*16th World Conference on Earthquake, 16WCEE 2017*
*Santiago Chile, January 9th to 13th 2017*
*Paper N° 2746*
*Registration Code: S-E1461993022*

# Failure Mechanism of Beam-column Joint of Reinforced Concrete Frame with Non-structural Walls

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## *Abstract*

In this study, the design procedure of failure mechanism around the beam-column joint of frame with non-structural wall were discussed. The experiment of the beam-column joint with non-structural walls were conducted. The parameter of the specimens are column-beam strength ratio considering the effect of non-structural wall, wall thickness, fixing condition of horizontal reinforcement of the standing and hanging wall, vertical reinforcement of column with wing wall and height of contrary flexure of column. The conclusions were obtained as follows; 1) the failure mode of beam-column joint with non-structural wall, that beam-column strength ratio is more than 1.5, would be beam failure mode clearly. 2) To use large size reinforcement for the vertical reinforcement of wing wall, the damage of the wing wall was avoided, and the failure mechanism was changed to the beam failure mode. 3) The height of contrary flexure of column to be higher, the failure mechanism was changed to the column failure.

*Keywords: Reinforced Concrete, Beam-column Joint, Non-structural Wall, Failure Mechanism*

## 1. Introduction

In recent years, the design method of the reinforced concrete frame with non-structural walls to control damage of the buildings were discussed. The reinforced concrete frame with non-structural walls could easily have high rigidity and strength than that without non-structural walls. And, forces acting on beam-column joint would be decreased. It is important to be a beam failure mechanism of the frame under the earthquake for continuous using. In this study, the design procedure of failure mechanism around the beam-column joint of frame with non-structural wall were discussed.

Tajiri et. al. and Suwada et. al. conducts the experiment of 2-story 1-span RC frame with non-structural walls, such as wing-wall, hanging-wall and spandrel wall.[1,2] The parameters of specimens are setting or not setting the structural slit at the edge of wall and wall thickness. The experimental results showed that the stiffness and horizontal strength of the frame were decreased as setting the structural slit. The failure mechanism of the both of the frames, that parameter is wall thickness, is total collapse mechanism: bending failure at 2nd floor beam and bottom of 1st floor column.

Tajiri et. al. also conducts the experiment of 2-story 2-span RC frame with non-structural walls [3]. The parameter of specimen is wall thickness. The failure mechanism of the specimen that with thin wall was total collapse mechanism and that with thick wall was partial collapse mechanism at 2nd floor. The failure condition of beam-column joint at the center of 2nd floor would affect the failure mechanism of the frame. To insure safety for that kind of RC buildings, the partial collapse mechanism should be avoided. The design of the beam column joint with non-structural wall is important to control the failure mechanisms of the whole frame.

In this paper, the design procedure of beam-column joint with non-structural wall are proposed. To apply the proposed design procedure, the experiment of the beam-column joint with non-structural walls are conducted. The parameter of the specimens are column-beam strength ratio considering the effect of non-structural wall, wall thickness, fixing condition of horizontal reinforcement of the standing and hanging wall, vertical reinforcement of column with wing wall and infraction point height of column.

## 2. Experimental Program

### 2.1 Specimens

The experiment of the beam-column joint with non-structural walls are conducted. The basic bar arrangement are designed due to the referred paper[3]. The scale of the specimen is about 5/16.

An example of bar arrangement (specimen No.3) are showed in Fig.1. The parameters of specimen are shown in Table 1. There are 8 specimens, named No.1 to No.8. The parameter of the specimens No.1 to No.4 is wall length of the wing wall as 150mm, 200mm, 250mm, 300mm, to control the column-beam strength ratio contains the effect of non-structural wall. Specimen No.5 has thin wall than specimen No. 3. Specimen No.6 has same bar arrangement of specimen No.1, but the horizontal reinforcement of standing and hanging wall is not fixed to the wing wall. Specimen No.7 has same column-beam strength ratio of specimen No.2, but the main reinforcement of column is decreased and vertical reinforcement of wall is increased than specimen No.2. Specimen No.8 has deferent infraction point height of column, that bar arrangement is same to specimen No.3.

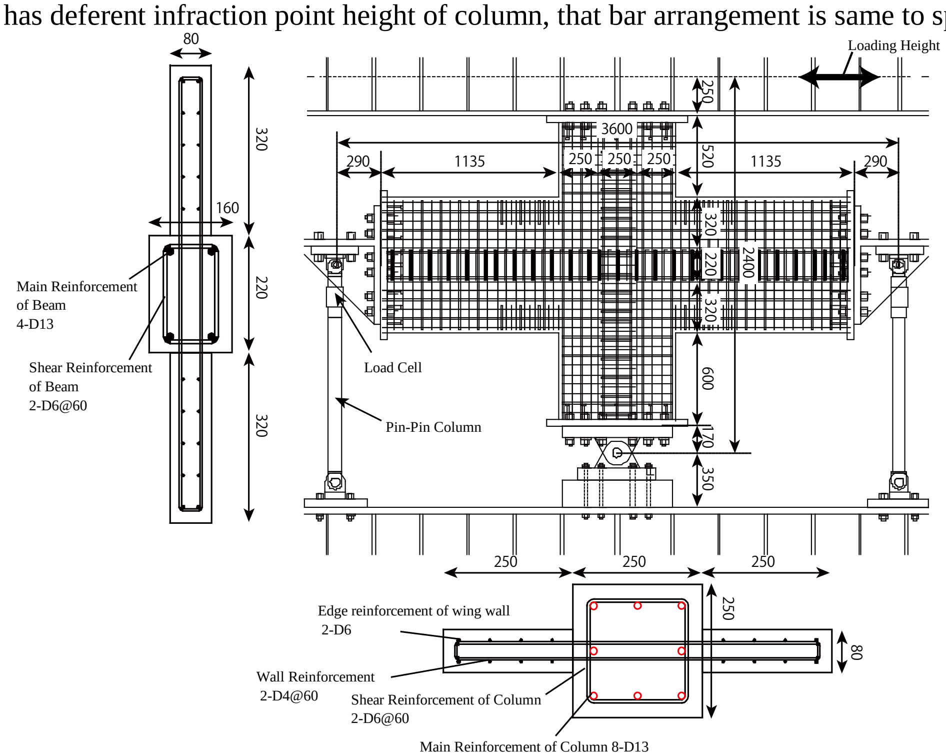



Fig. 1 – Example of bar arrangement (Specimen No.3)

Table 1– Parameters of Specimens

| No. | Wing Wall Length $L_w$ [mm] | Wall Thickness $t_w$ [mm] | Main Reinforcement of Column ($p_g$) | Horizontal Reinforcement of wall | Vertical Reinforcement of wing wall | Edge Reinforcement of wing wall | Fixed Condition of Horizontal wall Reinforcement | Infrection Point Height of Upper |
|---|---|---|---|---|---|---|---|---|
| 1 | 150 | 80 | 8-D13 (1.63%) | 2-D4@60 (0.58%) | 2-D4@60 (0.58%) | 2-D6 | Fixed | 1200 |
| 2 | 200 | | | | | | | |
| 3 | 250 | | | | | | | |
| 4 | 300 | | | | | | | |
| 5 | 250 | 50 | | D4@60 (0.47%) | D4@60 (0.47%) | D6 | | |
| 6 | 150 | 80 | | 2-D4@60 (0.58%) | 2-D4@60 (0.58%) | 2-D6 | Non-Fixed | |
| 7 | 200 | | 16-D6 (0.82%) | | 2-D6@60 (1.33%) | 2-D10 | Fixed | |
| 8 | 250 | | 8-D13 (1.63%) | | 2-D4@60 (0.58%) | 2-D6 | | 1600 |

## 2.2 Material Property

The material characteristics of concrete and steel are shown in Table 2 and 3. The specified compressive strength of concrete is about 28 N/mm$^2$, and yield strength of reinforcement is 357 N/mm$^2$ for wall reinforcement of wall, 375 N/mm$^2$ for shear reinforcement of column and beam and about 400 N/mm$^2$ for longitudinal reinforcement of column and beam.

Table 2 – Material characteristics of concrete

| Specimen | Young Modulus [N/mm$^2$] | Comp. Strength [N/mm$^2$] | Tens. Strength [N/mm$^2$] |
|---|---|---|---|
| No.1,2 | $2.28\times10^4$ | 28.4 | 2.00 |
| No.3,4 | $2.35\times10^4$ | 29.0 | 1.69 |
| No.5,6 | $2.37\times10^4$ | 27.8 | 2.55 |
| No.7,8 | $2.35\times10^4$ | 28.1 | 2.50 |

Table 3 – Material characteristics of steel

| Diameter | | Young Modulu [N/mm$^2$] | Yield Strength [N/mm$^2$] | Yield Strain [μ] | Tensile Strength [N/mm$^2$] |
|---|---|---|---|---|---|
| D4 | SD295A | $1.54\times10^5$ | 357 | 2361 | 519 |
| D6 | SD345 | $1.82\times10^5$ | 375 | 2066 | 503 |
| D10 | SD345 | $1.79\times10^5$ | 413 | 2317 | 566 |
| D13 | SD345 | $1.78\times10^5$ | 407 | 2294 | 569 |

## 2.3 Loading Program

A static cyclic loading test with constant axial force is conducted. The loading instrument is shown in Fig.2. Constant axial force is 165kN, as the axial force ratio for column is about 0.1. The loading cycle is controlled based on relative rotational angle of column R. The loading cycle is R=1/1600, 1/800, 1/400, 1/200, 1/100, 1/50, 1/33, 1/25. The infraction point height of upper column is changed due to the horizontal displacement of loading beam, as shown in Fig.2.

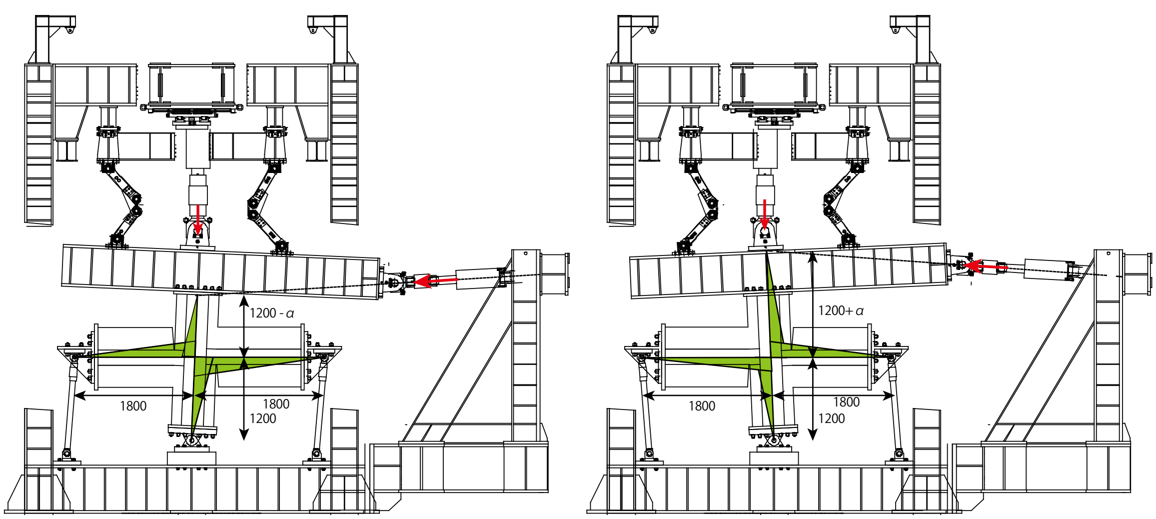



Fig. 2 –Loading Instrument

## 2.4 Design Procedure

In this section, the design procedure for the beam-column joint with nonstructural walls are proposed. The flow of the proposed design procedure are shown in Fig. 3. In this paper, we defined 3 types of failure mode of beam-column joint with non-structural wall; beam-failure mode without the failure at the crossing section of wing-wall and standing, hanging-wall (call Failure mode B), beam-failure mode with the failure at the crossing section of wing-wall and standing, hanging-wall (call Failure mode B+W), and column-failure mode without the failure at the crossing section of wing-wall and standing, hanging-wall (call Failure mode B). The steps of the proposed design procedure is as follows.

Step 1. Calculate the column-beam strength ratio $M_{jc}/M_{jbu}$ at the node to judge that the compressive failure at the edge of the wing wall is caused before the bending moment of the beam reaching the ultimate strength of beam with non-structural wall or not. If the column-beam strength ratio $M_{jc}/M_{jbu}$ is larger than 1.0, the failure mode of beam-column joint would be failure mode B. If the column-beam strength ratio $M_{jc}/M_{jbu}$ is less equal 1.0, the failure mode of beam-column joint would be failure mode B+W or C+W, go to step 2.

Step 2. To evaluate the compressive failure are (and line) of the crossing section of walls, calculate the neutral axis Xn of column and beam on the condition at the ultimate strength of column or beam. To calculate the neutral axis Xn, we assumed the distribution of compressive stress is stable as Fc. The compressive failure area is defined due to the neutral axis Xn, as shown in Fig.2. The compressive failure line is defined as the diagonal line of the compressive failure area.

Step 3. Continue calculation for reaching the compressive failure line to the face of the column or beam.

Step 4. Calculate the column-beam strength ratio $M_{jcu}'/M_{jbu}'$ , that is calculated based on the residual dimension of column with wing wall and beam with hanging/standing wall. If the column-beam strength ratio $M_{jcu}'/M_{jbu}'$ is larger than 1.0, the failure mode of beam-column joint would be failure mode B+W. If the column-beam strength ratio $M_{jcu}'/M_{jbu}'$ is less equal 1.0, the failure mode of beam-column joint would be failure mode C+W.

The calculation results to apply the proposed design procedure to the specimens are shown in Table 4. In the calculation, the maximum strength is calculated at rotational angle R=1/100, and considering the change of the infraction point height of upper column. Due to changing the wall length (specimen No.1 to No.4), $M_{jc}/M_{jbu}$ is increased and failure mode is changed C+W to B. The wall thickness don't affect the failure mode, compare with specimen No.3 and No.5. Not to fixed the horizontal reinforcement of wall, specimen No.5, the failure mode is changed to B, and maximum strength is quite decrease. To change the bar arrangement of column with wing wall (compare with specimen No.7 and No.2), the failure mode can control to failure mode B.

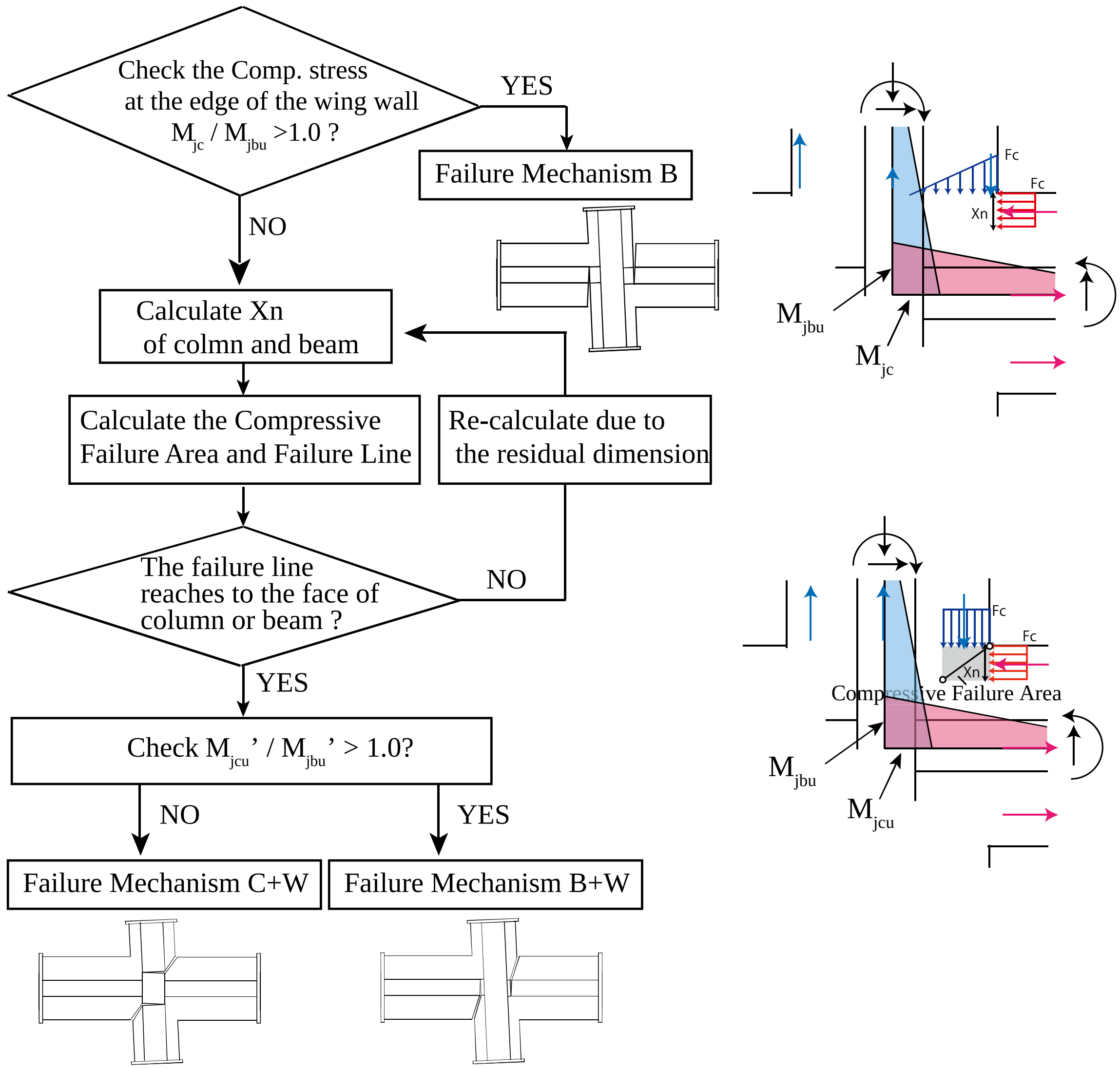



Fig. 3 –Flow chart of the proposed design procedure

Table 4 – Calculation Results

| No. | $M_c$* [kNm] | Ultimet Bending Moment $M_u$ [kNm] Column | Ultimet Bending Moment $M_u$ [kNm] Beam | $M_{jc}$ / $M_{jbu}$ | Positive Direction R=1/100 $M_{jcu}$ / $M_{jbu}$ | Positive Direction R=1/100 Max. Nodal Moment [kNm] | Positive Direction R=1/100 Failure mode | Negative Direction R=-1/100 $M_{jcu}$ / $M_{jbu}$ | Negative Direction R=-1/100 Max. Nodal Moment [kNm] | Negative Direction R=-1/100 Failure mode |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 31.4 | 100.3 | 124.0 | 0.88 | 1.03 | 292.7 | C+W | 0.97 | 283.9 | C+W |
| 2 | 39.6 | 127.9 | | 0.97 | 1.24 | 302.6 | B+W | 1.22 | 302.6 | B+W |
| 3 | 49.6 | 161.4 | 124.3 | 1.1 | 1.55 | 314.0 | B | 1.50 | 314.0 | B |
| 4 | 60.7 | 195.5 | | 1.25 | 1.81 | 325.4 | B | 1.76 | 325.4 | B |
| 5 | 34.0 | 119.0 | 94.3 | 1.01 | 1.52 | 238.2 | B | 1.47 | 238.2 | B |
| 6 | 31.1 | 98.9 | 78.1 | 1.38 | 1.59 | 184.4 | B | 1.49 | 184.4 | B |
| 7 | 42.4 | 131.1 | 123.6 | 1.02 | 1.31 | 301.7 | B | 1.26 | 301.7 | B |
| 8 | 49.4 | 160.0 | 124.0 | 0.75 | 1.13 | 313.3 | C+W | 1.00 | 313.3 | C+W |

*1 Mc: Bending moment of column, the comprressive stress at the edge of compressive wall is just reached Fc.

## 3. Experimental results

The relationship between nodal moment and rotational angle and crack pattern after the loading are shown in Fig. 4. The nodal moment is calculated using the measured shear force of beam, see Fig. 1. In the relationship between nodal moment and rotational angle, a calculated nodal moment at the bending failure of column is shown as dot line, and that of beam is shown as solid line.

From specimen No.1 to No.4, horizontal reinforcement of standing/hanging wall is yielded on R=1/400 cycle, and vertical reinforcement of wing wall is yielded on R=1/200 cycle, and reached maximum strength on R=1/100 cycle. On specimen No.1, main reinforcement of column and beam are yielded on R=1/100 cycle, and the compressive failure on the crossing section of walls are occurred. The failure mode of specimen No.1 is C+W. A calculated failure line, shown in Fig.4 (a) is good agreed with the experimental failure area. On specimen No.2, main reinforcement of beam is yielded on R=1/100 cycle, the compressive failure on the crossing section of walls are occurred. The failure mode of specimen No.2 is B+W. A calculated failure line, shown in Fig.4 (b) is good agreed with the experimental failure area. On Specimen No.3 and No.4, a main reinforcement of beam is yielded on R=1/200 cycle. The failure mode of specimen No.3 and No.4 are failure mode B that is agreed with calculated results.

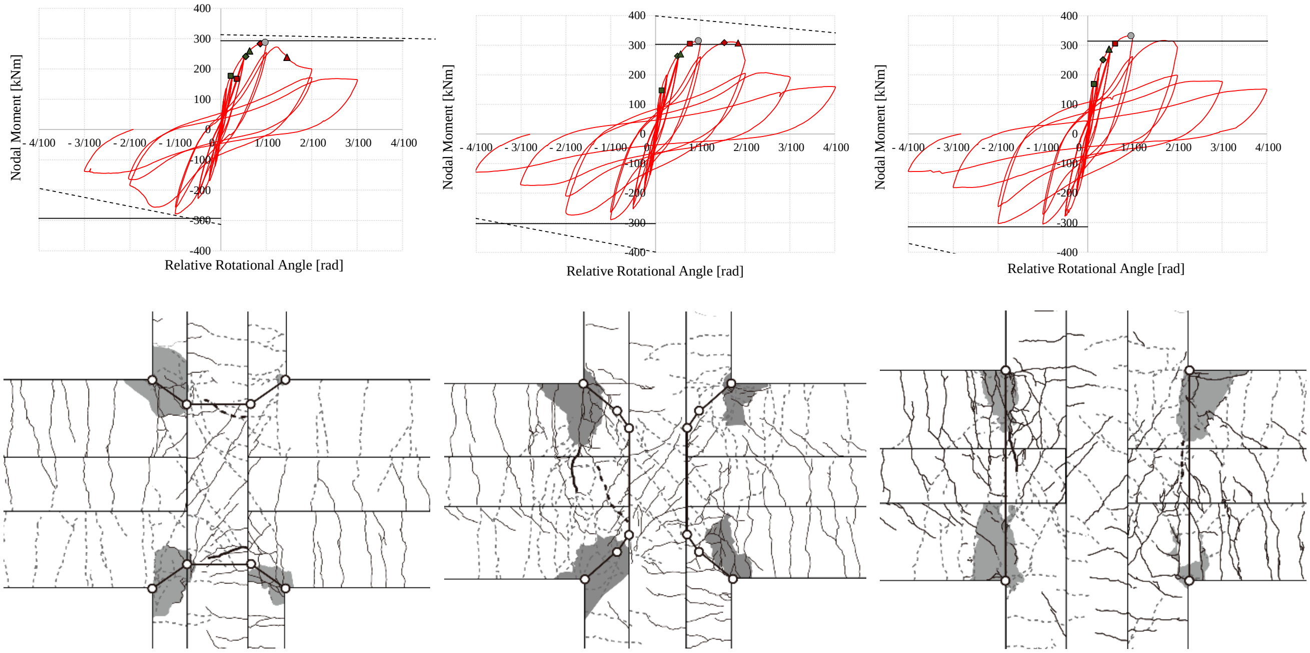
On Specimen No.5, the failure mechanism is almost same as specimen No.3. The maximum strength of specimen No.5 is quite smaller than specimen No.3. The failure mode of specimen No.5 is failure mode B that is agreed with calculated results.

On specimen No.6, the bending crack of beam is occurred on R=1/3200 cycle. After that, the stiffness is quite decreased. The cracks of beam with standing/hanging wall is less than the other specimens, and concentrated on the face of the wing wall. The shapes of the relationship between nodal moment and rotational angle are like slip type.

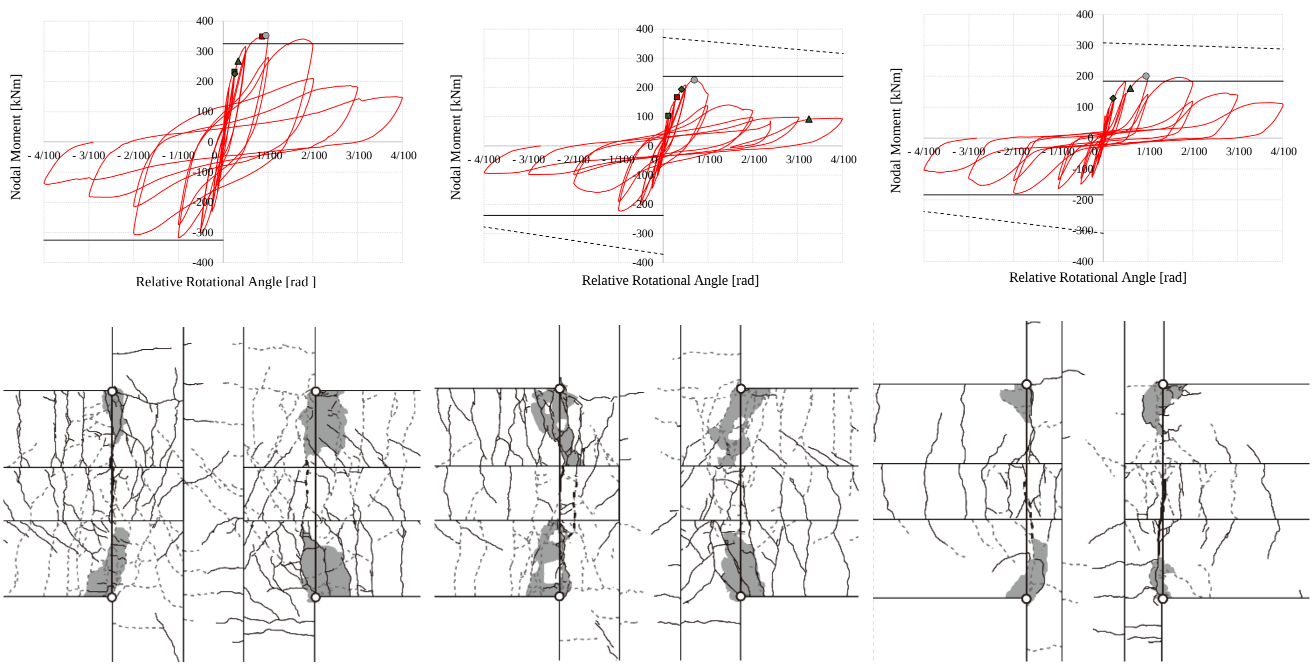
On specimen No.7, the failure area is concentrated on the face of the wing wall and compressive failure of the crossing section of walls is controlled, compared with specimen No.2. The failure mode of specimen No.7 is failure mode B that is agreed with calculated results.

On specimen No.8, a bending failure is occurred on upper column, because of the deference of infraction point height. The failure mode of specimen No.8 is failure mode C+W. A calculated failure line, shown in Fig.4 (h) is good agreed with the experimental failure area.

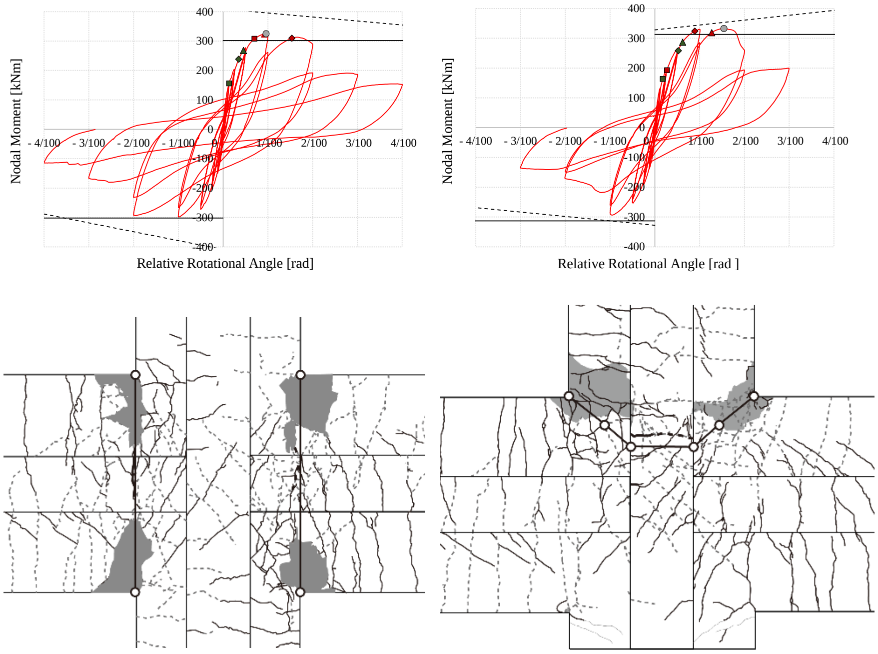
The experimental results showed that the proposed design procedure could evaluate the maximum strength and failure mode of the beam-column joint with non-structural wall clearly.




(a) Specimen No.1 (b) Specimen No.2 (c) Specimen No.3




(d) Specimen No.4 (e) Specimen No.5 (f) Specimen No.6




(g) Specimen No.7 (h) Specimen No.8

Fig. 4 –Relationship between nodal moment and rotational angle and crack patern

## 4. Conclusions

The design procedure for the beam-column joint with nonstructural walls were proposed. To apply the proposed design procedure, the experiment of the beam-column joint with non-structural walls are conducted. The parameter of the specimens are column-beam strength ratio considering the effect of non-structural wall, wall thickness, fixing condition of horizontal reinforcement of the standing and hanging wall, vertical reinforcement of column with wing wall and infraction point height of column. The proposed method was applied to the specimens, and the calculation result was good agreed with the experimental result.

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