength ratio in the range of 1.0-2.0 are extracted and plotted in Figure 6. Eighty five percent of the specimens were reported as joint shear failure after beam yielding (BJ type), and the story shear of 40% of them was lower than calculated based on flexural yielding of the beam section. If a subgroup with column-to-beam strength ratio in the range of 1.0-1.5 is extracted, ninety percent showed BJ type failure, and the story shear of sixty percent of them

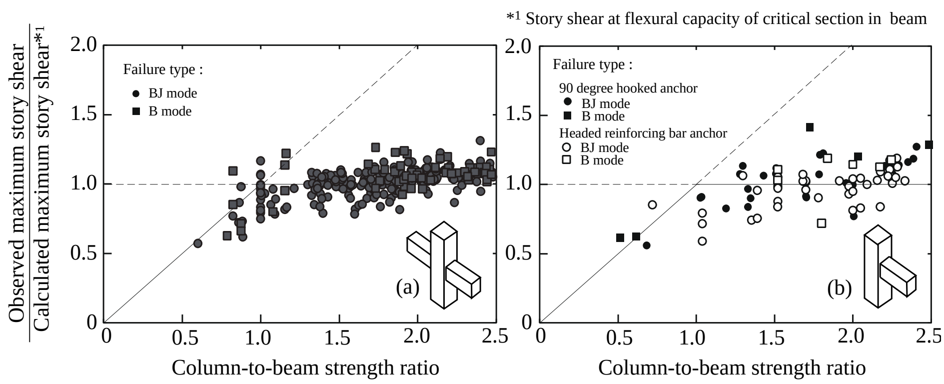


Figure 6. Strength reduction of BC joint with low column-to-beam strength ratio [13, 14]

was lower than calculated. [13, 14] There exist exceptions in Figure 6, which have larger strength than calculated even if the column-to-beam strength ratio is 1.0. These are attributed to high joint shear reinforcement. Other tests [15, 16, 17] recently reported in Japan, including 3D full-scale shaking table test of an RC frame structure, reveal that column-to-beam strength ratio is a crucial parameter governing the strength and failure pattern of BC joints.

COLLAPSE SIMULATION ON FOUR-STORY RC FISHBONE STRUCTURE

There have been various models developed for shear failure of beam-column joints. Tajiri model; a macro-element proposed by Tajiri and Shiohara [18] is one of them, which is developed for *joint hinging* mechanism. The macro element model gives stiffness equations for 12 DOF's at four ends of beams or columns which frame into a BC joint, as shown in Figure 7. The Tajiri model is so complicated that a simplified version was used for a simulation of a four story RC Frame structure by Kusuhara and Kim et al. [19]. A calibration study was also made with static test results to confirm the validity of the modeling [19]. The seismic response of a frame structure is calculated and compared. The model is for a four-story fishbone structure. The structure was designed as a weak beam-strong column mechanism with a base shear coefficient of 0.3, which satisfies the requirement of Japanese building code. The BC joint was modeled using the macro-element, consisting of uniaxial concrete springs, steel springs, and bond springs with non-linear hysteresis stress-strain relationship, whereas the beams and columns are modeled with force-based line elements with rotational springs. P-Delta effect is included in the model by considering the stiffness matrix with geometrical non-linearity. The structure was subjected to four base acceleration records. Maximum story drift responses are calculated for two different level of input acceleration record, amplified such that maximum velocity was 25 kine, or 50 kine respectively. The beam section was kept constant for all models, while the column reinforcement was varied such that the column-to-beam strength ratio was 1.0, 1.2 and 1.5. To compare the response of the macro-element with variation of column-to-beam strength ratio, a frame model with elastic BC joint model are set as a control structure.
The attained maximum story drifts are shown in Figure 8. The story drifts of the Tajiri model were 10 - 30 % larger for the case with small column-to-beam strength ratio than that of the control structure.
Incremental dynamic analyses (IDA) were also carried out and the results are shown in Figure 9. Maximum story drift increased with increasing level of base input motion. Figure 9 compares the structures with column-to-beam strength ratios of 1.0 1.2 and 1.5. The maximum story drift was larger for smaller column-to-beam strength ratio, for any level of base motion. The base input motion at collapse is also larger for larger column-to-beam strength ratio. The required over strength ratio was calculated from

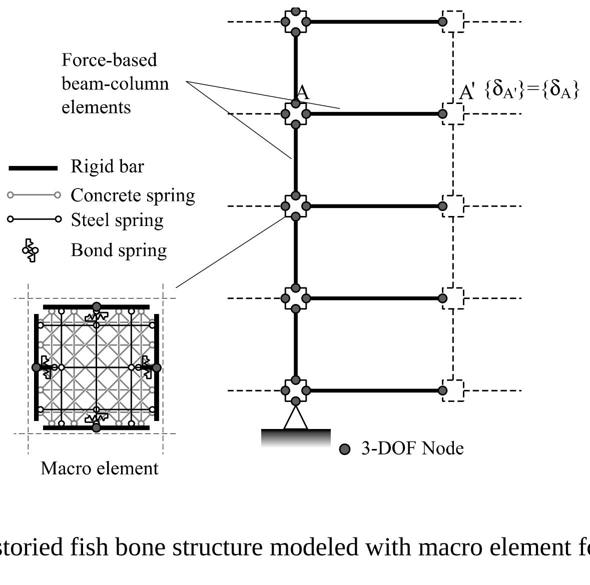


Figure 7. Four storied fish bone structure modeled with macro element for BC joint [19]

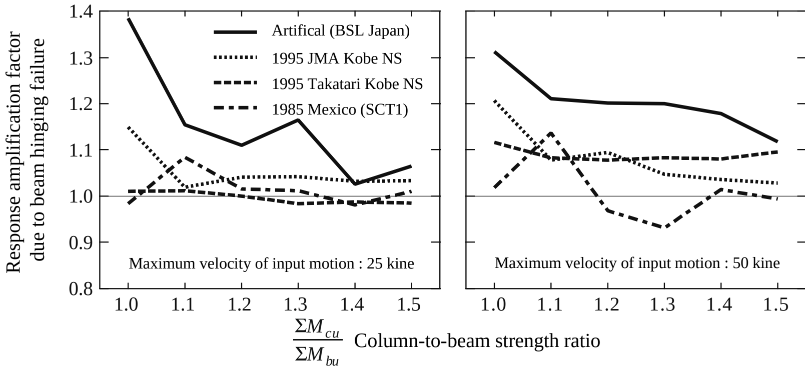


Figure 8. Amplification of maximum story drift angle response due to small column-to-beam strength ratio [19]

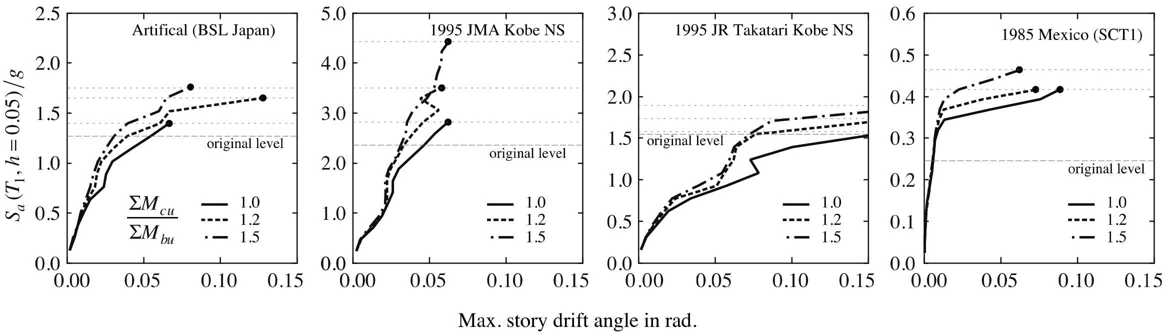


Figure 9. Result of incremental dyanamic analysis (IDA) and safety mergin [19]

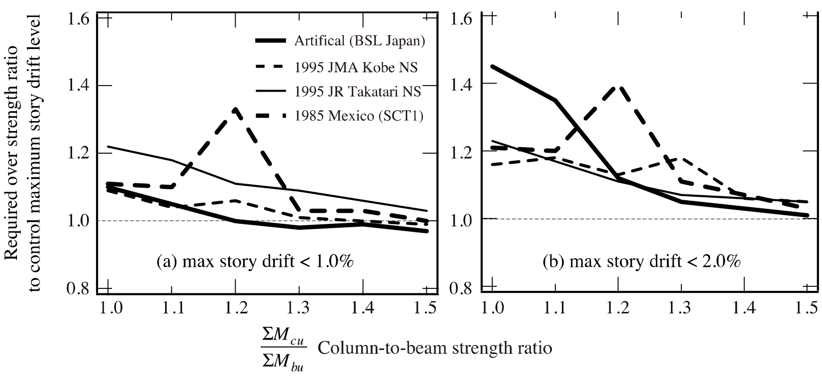


Figure 10. Required over strength to control maximum story drift within design limit

the IDA analyses and it was shown in Figure 10. It is revealed that the required lateral strength is larger to control the specified story drift if column-to-beam strength ratio is smaller.

It is concluded that joint hinging not only increased the damage to BC joints but also hinders the formation of beam sway mechanisms and story drift concentrates at a particular story. As a result, collapse prevention capacity decreases due to accumulation of residual story drift resulting in collapse due to P-delta effect.

DESIGN EQUATION FOR STRENGTH AT JOINT HINGING

To assess the seismic resistance of moment resisting frames, strength of the joint hinging should be predicted with high precision, because the flexural strength of beams overestimates the actual strength. To predict the strength of joint hinging failure, a new model is necessary. The Architectural Institute of Japan is going to propose the following equations, simplified based on the theoretical prediction. [12, 14] Test results were used for calibration of some factors. The equation gives the strength reduction factor β_j, which is defined as the ratio of the moment transferring capacity at the node from beams to columns considering joint hinging failure to the moment at the node when flexural strength at the critical section is attained.

Three parameters have been identified as major design factors relating to the strength reduction factor β_j, (a) column-to-beam strength ratio, which also an intrinsic function of the amount of column longitudinal reinforcement and axial force in the column, the depth of the column and the beam, (b) amount of longitudinal rebars in the beam, and (c) amount of joint reinforcement. The concrete compressive strength has been known to have relatively small effect on the strength of joint hinging failure because strength is primarily defined by the yielding of longitudinal rebars in the joint.

The predicted strength reduction factor β_j by the Eqns. 1 and 2 are compared with the tests in Figure 4, which shows a good correlation.

Interior BC joint:
$$\beta_j = \xi_r \left\{ 1 - \frac{a_t f_y}{b_j D_b F_c} + \frac{1}{2}\left(\frac{M_{cu} + M'_{cu}}{M_{bu} + M'_{bu}} - 1 \right) + \frac{1}{4}\left(\frac{a_j f_{jy}}{a_t f_y} \right) \right\} \quad (1)$$

Exterior BC joint:
$$\beta_j = \xi_r \left\{ 0.85 - \frac{a_t f_y}{b_j D_b F_c} + \frac{1}{4}\left(\xi_a \frac{M_{cu} + M'_{cu}}{M_{bu}} - 1 \right) + \frac{1}{2}\left(\frac{a_j f_{jy}}{a_t f_y} \right) \right\} \quad (2)$$

Corner BC joint:
$$\beta_j = \xi_r \left\{ 1 - \frac{a_t f_y}{b_j D_b F_c} + \frac{1}{2}\left(\xi_a \frac{M_{cu}}{M_{bu}} - 1 \right) + \frac{1}{4}\left(\frac{a_j f_{jy}}{a_t f_y} \right) \right\} \quad (3)$$

where, ξ_r : reduction factor listed in Table 1; a function of aspect ratio ξ, ξ: aspect ratio = D_{jc}/D_{jb} , ξ_a: ratio of effective column depth (= D_{jc}/D_c) (shown in Figure 11), D_{jc}: effective column depth , D_c: full depth of column, M_{cu} and M'_{cu}: nodal moment at flexural strength of critical section of upper column (or lower column), M_{bu} and M'_{bu} : nodal moment at flexural strength of critical section of right beam (or left beam), D_b: depth of beam, a_j: total sectional area of the horizontal reinforcement in the BC joint crossing the vertical plane, f_{jy}: yield point of the joint reinforcement steel, a_t: sectional area of the effective tensile reinforcement in the beam section, f_y : yield point of longitudinal reinforcement steel.

Table 1. Reduction factor due to aspect ratio

ξ aspect ratio	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0
ξ_r reduction factor	0.900	0.941	0.970	0.988	0.997	1.000	0.992	0.973	0.949	0.925	0.900

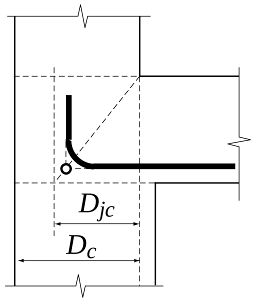


Figure 11. Definition of effective depth of column for exterior BC joint

CONCLUSION

This paper has discussed the key issues of the draft provisions of AIJ Standards with background, test data, theory and analysis with emphasis on why the new concept of joint hinging failure should be necessary. Collapse simulation is made by non-linear time history analysis for moment frames with BC joints failing in joint hinging failure mode, to demonstrate the challenge of simulating strength degradation and severe slip hysteretic relationships inherent to the joint hinging failure. It is concluded that joint hinging failure not only increases of damage to BC joints but also hinders the formation of beam sway mechanisms. As a result, collapse prevention capacity decreases due to accumulation of residual story and resulting collapse due to P-delta effect. The draft equations giving the joint hinging strength of BC joints are also introduced.

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