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STRENGTH MODEL OF REINFORCED CONCRETE BEAM-COLUMN JOINT WITH INSUFFICIENT TRANSVERSE REINFORCEMENT

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Abstract

Recent seismic design provisions for RC moment resisting frames require that reinforced BC joints shall be with sufficient transverse reinforcement. However, in regions of moderate and low seismicity, practice has been to use minimal joint reinforcement. BC joints lacking adequate transverse reinforcement can be vulnerable to shear failure and axial failure. For exterior BC joints, preferred detailing for beam longitudinal reinforcement is to extend the top and bottom bars to the far side of the joint, with hooks bending into the joint. But in older RC frame construction, top bars often have hooks bent upward, and bottom bars have only a short straight anchorage into the joint. This type of detailing affects the strength and failure mode of the joints and the collapse potential of the building. To retrofit the deficient local BC joint is challenging because BC joint is surrounded by beams and slabs and is not easy to access for retrofit construction work. So strategic strengthening by combination of alternative lateral resisting member and auxiliary axial load path to the structural system is necessary for practical seismic retrofit design. To achieve such a comprehensive retrofitting objective in rational way, assessment of the strength of the vulnerable BC joint is key issue. However no reliable model is currently available for lightly reinforced BC joint which does not have sufficient shear reinforcement required by the current codes. Recently, the Architectural Institute of Japan has adopted simplified equations based on model applicable to interior, exterior and knee joints. The equations gives the ratio of strength shortage, which is defined as the ratio of the actual moment transferring capacity at the node from beams to columns to the moment at the node when flexural strength at the critical section in beams is attained. Five major parameters have been considered as major design factors relating to the ratio of strength shortage, (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, (c) anchorage depth ratio of beam bars in beam-column joint, (d) aspect ratio of beam-column joint panel and (e) amount of joint transverse reinforcement. Application of the equations are presented and demonstrated for practical calculation.

Keywords: anchorage length of beam bars, beam-column joint, column-co-beam strength ratio, ratio of strength shortage, transverse reinforcement,

1. Introduction

Shear failure of reinforced concrete (RC) beam-column (BC) joints is an undesirable mode of failure, which lowers the seismic resistance of RC moment frame structures. Risk of collapse increases by the structural instability due to failure of BC joints to gravity load. For these reasons, shear failure of BC joints has been strictly regulated by seismic provisions in major concrete codes, such as ACI, EC8, NZS and AIJ Guidelines [1]. The seismic provisions for BC joint include design for joint shear by joint shear demand and joint shear capacity, which is usually a function of joint configuration of interior, exterior or knee joint, its dimensions and concrete compressive strength. In addition to that they require that BC joints shall be detailed with sufficient transverse reinforcements for confinement like a column. For exterior BC joints, detailing of longitudinal bars in beams should extend the top and bottom bars to the far side of the joint, with hooks bending into the joint.

In older concrete frame constructions, transverse reinforcements in BC joint is usually minimal, top bars often have hooks bent upward, and bottom bars have only a short straight anchorage into the joint. The full strength is not achieved by such types of detailing. The BC joints fails in unfavorable mode and the collapse potential of the building increases. Retrofit of such deficient BC joints to the level of the code compliant BC joint is challenging, because a BC joint is surrounded by beams and slabs and not easy for access and construction work. So strategic strengthening by adding alternative lateral resisting members and auxiliary axial load path to increase redundancy is necessary for practical seismic retrofit design of the building. To achieve such retrofit objectives in a rational way, assessment of the failure mode and estimation of strength of the vulnerable BC joint which does not satisfy the current seismic provision is key issue. But no reliable model for such BC joint is available.

A new AIJ standard for Seismic Capacity Calculation of RC buildings has been published [2] and going to be revised soon which have adopted simplified equations applicable for interior BC joint, exterior BC joint and knee joint including BC joints with insufficient joint hoop and shorter anchorage length. The equations give the strength model, and a way to estimate the mode of failure of BC joint, where, 1) anchorage depth ratio of beam bars in BC joint, 2) aspect ratio of BC joint panel and 3) amount of BC joint transverse are considered quantitatively. The provisions and the method of application of the equations are overviewed and demonstrated here for practical assessment of performance of BC joint including designed by old codes.

The background and necessity of the introduction of the new seismic provisions for RC BC joint in AIJ Standards [2] have been already presented in elsewhere [3]. This paper emphasizes in particular on the practical application of the equations adopted in the seismic provisions for vulnerability assessment of old BC joint.

2. Failure modes of RC beam-column Joint

Three different failure mechanism of BC joint are identified and explained in the AIJ Standard for Seismic Capacity Calculation of RC buildings [2]. They are 1) joint hinging, 2) balanced failure of BC joint and 3) beam hinging. Test results of three BC joint specimens B02 [4], B09 [4] and H01 [5] are selected for typical examples of each failure mechanism shown in Fig. 1, where damage pattern, strength, hysteresis loops, and values of design parameters are given.

Specimen B09 [4] is an over-reinforced BC joint, which failed in joint shear mode with crushing concrete at the center of joint panel, before yielding of longitudinal reinforcing bars, the strength of which is lower than predicted by flexural theory.

Specimens B02 [4] and H01 [5] are lightly reinforced BC joint having the same beam section and longitudinal reinforcement. Specimen B02 has lower strength than H02 and prediction by flexural theory and has poor hysteresis loops with slipping shape. The transverse reinforcement ratio in joint is minimal (= 0.3%) and the column-to-beam strength ratio is 1.0. Specimen B02 failed due to tensile yielding in the longitudinal

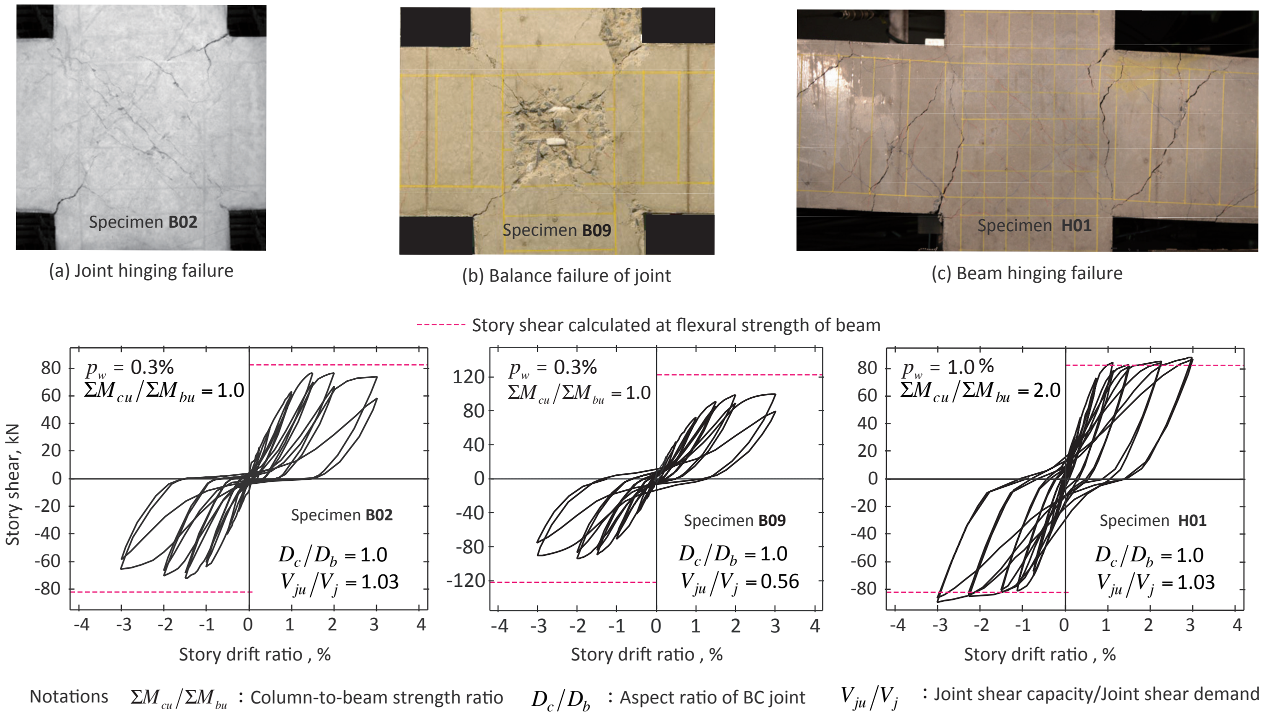

Fig. 1 – Three typical examples of BC joint failure mechanism

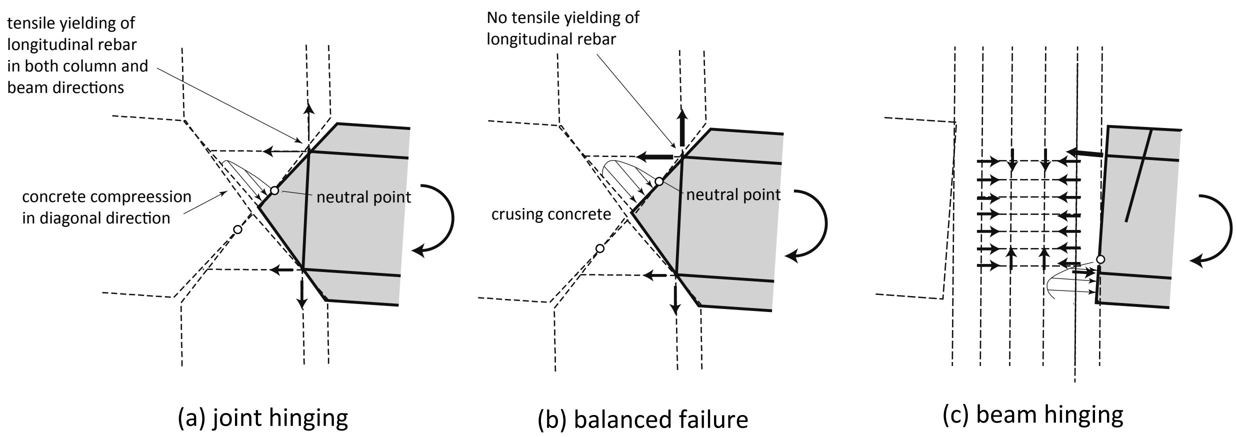

Fig. 2 – Mechanism of three failure types of beam-column joint

reinforcement passing through the joint, for both the vertical and the horizontal direction within the BC joint, just beneath the diagonal cracks near the joint corner. Such type of failure mechanism has been identified and named as joint hinging in the new AIJ Standard [2].

Specimen H01 [5] satisfies the most recent seismic provision. The transverse reinforcement ratio is 1.1% and column-to-beam strength ratio is 2.0, which has full strength of flexural theory and shows good hysteric loops without strength decay within the story drift ratio of 3%. The crack to the joint panel is scarce to see and most deformation occurs at the plastic hinge at beam ends.

The mechanism of the three failure types are explained in Fig. 2. The kinematics of concrete segments and internal forces are depicted. In the joint hinging mechanism, moment from the beams to the columns are transferred in the joint panel by the pair of the tensile force in the steel and the compressive force at the boundary of the triangular concrete segments. The series of test [4, 5, 6, 7, 8] has revealed that the capacity of joint hinging increases with larger amount of vertical and horizontal reinforcement passing through the joint, and the larger axial forces in compression in column and beams. When the amount of joint confinement and column reinforcement is very large, opening of diagonal cracks in BC joint are prevented and the failure mode of joint hinging shifts to beam hinging like Specimen H02.

Over reinforced BC joints like Specimen B09 fails due to so-called joint shear failure. This type of failure is renamed as balanced failure in the new AIJ Standard [2] to distinguish joint hinging from this type of joint shear failure, where concrete crushing occurs earlier than yielding of longitudinal bars in BC joint analogous to the balanced failure of RC sections in flexure.

3. Design Criteria for Balanced Failure of Beam-column Joint

The seismic provisions the new AIJ Standard [2] recommend to avoid balanced failure of BC joint if the BC joint which is designed as a part of a ductile moment resisting frame. The criteria for the BC joint to be satisfied are given by expressions of inequality from (1) to (3) for interior BC joint, exterior BC joint and knee joint respectively.

a) Interior BC joint:

$$\frac{(M_{bu}/j_b)+(M'_{bu}/j'_b)+0.5(N_b+N'_b)-0.5(V_c+V'_c)}{b_j D_{jc}} \le \frac{0.8\xi_R}{\left(1+(\varepsilon_y/\varepsilon_u)\right)}\beta_1\beta_3 F_c \quad (1)$$

b) Exterior BC Joint:

$$\frac{(M_{bu}/j_b)+0.5N_b-0.5(V_c+V'_c)}{b_j D_{jc}} \le \frac{0.8\xi_R}{\left(1+(\varepsilon_y/\varepsilon_u)\right)}\beta_1\beta_3 F_c \quad (2)$$

c) Knee Joint:

$$\frac{(M_{bu}/j_b)+0.5N_b-0.5V_c}{b_j D_{jc}} \le \frac{0.8\xi_R}{\left(1+(\varepsilon_y/\varepsilon_u)\right)}\beta_1\beta_3 F_c \quad (3)$$

where,

M_{bu} and M'_{bu}: bending moment of critical section on the left (right) beam at collapse mechanism,
V_c and V'_c: column shear in upper (lower) column,
N_b and N'_b: thrust force in left (right) beam,
b_j: effective width of BC joint for balanced failure (Fig. 3),
D_{jc}: effective depth of column framing into BC joint (Fig. 4) ,
D_{jb}: effective depth of beam framing into BC joint (Fig. 4),
j_b: distance of resultant in beam section (= 7/8 of effective depth of beam),
β_1 and β_3: factors for stress block of concrete,
F_c: compressive strength of concrete,
ε_y: yield strain of longitudinal reinforcing bars,
ε_u: ultimate strain of concrete (= 0.3 % for ordinary concrete),
ξ_R: modifying factor of strength for balanced failure considering aspect ratio and
ξ: aspect ratio of BC joint (= D_{jb}/D_{jc}).

There is no need to satisfy the criteria for the BC joints monolithically constructed continuous to in plane RC shear walls in the direction of loading as shown in Fig. 5, because an auxiliary load path for moment transfer formed in the RC panel and the BC joint is not vulnerable to joint shear failure.

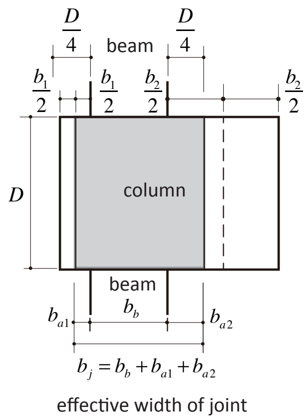

Fig. 3 Effective width of BC joint (balanced failure)

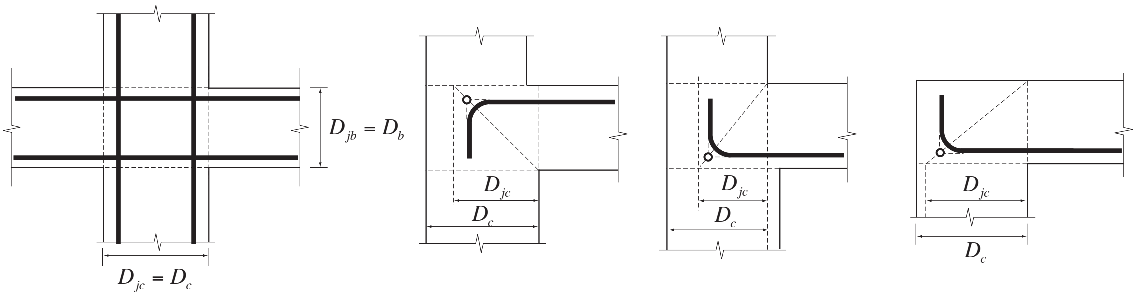

Fig. 4 Effective depth of column and beam frame into BC Joint

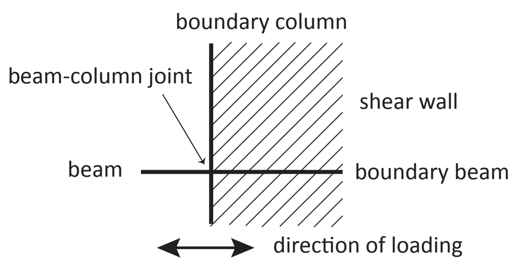

Fig. 5 – BC joint continuous to RC shear wall

To calculate the ultimate bending moment of beam M_{bu} and M'_{bu} for beams the section at the column face are to be considered for critical section. Determine them for each direction of lateral force and critical if the capacity of the beam section is different for positive and negative bending, depending on the directions of lateral load. The effect of slab reinforcement in T-beam section should be considered. The column shear and axial force in beam are to be determined based on the collapse mechanism. The axial force in beams could be neglected except the prestressed beam.

The effective width of BC joint (Fig. 3) is the average of the width of the diagonal compressive strut in BC joint which shares same concept to the older AIJ Guidelines. The effective depth of BC joint (Fig. 4) is determined based on the horizontal dimension of column. It is equal to the full depth of column in case of interior BC joint which the BC joint with beam longitudinal bars passing through the joint. For exterior joint and knee joint, it is determined based on the horizontal distance from the critical section of beam to far end of anchorage bending into the joint, because the diagonal concrete strut develops not from corner to corner but from corner to the far end of anchorage. AIJ Standard require the standard hook for the anchorage in other provisions as a scope. So the criteria is out of scope to the case, where bottom bars in beam have only a short straight anchorage into the joint

It is noted that the value of the term on the right side of the expression becomes smaller when higher strength steel is used analogous to the strength of section at balanced failure. This is also based on the fact the usage of high strength steel cause reduction of joint shear strength in past tests. Factor for concrete stress block β_1, β_3 are same as adopted in ACI 318. Aspect ratio is the ratio of column depth to beam depth. When the aspect ratio is calculated, the effective depth of BC joint (Fig. 5) need to be used. The strength of balanced failure is always maximum at aspect ratio is 1.0 while it decrease if the ratio is smaller than 1.0 or larger. Hence the expression of $\xi_R = (1/2)(\xi + 1/\xi)$ is assumed. This is based on an analytical study by Kusuhara et al [8] but not thoroughly validated by experimental investigation. It is recommended to consider conservative assumption in design. The term on the left side of each expressions is almost the same to the shear stress of BC joint seen in the existing design criteria for joint shear demand. The term on the right side of the expressions are interpreted as joint shear capacity and same despite of joint configuration. This decision is made based on the concept that the shear resistance of BC joint is transferred by compression in diagonal strut and the shear capacity is independent on the configuration of BC joint.

4. Estimation of Strength and Criteria for Failure Mechanism

The other equations adopted by the new AIJ Standard [2] are provided to be used for estimation of moment capacity of joint hinging and failure mode prediction. They are derived from mechanical model prediction by Kusuhara et al. [8,9]. Actually, the equations are formulated to give the ratio of strength reduction β_j, which is the ratio of the moment transferring capacity at the node from beams to columns by joint hinging mechanism to the moment transferring capacity at the node by flexure action of beams.

Major design factors affecting the strength reduction factor β_j are (a) column-to-beam strength ratio, which also an intrinsic function of the amount of column longitudinal reinforcing bar and axial force in the column, (b) amount of longitudinal rebars in the beam, and (c) amount of joint transverse reinforcement. The AIJ Standard [2] recommends to use criteria for design of ductile moment resisting frame with beam hinging mechanism by beam sway mechanism to be achieved the strength reduction factor β_j is to be larger than 1.5.

The strength reduction factor β_j are given from the Eqns. (4) to (6).

a) Interior BC joint:
$$\beta_j = \left\{ 1 - \frac{\Sigma A_t f_y}{b_j D_b F_c} + \frac{1}{2}\left(\frac{\tilde{M}_{cu} + \tilde{M}'_{cu}}{\tilde{M}_{bu} + \tilde{M}'_{bu}} - 1 \right) + \frac{1}{4}\left(\frac{\Sigma A_{jw} f_{jy}}{\Sigma A_t f_y} \right) \right\} \xi_r \tag{4}$$

b) Exterior BC joint:
$$\beta_j = \left\{ 0.85 - \frac{\Sigma A_t f_y}{b_j D_b F_c} + \frac{1}{4}\left(\frac{\tilde{M}_{cu} + \hat{M}'_{cu}}{\tilde{M}_{bu}} \xi_a - 1 \right) + \frac{1}{2}\left(\frac{\Sigma A_{jw} f_{jy}}{\Sigma A_t f_y} \right) \right\} \xi_r \tag{5}$$

c) Corner BC joint:
$$\beta_j = \left\{ 1 - \frac{\Sigma A_t f_y}{b_j D_b F_c} + \frac{1}{2}\left(\frac{\tilde{M}_{cu}}{\tilde{M}_{bu}} \xi_a - 1 \right) + \frac{1}{4}\left(\frac{\Sigma A_{jw} f_{jy}}{\Sigma A_t f_y} \right) \right\} \xi_r \tag{6}$$

where,

ξ_r: reduction factor given in Table 1; a function of aspect ratio ξ,
ξ: aspect ratio (= D_{ic}/D_{ib}),
ξ_a: ratio of effective column depth (= D_{ic}/D_c),
D_{ic}: effective column depth (Fig. 5),
D_c: depth of column,
$\tilde{M}_{cu}$ and $\tilde{M}'_{cu}$: nodal moment at ultimate bending moment of critical section of upper column (or lower column), which considers only the longitudinal reinforcing bars within the effective width of BC joint (Fig. 6),
$\tilde{M}_{bu}$ and $\tilde{M}'_{bu}$: nodal moment at ultimate bending moment of critical section of right beam (or left beam), the contribution of slab reinforcement in T-beam are considered in estimating ultimate bending moment, which should be coincident with the contribution in estimating the lateral capacity of structure,
D_b: depth of beam,
Σa_{jw} : total sectional area of the transverse reinforcement in the BC joint crossing the vertical plane, which is provided between upper and bottom longitudinal reinforcing bars in beam,
f_{jv}: yield point of the joint transverse reinforcement steel,
Σa_t: sectional area of the effective tensile reinforcement in the beam section including the slab reinforcement in T-beam section; if Σa_t in left and right beams are not same, the average value need to be used,
f_y: yield point of longitudinal reinforcement steel, in case, f_y is larger than 395 MPa, the value of f_y should be 395 MPa.

Table 1 – reduction factor for aspect ratio

ξ	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0
ξ_r	0.90	0.94	0.97	0.99	1.00	1.00	1.00	0.97	0.95	0.93	0.90

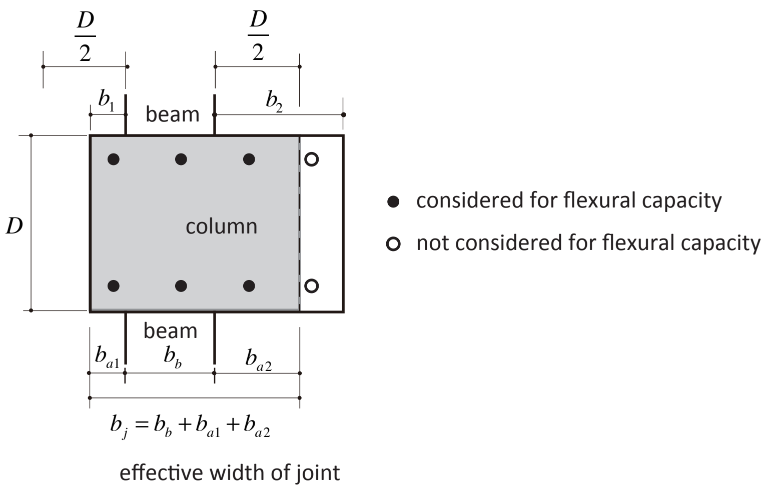

Fig. 6 – Effective width for calculation of column-to-beam strength ratio

The equations from (4) to (6) are applicable to calculation of strength reduction factors β_j provided column-to-beam column joint is larger than 1.0, for interior BC joint, exterior BC joint and knee joint respectively. When the value of β_i is larger than 1.0, the strength at ultimate bending moment of the beam section is achieved. But β_j> 1.0 is not sufficient to keep BC joint within elastic range. This is empirical factor confirmed based on a database examination [4]. AIJ Standard recommend β_j should be larger than a critical value of 1.5 (β_j> 1.5) to expect good plastic hinge of beam ends develops.

For the calculation of the ultimate bending moment of beam-section, the flexural theory assuming plain sections remain plain should be used. For evaluation of column-to-beam strength ratio, usage of nodal moments but moment at critical section are recommended. Full scale 3D shaking test of 10 story RC moment resisting frame tested in 2019 at E-Defense [11] was reported that the performance of BC joint is satisfactory to get beam hinges at beam-ends and joints remained plastic by design of BC joint with β_j=1.5. The equations for strength reduction β_j consider the design parameters including (a) column-to-beam strength ratio, (b) tensile reinforcement ratio in beam, (c) amount of joint hoop, and (d) aspect ratio of BC joint. For exterior beam-column joint and knee joint, the anchorage length of beam longitudinal reinforcement in BC joint. The other parameters indirectly considered are (e) concrete compressive strength, (f) effect of slab, (g) eccentricity of beam axis to column axis, (h) axial force in column. The effect of transverse beams are neglected in the design equations.

The second term in the parenthesis in each equation represents the effect of tensile longitudinal reinforcing bars in beam. As increasing the tensile reinforcement in beam, the strength at joint hinging also increase. But it is not proportional to the tensile reinforcement ratio, because the distance of compressive and tensile resultants decrease in moment resisting mechanism of BC joint. The reduction of this term is slightly decreased by using the high strength concrete. The strength of joint hinging BC joint is known to be decreases as longitudinal reinforcing bars and axis force in column, which is explained by analysis [9,10] and calibrated by tests carried out by the authors [3, 4, 5, 6, 7].

The column-to-beam strength ratio is calculated as follow,

$$\frac{\tilde{M}_{cu}+\tilde{M}'_{cu}}{\tilde{M}_{bu}+\tilde{M}'_{bu}}\ \text{(interior BC joint)}\qquad \frac{\tilde{M}_{cu}+\tilde{M}'_{cu}}{\tilde{M}_{bu}}\ \text{(exterior BC joint)}\qquad \frac{\tilde{M}_{cu}}{\tilde{M}_{bu}}\ \text{(knee joint)}$$

In selecting from the three equations, the configuration of the joint need to be determined by the members contributing to the resistance to the direction of lateral force only. If a crucial shape BC joint is given and one of the beam is cantilever resisting only to gravity load, then the BC joint is exterior. A BC joint at roof floor with extended column upper ward and two transverse beam is knee joint. A beam-column joint in outer frame is interior BC joint if it is loaded to frame direction, whereas it is exterior BC joint in transverse direction.

In each equation for β_j, the third term in the parenthesis represent the effect that beam-column joints with column-to-beam strength ratio close to unity tend to fail in joint hinging. The facter of the term is 1/2 and 1/4 is theoretical. The facter 1/2 is applicable to interior and knee joint, whereas the factor 1/4 is applicable to exterior joint. It relats to the fact where the number of beam per column is half for exterior BC joint than interior BC joint and knee joint.

$$\frac{1}{2}\left(\frac{\tilde{M}_{cu}+\tilde{M}'_{cu}}{\tilde{M}_{bu}+\tilde{M}'_{bu}}-1\right)\ \text{(interior BC joint)}$$

$$\frac{1}{4}\left(\frac{\tilde{M}_{cu}+\tilde{M}'_{cu}}{\tilde{M}_{bu}}\xi_a-1\right)\ \text{(exterior BC joint)}$$

$$\frac{1}{2}\left(\frac{\tilde{M}_{cu}}{\tilde{M}_{bu}}\xi_a-1\right)\ \text{(knee joint)}$$

It is also confirmed by the tests for joint hinging of exterior BC joint [6,8] that the anchorage length of longitudinal beam bars decreases, the joint hinging strength decrease. So effective joint depth ratio is included to count for this fact by multiplying the factor ξ_a to modify the column-to-beam strength ratio.

When the ultimate moment of column section is calculated, the axial force of gravity load should be considered, whereas in the case exterior BC joint, varying axial load needs to be considered at collapse mechanism.

Increasing amount of joint hoop confining BC joint also increases strength at joint hinging significantly independently to column-to-beam strength ratio. So the fourth term in the parenthesis in each equation for β_j represents the effect by normalized by the amount of tensile reinforcing by longitudinal reinforcement in beam. The effect of joint hoop are given as follows,

$$\frac{1}{4}\left(\frac{\Sigma A_{jw} f_{jy}}{\Sigma A_t f_y}\right) \text{ (interior BC joint and knee joint)} \qquad \frac{1}{2}\left(\frac{\Sigma A_{jw} f_{jy}}{\Sigma A_t f_y}\right) \text{ (exterior BC joint)}$$

The value of the factors are validated by a series of test to confirm the theoretical prediction [4,5,6,7,8]. To reduce the deformation of joint relative to beam the sectional area of joint hoop is important than the yield strength of joint hoop. So in design of ductile moment resisting frame structure recommended that the value of β_j is larger than 1.5. For the yield point of joint transverse reinforcement, 390 MPa should be used for the calculation of β_j if the yield point is larger than 390 MPa, due to the fact that the test of joint hinging beam-column joint with joint hoop of high strength steel are scarce and the effect is not well known.

Modification factor ξ_r considers aspect ratio of BC joint to reflect the fact that the joint hinging strength is maximum at aspect ratio = 1.0 [4,5,6,7,8]. The values are shown in Table 1.0 calculated from the equation. The application of the equations to BC joint with aspect ratio smaller than 0.5 or 2.0, where no data for experimental verification exist. But for practical design of BC joint with aspect ratio larger than 2.0, column-to-beam joint are recommended to be larger than reciprocal of the aspect ratio.

Eccentric beam-column joint is BC joint where the center line of beam does not exists on the center line of column. This type of BC joint is pointed to be more vulnerable to joint shear failure by many researchers. There has been no rational seismic provision for this type of BC joint before. The new AIJ Standard [2] treats with this issue by calculating ultimate bending moment of column considering only the longitudinal reinforcing bar in the column close to the centerline of beam to the 3D effect of moment transfer from beam to column, where only the column bars close to beam only effective. It was confirmed by tests that behavior of eccentric BC joint is improved by shift the location of column longitudinal bars far to the beam center to the near the center, strength decrease and damage concentration in BC joint is prevented from.

Actual BC joint in two-way moment resisting frame is subjected to two-direction loading. Also in this case the column-to-beam strength ration have important roll. When it is loaded to 45 degree direction, it is expected that the joint is more vulnerable to joint hinging failure, because column-to-beam strength ratio becomes small. In particular the corner column subjected to 45 degree direction and joint hinging is critical to the collapse vulnerability of the building. The bucking of longitudinal bars in column at damaged BC joint causes loss of axial load carrying capacity and may trigger the structural collapse due to gravity. It is important to have the joint with large safety margin and investigate the behavior for two-way moment resisting frame.

To demonstrate the reliability of the Eqns. (4) and (5), The relationship of the value β_j and column-to-beam strength ratio derived from test result reported in [4, 6] are shonw in Fig. 7, where column-to-beam strength ratio varies from 0.7 to 1.5 for interior BC joints and exteriar BC joints. The joint transverse reinforcement ratio is minimul value of 0.3% for all these specimen. All the BC joints within the range of column-to-beam strength ratio (0.8-2.0) shows joint hinging and joint hinging. It is revealed that the predicted strength reduction factor β_j by the Eqns. 4 and 5 shows a good correlation.

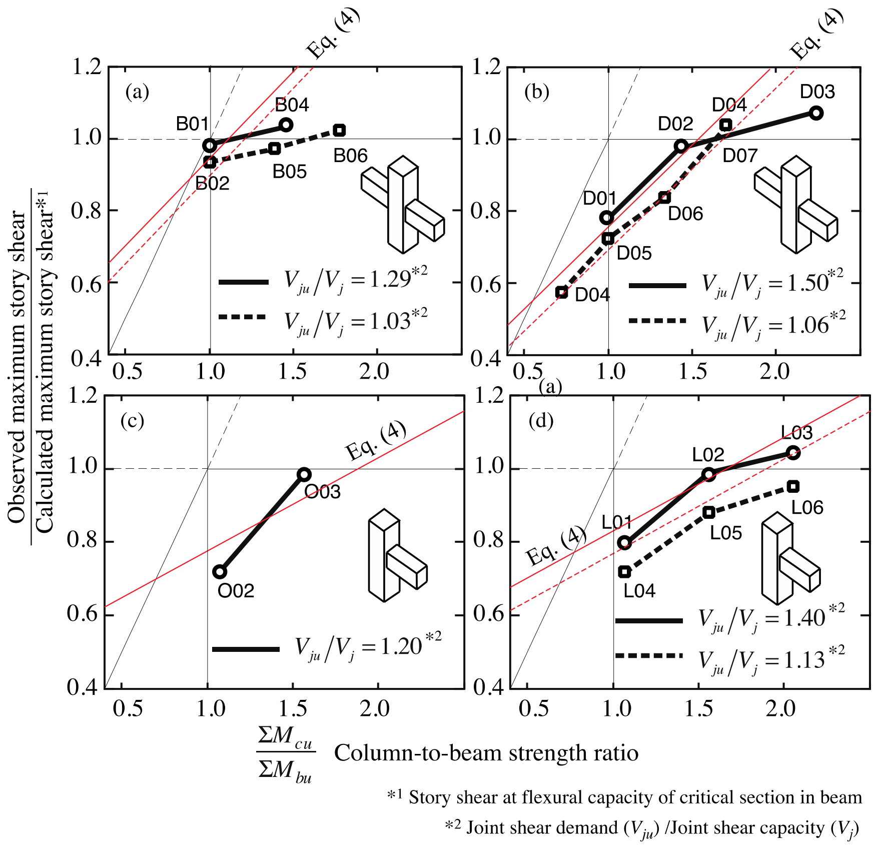

Fig. 7 – Strength reduction of BC joint [4, 6]

6. Concluding Remarks

A new AIJ standard for Seismic Capacity Calculation of RC buildings has been published which adopted simplified equations applicable for interior BC joint, exterior BC joint and knee joint including beam-column joints with insufficient joint hoop and shorter anchorage length. The equations give the strength model, and a way to estimate the mode of failure of BC joint, where, 1) anchorage depth ratio of beam bars in BC joint, 2) aspect ratio of BC joint panel and 3) amount of BC joint transverse are considered quantitatively. The provisions and the method of application of the equations has been overviewed and demonstrated here for practical assessment of performance of BC joint.

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