

DAMAGES TO BEAM-TO-COLUMN JOINT PANELS OF R/C BUILDINGS CAUSED BY THE 1995 HYOGO-KEN NANBU EARTHQUAKE AND THE ANALYSIS

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SUMMARY

During the 1995 Hyogo-ken Nanbu earthquake, it was in beam-column joints and not in columns that the considerable damage occurred in dozens of new reinforced concrete (RC) buildings most of which had to be demolished subsequently.

The buildings that damaged were all one or two-way pure framed structure without walls and the number of stories were more than five. The framed structure of many damaged buildings was one or two spans in one-way and had beams eccentrically connected to columns. Some buildings showed the brittle fracture of joints while others showed the failure of joints after large deformation. In a steel framed RC (SRC) building, crush of concrete in the beam-column joint was confirmed by a core sampled from the joint panel zone. The crush of concrete was restricted to the particular side of the column to which the beam was eccentrically connected. The safety factor for the shear failure of the joints in these buildings was estimated, based on the current design methods, to be more than 1.5 except for several buildings.

This paper shows the state of seismic damage to joints and the distribution of safety factors for the shear failure, and as a consequence, points out the role of eccentric beam-column joints as a cause of the capacity reduction of the joints. Furthermore, we present evaluation methods for the capacity reduction of the eccentric joints in new buildings and the seismic performance of existing buildings taking into account of the shear failure of the joint. Eccentric beam-column joints can cause noticeable reduction of strength in joints and in columns thereby the seismic design in the future may have to take into account of the effect of eccentric convection of beams to a column on the strength of joints and columns.

SEISMIC DAMAGE TO BEAM-COLUMN JOINTS OF RC BUILDINGS IN JAPAN AND RELATED STANDARDS

History

History of the change in the seismic design standards, relating to the seismic damage to beam-column joints in RC buildings in Japan and other countries, is shown in Table 1 where examples of torsional failure of columns and joints due to the eccentric beam-column joints are also included. As shown in the Table, shear failure of columns were found in many school buildings during the 1968 Tokachi-oki earthquake including the ground floor story-collapse of the 4-story RC buildings of Hakodate University where the narrow girders were eccentrically connected to the flat columns, as shown in Fig.1, resulting in the torsional damage to the beam-column joints (Photo 1 and 2). Two years later, experiments of columns and joints with eccentric beam-column joints were executed and the effect of eccentricity on the shear failure was pointed out.

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Table 1: Historical review for observed seismic damages in beam-column joints and columns affected by torsional stress

*May 1968	Damage to Hakodate Univ. due to the Tokachi-oki earthquake (<i>JT, CT</i>)
1970~	Experimental verification of the damage by Morita S. (<i>JT, CT</i>), Sibata T. etc. (<i>CT</i>) and Kamimura T. etc. (<i>JT</i>)
May 1971	Lessons from the Tokachi-oki earthquake was edited in the revision of AIJ RC code (<i>CT</i>) Revision of AIJ SRC code (<i>J</i>)
Nov. 1976	Enforcement of the current building standard code
Jun. 1981	AIJ, Technical note on horizontal capacity and deformability (<i>J</i>) Michoacan earthquake, Mexico (<i>J</i>)
*Sep. 1985	AIJ, data for ultimate strength design (<i>J, T</i>)
Sep. 1987	Luzon earthquake, Philippines (<i>J</i>)
*Jul. 1990	AIJ, RC design guidelines based on ultimate strength concept (<i>J</i>)
Nov. 1990	Northridge earthquake(<i>J</i>)
*Jan. 1994	Hyogo-ken Nanbu earthquake (<i>J, JT, CT</i>)
*Jan. 1995	BCJ, recommendation on structural design for buildings (<i>J</i>)
Oct. 1995	Kagosima-ken Hokuseibu earthquake (<i>JT, CT</i>)
*Mar. 1997	AIJ, RC design guidelines based on inelastic displacement concept (<i>J</i>)
Jul. 1997	BCJ, Structural design guidelines for buildings (<i>J</i>)
Dec. 1997	AIJ, Recommendation to RC structural design after the 1995 Hyogo-ken Nanbu earthquake
Oct. 1998	earthquake (<i>J, JT, CT</i>)

(Marks) *J*: Damage or regulations on beam-column joints, *JT*: Joints with torsion, *CT*: Columns with torsion, *T*: Torsion

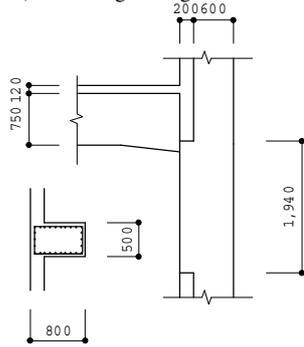


Figure 1: Details of the beam-column joint damaged by the 1968 Tokachi-oki earthquake



Photo 1: The school building of Hakodate Univ. collapsed by the 1968 Tokachi-oki earthquake

With this as a trigger, a big research project dealing with the improvement of deformation capability of buildings was conducted subsequently resulting in the current ductility-oriented seismic regulation in 1981. Unfortunately, before these lessons of the damage and subsequent research results were reflected in the practical design guidelines such as JBC guideline, the 1995 Hyogo-ken Nanbu earthquake occurred and many damages of the same type repeated. However during the interval of these two earthquakes, the ultimate strength type design method for the SRC beam-column joints [AIJ, 1975] was specified as the AIJ (Architectural Institute of Japan) recommendation in 1975 and subsequently for the RC beam-column joints [AIJ, 1990] in 1990. In the subsequent earthquakes such as the 1997 Kagoshima-ken Hokuseibu earthquake and others, the shear or the torsional failure of columns were occasionally observed.



Photo 2: Damaged eccentric beams-column joints due to the 1968 Tokachi-oki earthquake

In the 1995 Hyogo-ken Nanbu earthquake, noticeable damage to the joints was found in more than 50 new mid-to-high rise buildings. As a result, it was commented in the JBC recommendations in October 1995 that the structural design must in principle be applied to the beam-column joints of RC structures, and the revised edition including the design method was issued in December 1997 [BCJ, 1997]. The design method was referred to the revised AIJ recommendation published in July 1997 [AIJ, 1997] but neither the necessary allowance nor the torsional effect were mentioned.

The final report on the analysis of damage in the 1995 Hyogo-ken Nanbu earthquake was issued by AIJ in October 1998 [AIJ, 1998] where notice of the eccentric beam-column joints was pointed out as the necessary improvement for the current seismic design of the beam-column joints.

Current seismic design for the beam-column joint and its improvement

Design method in the Recommendation of Ductility Design of RC Structures [AIJ, 1997]

Outline of the design method of beam-column joints in the AIJ recommendation 1997 is as follows (Fig. 2).

$$S_j = V_{ju} / V_j \geq 1.0 \quad (1)$$

$$V_j = T_1 + C_2 \quad | \quad V_c = T_1 + T_2 - z \cdot f_j \cdot V_j \quad (2a)$$

$$V_j = (T_1 + T_2) / (1 + z \cdot f_j) \quad (2b)$$

$$V_{ju} = (\kappa \cdot \phi) \cdot F_j \cdot (b_j \cdot D_j) \quad (3a)$$

$$V_{ju} = \tau_{ju} \cdot b_c \cdot D_c \quad (3b)$$

here κ and ϕ are shape factors ($1 \sim 0.34$), F_j is the standard concrete strength of joints ($= 1.6 F_c^{0.7} \cong 0.3 F_c$), $b_j \cdot D_j$ are the effective sectional area ($\cong (1 \sim 0.3) b_c \cdot D_c$), b_c and D_c are the width and height of the cross section of the column below the joint, f_j is the ratio of shear force of the column to that of the joint ($= V' / V_j$) and z is the ratio of shear force of the column of upper-story to that of lower-story (V / V'). It is noted that the actual yield strength of the main reinforcement of beams can be used for the calculation of T_1 in the equation (2a), and also taking into account of the yield strength of the relevant floor slab reinforcement.

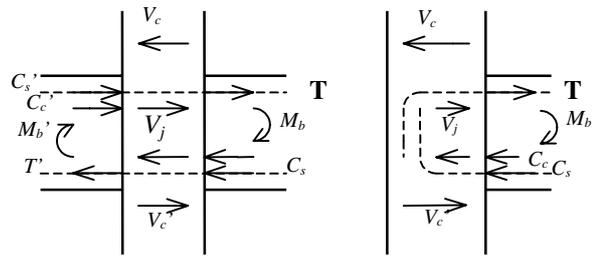


Figure 2: Beam-column joint shear force, V_j

A proposal based on the seismic damage analysis [AIJ, 1998]

It was proposed in the final report [AIJ, 1998] to improve the current structural design method in the following manner.

$$V_{ju} \geq S_j' (1 + e_1) V_j \quad (4)$$

$$S_j' = m \cdot n \geq 1.1 \quad (5)$$

where m is the shear safety factor necessary for the joints and should be more than 1.0, n is the required additional rate for reinforcement due to a strength rise and increase in effective yield strength of reinforcement in floor slabs and should be more than 1.1, e_1 is the ratio of shorter dimension of a column ($\text{Min}(B_c, D_c)$) to the eccentric beam-column distance e and can take $e_1 = 0$ when in the internal frame.

In summary, $S_j \geq 1.0$ in the equation (1) raised $S_j' \geq 1.1 (1 + e_1)$ as a result of taking into account of the eccentric beam-column joints.

A proposal for the seismic retrofitting of existing buildings [AIJ, 1998]

It was proposed in the final report [AIJ, 1998] to add the effect of torsional stress due to the eccentric beam-column joints to the shear capacity of joints evaluated by the current structural design method in the following manner.

$$S_{ij} = V_{ju} / ((1 + e_1) \cdot V_j) \quad (6a)$$

$$F_{ij} = \sqrt{\delta \cdot S_{ij} - \gamma \cdot S_j} \quad (6b)$$

$${}_c Q_{cj} = f_j \cdot S_{ij} \cdot V_{ju} \quad (7)$$

where S_{ij} is the shear safety factor of the joint taking into account of torsion, F_{ij} is the ductility index based on S_{ij} , $c_{Q_{cj}}$ is the shear capacity of column based on the shear capacity of the joint by taking into account of torsion $S_{ij} \cdot V_{ju}$ with $S_{ij}=1.0$ when $S_{ij}>1.0$.

The above equation (6a) evaluates the safety factor in the shear failure of beam-column joints by taking into account of the effect of eccentric beam-column joints.

ANALYSIS OF THE CAUSE OF DAMAGE TO BEAM-COLUMN JOINTS IN BUILDINGS DURING THE 1995 HYOGO-KEN NANBU EARTHQUAKE AND A PROPOSAL FOR NEW DESIGN METHOD

Introduction

The final report on the analysis of damage to RC buildings in the 1995 Hyogo-ken Nanbu earthquake was issued by AIJ in October 1998 [AIJ, 1998]. As one of the four damage characteristics, the damage to the beam-column joint was reviewed in a various manner, the diagnosis of damage, detailed report on the damaged joints, analysis of the cause of the failure and resulting design methods. Thus the AIJ report provided the up-to-date technical information on the seismic damage to the beam-column joints which, however, has not yet reflected in the design method for the new building or seismic retrofitting of the existing building.

Summary of the damage to beam-column joints

The damage to beam-column joints in buildings was summarized as follows.

1. The number of recorded RC buildings with the damage to joints was as much as 50 but the actual number was estimated to be larger.
2. The common factors among the buildings with damage to joints are as follows,
 - a. Not only in RC buildings but also in SRC buildings, damage to the joint was found in the framed structures without walls.
 - b. Nearly all damaged buildings were mid-to-high rise (higher than 6-story) apartment house and the rest was 4 or 5-story school buildings.
 - c. In the damaged buildings whose date of completion were known, two third were built after the current design standard which was put into operation in 1981; Many new buildings were damaged.
 - d. The number of spans in the span direction was one or two, and in the ridge direction, many beams were eccentrically connected to the columns.
 - e. The buildings damaged to the joints were generally demolished without being repaired.

Damage to beam-column joints

As a result of the analysis of the damage to beam-column joints, followings were pointed out.

- a. Among nine severely damaged and carefully inspected buildings, nearly a half of them showed large deformation after the flexural yield of the beam while the rest showed failure of the joints at the moment or before the flexural yield of the beam.
- b. Six of the nine severely damaged buildings had beams eccentrically connected to columns showing noticeable damage only to a side of columns with a beam jointed eccentrically, but nearly no damage to the other side.
- c. The damage to the beam-column joints was particularly noticeable in the cross-shaped joint rather than the T-shaped joint and in the lower stories. The extents of damage to the joints were nearly equal at the same floor.
- d. The shear safety factor S_j (Shear capacity V_{ji} /design shear force V_j) obtained with the newest approach were approximately 1.5 in average and much greater than 1.0 for all the joints damaged except for one example with $S_j<1.0$ showing the brittle fracture. This means that the joints designed to be damage-free failed actually in shear.

A proposal for a new design method

After careful examination of the damage and the current seismic design method for the beam-column joints, we concluded that the increase of the design shear force V_j and the decrease of the shear capacity V_{ju} should be considered. Factors increasing V_j were the increase of the effective range of floor slab reinforcement at the yield of the beam top and the increase of the tensile yield point of reinforcement from the standard value. Factors decreasing V_{ju} were the eccentric beam-column joints and strength reduction due to the large seismic story displacement. We have pointed out these factors and presented their variance in a quantitative manner.



Photo 3: Cracking patterns observed in eccentric beam-column joints of a 9-story RC building (A) with $e_1=0.25$



Photo 4: Concrete crushes observed at surface of eccentric beam-column joints of all story SRC building (B) with $e_1=0.175$

ESTIMATION OF SHEAR CAPACITY REDUCTION DUE TO ECCENTRIC BEAM-COLUMN JOINTS

Seismic damage and related studies

As shown in Table 1 and Fig. 1, the seismic damage to the school building of Hakodate University in the 1968 Tokachi-oki earthquake was the first evidence showing the effect of torsional stress due to the eccentricity on the shear failure of columns and beam-column joints. Subsequent model experiment confirmed a 40% capacity reduction due to the eccentricity. Other seismic damages associated with the torsion can be found and followed by related experiments.

Noticeable damages to joints in the 1995 Hyogo-ken Nanbu earthquake were associated with the eccentric beam-column joints. Examples of damage to the joint are shown in Photo. 3, a 9-story RC building ($e_1=0.25$) and in Photo. 4, an 11-story SRC building ($e_1=0.175$). Photo. 5 shows damage to concrete sampled from the eccentric joint shown in Photo. 4. The damage to joints were noticeable only in the perimeter frame where beams were eccentrically connected to columns but nearly no damage was observed in the inner frames see also Fig. 3.

In order to evaluate the above damages and related experiments, we have proposed an evaluation method taking into account of the torsional stress affecting the shear capacity of beam-column joint.

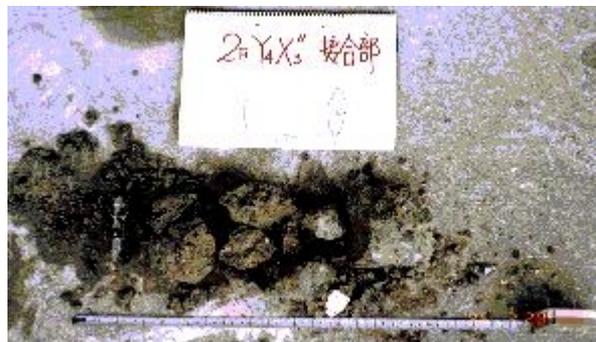


Photo 5: Concrete crushes observed in a concrete core drawn out from the damaged joint of the building B

The failure criteria formula has been proposed for RC members where the torsional moment and the bending shear work in the same way [Ersoy and Ferguson, 1967].

$$\left(\frac{Q_u}{Q_{uo}}\right)^2 + \left(\frac{T_u}{T_{uo}}\right)^2 = 1 \quad (8)$$

where Q_u and Q_{uo} are the shear force at failure and pure shear capacity under the combined stresses and T_u and T_{uo} are the torsional moment at failure and pure torsional capacity, respectively.

We adopted equation (8) to evaluate the shear capacity of the beam-column joint under torsional stress, but for the torsional moment and the pure torsional capacity, we proposed the following formula.

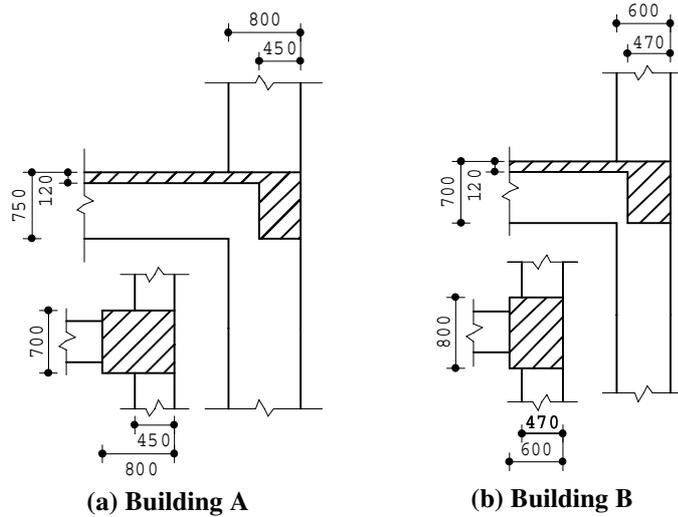


Figure 3: Details of eccentricity of beams to columns in the buildings A and B (in mm)

Let $Q_u=V_{jt}$ be the shear capacity of the beam-column joint at failure under the torsional moment, $Q_{uo}=V_{ju}$ be the shear capacity of the beam-column joint based on the equation (3a), $T_u=T_j$ be the torsional moment at failure under combined torsion and shear, which may be evaluated as $T_j = V_{jt} \cdot e$ and $T_{uo}=T_{jo}$ be the pure torsional capacity of the beam-column joint and can be evaluated with the equation (9)[Hirosawa, 1998].

$$T_{jo} = (0.8\sqrt{F_c} + 0.45 p_j \cdot \sigma_{jy}) B^2 \cdot D \quad (9)$$

Where p_j and σ_{jy} are the shear reinforcement ratio of the perimeter beam-column joint and the yield point, and B and D are the dimensions of short and long dimension of the column in the joint, respectively.

Relationship between calculated value using equation (8) to (9) and measured value are shown in Fig. 4 where the calculated values based on the proposed equation agree well with the experimental values.

Shear capacity reduction rate of the beam-column joints due to the eccentricity

Evaluating the shear capacity of the eccentric beam-column joints using equations (8) to (9), the capacity reduction rate β_{jt} due to the eccentricity can be given by the equation (10).

$$\beta_{jt} = \frac{V_{jt}}{V_{ju}} = \frac{1}{\sqrt{1 + (e_j \cdot K_{ju} / K_{to})^2}}$$

where $K_{ju} = V_{ju} / (B_c \cdot D_o)$, $K_{to} = T_{jo} / (B^2 \cdot D)$ and $e_j = e/B$, so that the shear capacity of the beam-column joint under torsion (V_{jt}) and the shear safety factor (S_{jt}) can be evaluated with equations (11) and (12) respectively.

$$V_{jt} = \beta_{jt} \cdot V_{ju}$$

$$S_{jt} = V_{jt} / V_j$$

Equivalent story shear coefficient at the failure of joints

The shear failure of the beam-column joints leads to more serious damage when all the joints in a building failure at the same time, thereby it is necessary to know the horizontal load-carrying capacity of a building at the moment of the failure of joints. We have derived an equation to evaluate the

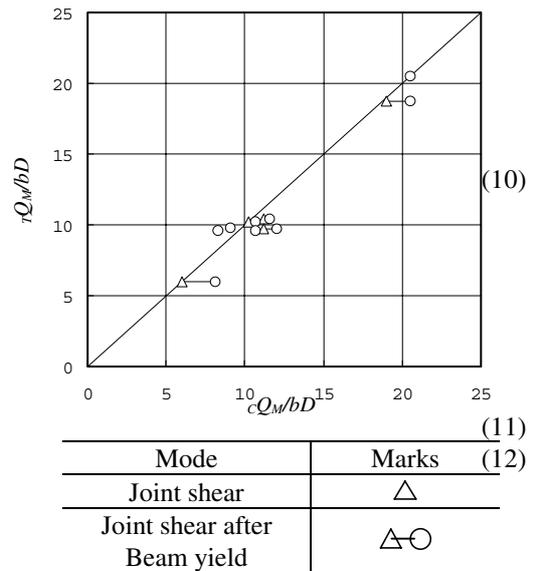


Figure 4: Comparison of calculated capacities (cQ_M) with test results (τQ_M) due to combined stresses

equivalent story shear coefficient at the shear failure of joints on the basis of the following two assumptions.

- a. All the beam-column joints in a floor failure at the same time.
- b. The frame stress due to the horizontal load has the inflection points at the mid-span of the beams and the columns.

$$C_{ji} = \sum_c Q_{cji} / W_i \quad (13a)$$

where C_{ji} is the equivalent story shear coefficient of the i -th floor at the shear failure of the beam-column joints, $Q_{cji} = f_{ji} \cdot \beta_{ji} \cdot V_{jii}$ is the shear force of columns of the i -th floor at the shear failure of the beam-column joints and is $W_i = w_i \cdot \sum A_{fi}$ the mass of building higher than the i -th floor with $\sum A_{fi}$ the total floor area and w_i the unit mass of floor.

With equation (3b), C_{ji} can be rewritten as (13b),

$$C_{ji} = f_{ji} \cdot \beta_{ji} \cdot \overline{\alpha_{ji}} \cdot a_{ci} / w_i \quad (13b)$$

where $\overline{\alpha_{ji}}$ is the mean shear stress of all the i -th floor columns at the shear failure of the beam-column joints and a_{ci} is the ratio of the sum of the sectional areas of all the i -th floor columns $\sum A_{ci}$ to the $\sum A_{fi}$.

With equation (13b), C_{ji} can be calculated without regard to the reinforcement arrangement of the beam and column by substituting parameters such as mass of the building, dimensions of beam and column cross section, floor height and span and the beam-column eccentricity.

3.4 S_j, β_{ji}, C_{ji} of damaged buildings

Using the equations mentioned above, the shear safety factor (S_j and S_{ji}), the eccentric ratio (e_j), the capacity reduction ratio due to eccentricity (β_{ji}) and the equivalent story shear coefficient at the failure of joints (C_{ji}) were determined covering the buildings with damage to joints as examined in the AIJ report [AIJ, 1998] in detail. The results are shown together with the extent of damage of joints or buildings in Table 2 where the followings are found.

- a) When damage to joints occurred before noticeable cracks was found in beams and columns, S_{ij} of many buildings was approximately 1.0.
- b) When beams, columns and joints were severely damaged, C_{ji} of many buildings was approximately 0.3 or S_{ij} and C_{ji} were 1.3 to 1.4 and approximately 0.5 respectively.
- c) The rate of capacity reduction due to beam-column eccentricity ranged from 0.75 to 0.99 in RC buildings and 0.64 in SRC buildings where the shear stress level was high at the failure of joints.
- d) Of the seven damaged buildings, five were designed according to the current seismic design standards and their equivalent story shear coefficients at the failure of joints were generally greater than 0.4. Appropriate values have to be given both to S_j and C_j for strong earthquakes

CONCLUSIONS

The shear failure of the beam-column joints was found in many RC mid to high rise buildings damaged during 1995 Hyogo-ken Nanbu earthquake. Though the collapse was unconfirmed, the failure of joints, a dangerous failure type likely to result in the total collapse, has to be avoided.

We studied the factors affecting the failure and proposed an objective design method as follows.

- a) We showed that the shear capacity of the beam-column joints can be significantly reduced by the eccentric beam-column joint and proposed an equation capable of evaluating the capacity reduction due to the eccentricity.
- b) To avoid the shear failure of joints, it is necessary to give an appropriate value not only to the shear safety factor of joint S_j but also to the equivalent story shear coefficient of building C_j at the moment of the shear failure of joints. An equation capable of evaluating C_j is proposed.

Table 2: Safety factors for joint shear failure at the joints of the damaged buildings with beam-column eccentric connection and story shear coefficients at joint shear failure

Mark of Building	Construction No. of stories	Mode ^{*1}	i-th floor ^{*2} Type of Joint	K_{ju} ^{*4}	$\frac{V_j}{(b_c \cdot D_c)}$ ^{*4}	S_j	e_1	K_{TO} ^{*4}	β_{ji}	S_{ji} ^{*2}	C_{ji}
RM-M	RC-8	Collapsed CS, JS	2nd ┣	55.4	29.6	1.87	0.25	20.5	0.83	1.55 ^{*3}	0.34~1.04
CA (B)	SRC-11	Hardly damaged BY, JS	6th +	87.9	57.0	1.54	0.13	16.6	0.80	1.23	0.66~2.13
DH-B	RC-8	Hardly damaged BY, JS	5th +	45.1	32.3	1.40	0.21	12.8	0.80	1.12	0.46~0.78
JR (A)	RC-9	Hardly damaged BY → JS	3rd +	58.4	39.5	1.48	0.25	21.8	0.83	1.23	0.63~1.17
M	RC-5	Hardly damaged BY → JS	2nd ┣	21.5	26.3	0.82	0.23	11.3	0.91	0.75	0.25~0.33

(Note) *1 CS, JS: Shear failure of columns and joints; BY: Flexure yield of beams;

BY → JS: Joint shear failure under large deflection after beam yield

*2 Results of the i-th-floor with the smallest S_j , S_{ji} are listed.

*3 Noticeable influence due to stresses from two directions was observed.

*4 Unit: kg/cm^2

c) Buildings damaged to the joints during the 1995 Hyogo-ken Nanbu earthquake showed the failure of joints before the plastic deformation of beam-column developed when S_{ji} was approximately 1.0, but buildings with S_{ji} more than 1.3 showed the failure of joints under a large deformation such as the plastic deformation of beams and columns.

d) To avoid the shear failure of beam-column joints, the shear safety factor S_{ji} and equivalent story shear coefficient C_{ji} , taking into account of eccentric joints, should be more than 1.3 and 0.4 respectively for strong earthquake such as the 1995 Hyogo-ken Nanbu earthquake.

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