Seismic Response of Three-dimensional Multi-story Steel Moment Frames with Eccentricity

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SUMMARY:
This paper presents the seismic response of three-dimensional multi-story steel moment frames with eccentricity. A simplified structural model was used to analyze the frames with eccentricity either in a particular story or on all stories of column or beam. The results of our analyses revealed damage concentration and in some cases even story collapse near the stories with eccentricity. In addition, factors that caused damage concentration or story collapse were evaluated with the story shear, torsional and bending moment observed in the frames. The simplified structural model was used to clarify the characteristics of the seismic response in the frame with floor eccentricity.

Keywords: Seismic response, Eccentricity, Torsional vibration, Space frame, Steel Structure

1. INTRODUCTION

The design process of planar frames is far simpler than that of three-dimensional frames. The structural designers can take advantage of the planar frames to minimize problems in structural design of constructions. Therefore, the structural design of planar frames has been widely adopted by a growing number of designers and researchers, and it has shown remarkable advancement and sophistication. Although the use of planar frames is advantageous during the structural design process, the major problem of eccentricity in the story emerges at the time of designing three-dimensional (3D) frames. Most of the studies on effects of eccentricity in the story have been conducted in one-story frames. However, the research on multi-story frames is sparse, and a number of questions regarding multi-story frames with floor eccentricity remain unanswered. Therefore, the present study investigated the effect of floor eccentricity on the seismic response of the frames.

Although structures are 3D objects and ground motions are 3D phenomena, these 3D issues regarding eccentricity have been largely overlooked to date. The reason is why there is only the analysis method that modeled member-by-member frame, in order to examine the seismic behavior of 3D frame. In addition, a lot of numerical effort is needed to obtain a quantitative estimation of multi-story frames by means of complicated models covering wide range of physical parameters. Therefore, more simplified analytical model is needed to solve the problems without complicated and elaborate calculation.

The authors propose a simplified structural model for elasto-plastic response analysis of 3D steel moment frames with floor eccentricity under earthquake excitation in another paper of this proceeding. The model can simulate the collapse mode and the behavior of 3D steel moment frames with eccentricity for the seismic response analysis. In this research, the analyses are conducted using the model by means of parameters covering over wide range, which are eccentricity ratio, column-to-beam strength ratio, the position of story with eccentricity, members of eccentricity etc. The purpose of this research is that the influence of the above-mentioned parameters is clarified on a story drift angle response or the dynamic collapse mechanism characteristic.

2. ANALYTICAL MODEL

In this chapter, the outline of an analytical model, which is called a simplified structural model and used for seismic response analysis of 3D steel moment frames with eccentricity, is explained as shown Fig. 2.1. The details of this model are explained in another paper of this proceeding that the authors wrote. This model can simulate the collapse mode and the behavior of 3D steel moment frames for the seismic response analysis. The simplified dynamic model can be completed with the methodology that all beams of an original frame at each floor level are condensed into a couple of beams in orthogonal direction, and all columns of an original frame in each story are also condensed into one representative column. This procedure leads to reduction of the number of the deformation degrees of freedom in each story. The effect of eccentricity by taking account of radius distance that expresses resistance against torsion in each story and eccentric distance are considered in this model. Here, the radius distance and the eccentric distance on this model are concerned with inertial characteristics and with rigidity and strength of each structural element.

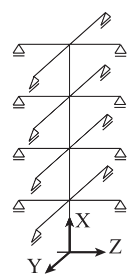


Figure 2.1. Simplified dynamic model

Deformations of each story in the simplified dynamic model can be expressed with six degrees of freedom in each story shown below.
1) θ_Y : the nodal rotation at the X-Y structural plane
2) θ_Z : the nodal rotation at the X-Z structural plane
3) ξ_X : the index of nodal rotation when floor rotates on the origin of the model
ξ_X multiplied by the distance from the origin of the model to a structural plane of the original frame is the nodal rotation angle according to the torsion of the frame. Therefore, the nodal rotation angle according to the torsion of the frame becomes large in the structural plane where the distance from the origin of the frame is distant.
4) θ_X : the horizontal rotational displacement of a node at the Y-Z structural plane
5) v : the horizontal displacement at the X-Y structural plane
6) w : the horizontal displacement at the X-Z structural plane
It is assumed that the rigidity of a floor is infinite.

Moreover, the stresses of ith story corresponding to the above-mentioned degrees of freedom are denoted by the following signs respectively.
a) $M_{Y,i}$: the stress of ith story corresponding to θ_Y
b) $M_{Z,i}$: the stress of ith story corresponding to θ_Z
c) S_i : the stress of ith story corresponding to ξ_X
d) T_i : the stress of ith story corresponding to θ_X
e) $Q_{Y,i}$: the stress of ith story corresponding to v
f) $Q_{Z,i}$: the stress of ith story corresponding to w

In the simplified dynamic model, the resistance to torsion and the amount of eccentricity of a frame is expressible with the following parameter.
Distances of the Y-direction and the Z-direction from the origin of the model to the center of gravity of the ith story are denoted by ${}_My_i$ and ${}_Mz_i$ respectively. Moreover, when the mass of the ith story is denoted by m_i and the radius distance is denoted by ${}_Mr_i$, the rotation inertial mass in the center of gravity can be expressed as $m_i \cdot {}_M r_i^2$.
Distances of the Y-direction and the-Z direction from the origin of the model to the center of rigidity on the column in the ith story are denoted by ${}_Sy_{c,i}$ and ${}_Sz_{c,i}$ respectively. Moreover, the torsional rigidity of the column about the center of rigidity ($K_{R,c,i}$) can be denoted by the following equation using the radius distance of the center of rigidity on the column (${}_Sr_{c,i}$).

$$K_{R,c,i} = {}_s r_{c,i}^2 \cdot K_{c,i} \tag{2.1}$$

where, $K_{c,i}$ is the horizontal rigidity of the column of the ith story.
Distances of the Y -direction and the Z-direction from the origin of the model to the center of strength on the ith story column are denoted by ${}_Ry_{c,i}$ and ${}_Rz_{c,i}$ respectively. Moreover, the torsional strength of the column about the center of strength ($S_{p,c,i}$) can be denoted by the following equation using the full plastic moment of the column at the ith floor ($C_{p,i}$) and the radius distance of the center of strength at the ith floor (${}_Rr_{c,i}$).

$$S_{p,c,i} = {}_R r_{c,i} \cdot C_{p,i} \tag{2.2}$$

Distances of the-Z direction from the origin of the model to the center of rigidity on the beam of the X-Y structural plane in the ith story is denoted by ${}_Sz_{b,i}$. Moreover, the torsional rigidity of the beam of the X-Y structural plane in the ith story about the center of rigidity ($K_{R,b,i}$) can be denoted by the following equation using the radius distance of the center of rigidity (${}_Sr_{b,Y,i}$).

$$K_{R,b,Y,i} = {}_S r_{b,Y,i}^2 \cdot K_{b,Y,i} \tag{2.3}$$

where, $K_{b,Y,i}$ is the horizontal rigidity of the beam of the X-Y structural plane in the ith story.
Distances of the Z-direction from the origin of the model to the center of strength on the beam of the X-Y structural plane in the ith story is denoted by ${}_Rz_{b,i}$. Moreover, the torsional strength of the beam of the X-Y structural plane about the center of strength ($S_{p,b,Y,i}$) can be denoted by the following equation using the full plastic moment of the beam at the ith floor ($B_{p,i}$) and the radius distance of the center of strength at the ith floor (${}_Rr_{b,Y,i}$).

$$S_{p,b,Y,i} = {}_R r_{b,Y,i} \cdot B_{p,i} \tag{2.4}$$

Although omitting it here, there is also the amount about the beam of the X-Z structural plane of the ith story.
For the end of the column of the ith story on the simplified dynamic model, the yield surface is defined by three stresses ($M_{Y,i}$, $M_{Z,i}$ and S_i). It assumes that the yield surface is a three-dimensional rotational ellipse. Similarly, about the beam of the ith story on the simplified dynamic model, the yield surface is defined by two stresses ($M_{Y,i}$ or $M_{Z,i}$ and S_i). It assumes that the yield surface is a two-dimensional ellipse.
In this study, the center of gravity of each story on this model is on the X-axis. The center of rigidity and the center of strength exist in the same position. Moreover, analyses target on the frames with uni-axial eccentricity of the Y-direction. The eccentricity ratio on the simplified dynamic model is defined as following equations for the column or the beam.

$$R_{e,Y,c,i} = \frac{{}_S z_{c,i}}{{}_S r_{c,i}} = \frac{{}_R z_{c,i}}{{}_R r_{c,i}} \tag{2.5}$$

$$R_{e,Y,b,i} = \frac{{}_S z_{b,i}}{{}_S r_{b,Y,i}} = \frac{{}_R z_{b,i}}{{}_R r_{b,Y,i}} \tag{2.6}$$

where, $R_{e,Y,c,i}$ is the eccentricity ratio on the column of the Y-direction in the *i*th story. $R_{e,Y,b,i}$ is the eccentricity ratio on the beam of the Y-direction in the *i*th story.

3. ANALYTICAL PARAMETERS

3.1. Analytical Frame

The structural model for analysis is the simplified model as shown in chapter 2. The number of stories (N) is 10. The each story height (h_i) is fixed to 4 m, and the story weight is the same for all the stories. The both bending stiffness and bending strength of the beams at the floor are the same, and also the bending stiffness and the bending strength of the column is equal in all directions.
The stiffness and the strength of the members were determined as follows.
The design story-shear force (Q_i) at the *i*th story can be derived from Eqn. 3.1.

$$Q_i = C_0 R_t A_i \alpha_i W_t = C_0 R_t \sqrt{\alpha_i} W_t \tag{3.1}$$

Here, W_t is the total weight of the frame and α_i is the ratio of the weight from the top through the *i*th story (W_i) and W_t. R_t is determined using the seismic design code of Japan. R_t is applied with 0.8. A_i gives the distribution of the story shear force coefficient in the frame, which is expressed by Eqn. 3.2.

$$A_i = \frac{1}{\sqrt{\alpha_i}} \tag{3.2}$$

When the position of the inflection points on the deformed column is at the center of the member and the story-shear force corresponds to a standard shear force coefficient (C_0) of 0.2 is applied along the direction of the structural plane, the rotational angle at the end of all the members in the structural plane reaches 1/400 and the story drift angle reaches 1/200. In the frames for which the column-to-beam strength ratio is 1.0, when a story-shear force that corresponds to a C_0 with value of 0.3 is applied along the direction of the structural plane, the end of all the members in the structural plane attains a full plastic moment. In the frame for which the column-to-beam strength ratio is γ, a full plastic moment of all the columns and beams on the top story increases by γ times that of the standard frame, and the values of full plastic moment of the other beams are the same as the standard frame whose column strength equal to that of beam. The full plastic moments of the column and the beam at the *i*th story of the frame ($C_{p,i}$ and $B_{p,i}$) are shown in Eqn. 3.3.

$$C_{p,i} = \gamma \frac{Q_i h_i}{2}, B_{p,N} = \gamma \frac{Q_N h_N}{2}, B_{p,i} = \frac{Q_i h_i + Q_{i+1} h_{i+1}}{2} \tag{3.3}$$

In these analyses, the beam is idealized as an elastic-plastic spring that restrains the in-plane nodal rotation, and the column is modeled by using a general plastic hinge method that is based on the plastic flow rule. The bilinear relationship according to which the elastic limit is the full plastic moment that can be derived from Eqn. 3.3 was adopted for the load versus deformation relationship of the columns and beams, and the strain-hardening coefficient is assumed to be 0.01. The reduction in the bending stiffness of the columns subjected to an axial force and vertical displacement of the node are neglected. The P-Δ effects are considered. Viscous damping is taken as the Rayleigh type whose damping constant to the first natural period of the two structural planes is 0.01 in the analyses.

The amount on the eccentricity of the analytical model is set up as follows.
The eccentricity of the analytical model is defined as two types below.
1) Frames with the eccentricity of the rigidity and strength of columns (called *column eccentricity frame*)
2) Frames with the eccentricity of the rigidity and strength of beams (called *beam eccentricity frame*)
The center of gravity of each story is on the X-axis. The center of rigidity and the center of strength exist in the same position. Moreover, the analyses target on the frames with uni-axial eccentricity of the Y direction. As for this analytical frame, the amount of eccentricity and the resistance to torsion have been given with the specified values as follows. Mass is on the X-axis of the simplified model in all the stories. The distance ${}_My_i$ of the Y-direction from the origin to the center of gravity of ith story and the distance ${}_Mz_i$ of the Z-direction are 0m. The eccentricity ratio of the column eccentricity frame ($R_{e,Y,c,i}$) and the beam eccentricity frame ($R_{e,Y,b,i}$) set up 7 kinds (0.1, 0.3, 0.5, 0.7, 1.0, 1.5, and 2.0). The distances of eccentricity (${}_Sz_{c,i}$, ${}_Rz_{c,i}$, ${}_Sz_{b,i}$ and ${}_Rz_{b,i}$) are given the same value according to the eccentricity ratio denoted by Eqn. 2.5 and Eqn. 2.6. The position of story with eccentricity is made into four kinds following, the top (10th story), the intermediate (5th story), the bottom (1st story) and all the stories.

3.2. Input Ground Motion

The input direction of ground motion is made into the Y-direction of the analytical frame, which has eccentricity. Two kinds of ground motions shown in Table 3.1 are used for the analyses. The maximum acceleration of the original ground motions is also shown in Table 3.1. In the input ground motions, to make the levels of the responses of the frames uniform, input level was set by using the value (V_{dm}) that converted the earthquake input energy causing damage into an equivalent velocity. This was V_{dm}=1.5 m/s, whose earthquake size is thought by the seismic code of Japan. To reference, Table 3.1 shows the maximum acceleration of each ground motion that was adjusted, when the ground motion was inputted along the Y-direction of the no eccentricity frame with the column-to-beam strength ratio of 1.2. The step time of numerical integration of seismic response analyses is 0.002 s. The duration of the analyses is 15.0 s.

Table 3.1. Maximum accelerations of ground motions (m/s^2)

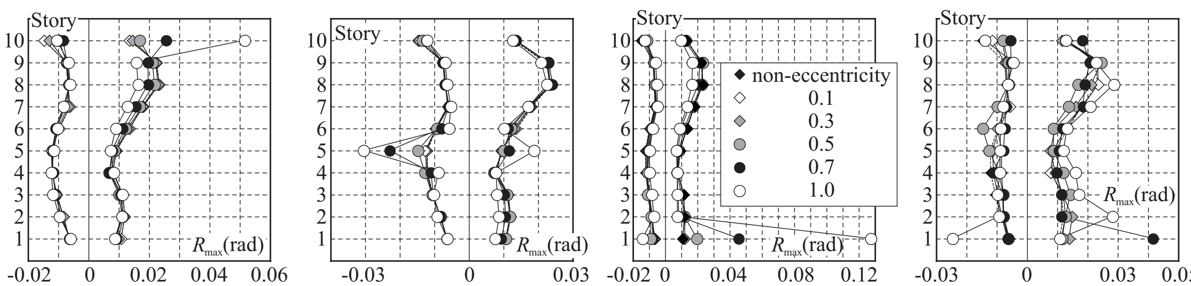
Ground motion name	Original	V_{dm} 1.5m/s
El Centro NS, 1940	3.42	7.81
NTT Kobe NS, 1995	3.31	3.30

4. STORY DRIFT DISTRIBUTION

The previous study reported that the column-to-beam strength ratio of the 2D steel frame to prevent the damage concentration in particular story is 1.2 when the input level of V_{dm} =1.5 m/s was used for the frame. Therefore, the frames with the column-to-beam strength ratio of 1.2 are examined when V_{dm} is 1.5 m/s in this chapter. Although the analysis was carried out using two types of input ground motions, the typical analysis results with respect to story-drift distribution are presented for El Centro NS because they all have similar results for NTT Kobe NS in this research.

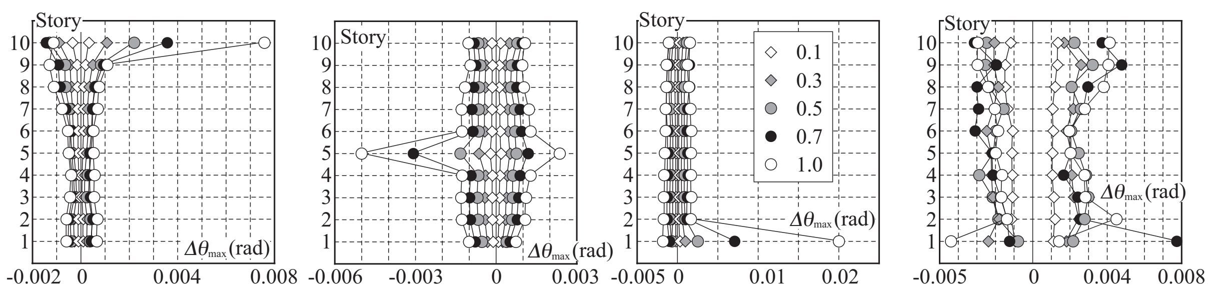
4.1. Column Eccentricity Frame

Fig. 4.1 and 4.2 show the maximum story drift angle of each story ($R_{\max}$), and the maximum story torsional angle of each story ($\Delta\theta_{\max}$) about five sorts of the frames having the story with the eccentricity of the column. The eccentricity ratio of the frames is 0.1, 0.3, 0.5, 0.7, and 1.0. The frames having $R_{e,Y,c,i}$ =1.5 or 2.0 carry out whole collapse in many examples. Therefore, the frames of the above-mentioned eccentricity ratio are removed in Fig. 4.1 and 4.2. $R_{\max}$ is defined as the story drift angle in the center of gravity of each story. $\Delta\theta_{\max}$ is defined as the subtraction the twist rotation angle in the *i*th story from the torsional rotation angle in the story under the *i*th.
The values of $R_{\max}$ in all the stories are almost changeless in the range of certain eccentricity ratio in Fig. 4.1. However, there is a tendency for $R_{\max}$ of the story having eccentricity to increase rapidly when eccentricity ratio exceeds a steady value. This is based on the partial story collapse. On all the story eccentricity frames, story collapse takes different position by the eccentricity ratio.
According to Fig. 4.2, eccentricity ratio follows on becoming large, and $\Delta\theta_{\max}$ becomes large-like proportionally at eccentricity ratio in all the stories. $\Delta\theta_{\max}$ has arisen not only in the story having eccentricity but also in all the stories. $\Delta\theta_{\max}$ of others except the story having eccentricity are almost constant. However, when the eccentricity ratio exceeds a steady value, $\Delta\theta_{\max}$ of the story having eccentricity increases rapidly by the partial story collapse.



(a) Top story (b) The 5th story (c) Bottom story (d) All stories

Figure 4.1. $R_{\max}$ of *column eccentricity frame*



(a) Top story (b) The 5th story (c) Bottom story (d) All stories

Figure 4.2. $\Delta\theta_{\max}$ of *column eccentricity frame*

4.2. Beam Eccentricity Frame

Fig. 4.3 and 4.4 show the maximum story drift angle of each story ($R_{\max}$), and the maximum story torsional angle of each story ($\Delta\theta_{\max}$) about five sorts of the frames having the story with eccentricity of the beam. The eccentricity ratio of the frames takes 0.1, 0.5, 1.0, 1.5, and 2.0.
The results of *beam eccentricity frames* are similar to those of *column eccentricity frames*. $R_{\max}$ in all the stories keep almost constant in the range of certain eccentricity ratio in Fig. 4.3. However, when the

eccentricity ratio exceeds a steady value, there is a tendency for R_{max} of the story having eccentricity to increase rapidly. This is based on the partial story collapse as also *column eccentricity frames*.

According to Fig. 4.4, the eccentricity ratio follows on becoming large, and $\Delta\theta_{max}$ becomes large-like proportionally at the eccentricity ratio in all the stories. $\Delta\theta_{max}$ has arisen not only in the story having eccentricity but also in all the stories. $\Delta\theta_{max}$ of others except for the story having eccentricity are almost constant. However, when eccentricity ratio exceeds a steady value, $\Delta\theta_{max}$ of the story having eccentricity increases rapidly.

Different points from *column eccentricity frames*' case are following two. The one is that $\Delta\theta_{max}$ becomes large in a couple of stories of upper and lower sides of the beam having eccentricity. The another is no tendency of increase of R_{max} accompanying the story collapse at *beam eccentricity frames* having $R_{e,Y,b,i}$ =1.0, although increase of R_{max} according to the story collapse was checked with *column eccentricity frames* having $R_{e,Y,c,i}$ =1.0. Increase of R_{max} according to story collapse at *beam eccentricity frames* having $R_{e,Y,b,i}$ =1.5 or 2.0 can be checked. However, it is not so remarkable as *column eccentricity frame*.

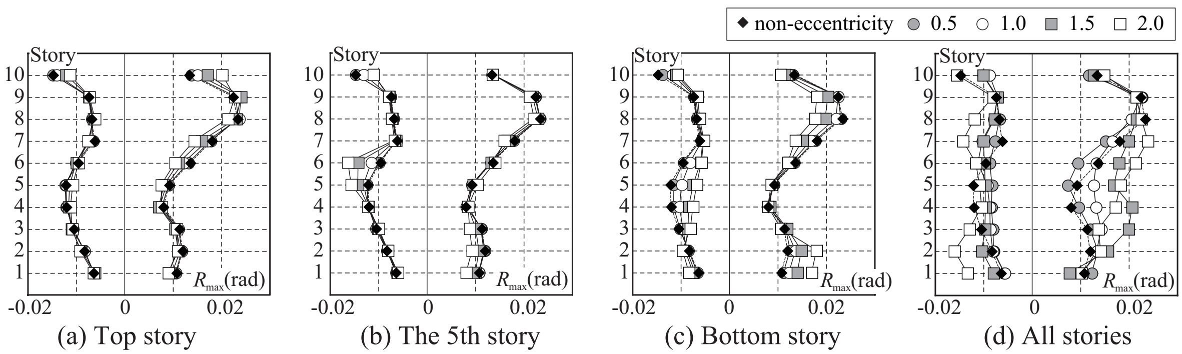


Figure 4.3. R_{max} of *beam eccentricity frame*

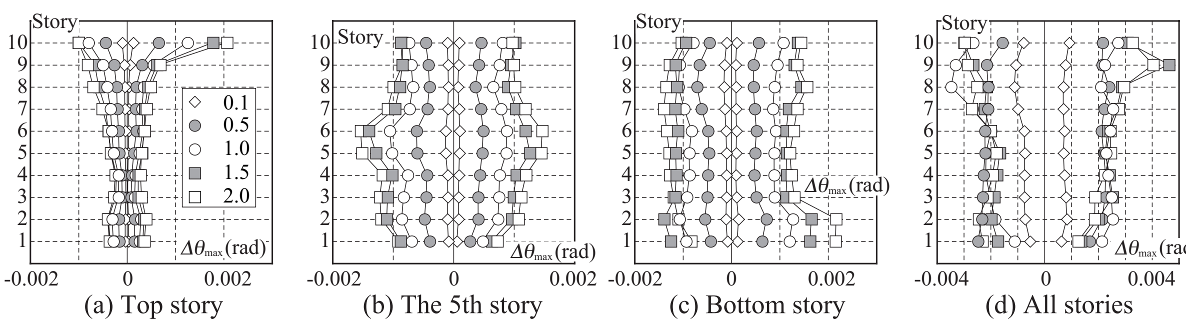


Figure 4.4. $\Delta\theta_{max}$ of *beam eccentricity frame*

5. STRESS DISTRIBUTION

In this chapter, the cause of the partial story collapse is examined by paying attention to the stress which arises in stories and each structural member for *column eccentricity frames* and *beam eccentricity frames* which have eccentricity in the top story, the 5th story (intermediate), the bottom story, and all the stories. Here, the frames having eccentricity ratio of 2.0 are targeted as cases where the influence of torsion is remarkable. In addition, in order to investigate on the stress change under the influence of eccentricity, the elastic response analysis results are used in this chapter.

5.1. Maximum Story Shear Distribution

Fig. 5.1 shows the ratio of the maximum story shear which arises in the bottom story (Q_1) and the maximum story shear which arises on each story (Q_i) about *column eccentricity frames*, *beam eccentricity frames* and the non-eccentricity frames. Since the natural period of the frame changes according to the positions of the story with eccentricity, the story shear distribution also changes. There is no evident tendency for the story shear to increase and decrease in the story having eccentricity.

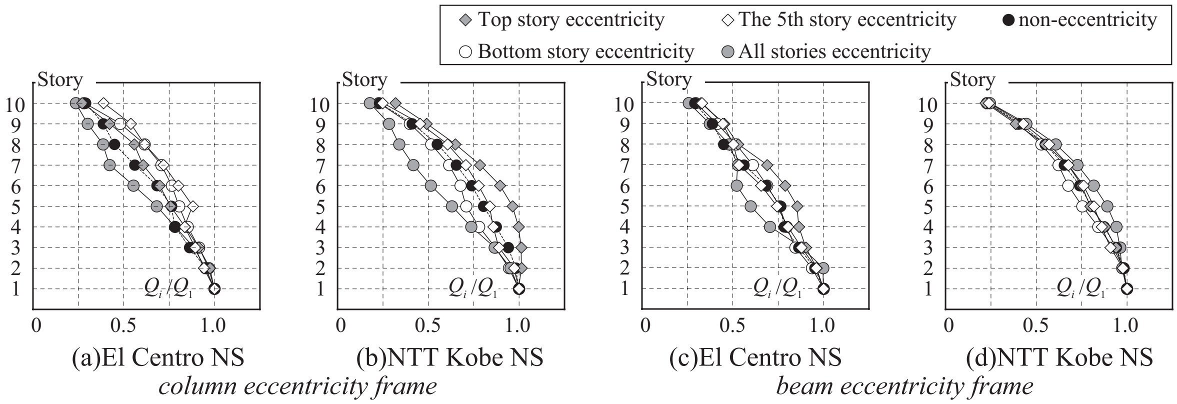


Figure 5.1. Maximum story shear distribution

5.2. Maximum Torsional Moment Distribution

Fig. 5.2 shows the ratio of the maximum torsional moment which arises in the bottom story (T_1) and the maximum torsional moment which arises on each story (T_i) about *column eccentricity frames* and *beam eccentricity frames*. In Fig. 5.2, the frame twisted in all the stories according to the effect of the torsional vibration by eccentricity. The torsional moment of all the stories cause the torsional angle in all the stories in the range where the story collapse did not occur. Since the natural period changes with the positions of the story having eccentricity as the same as the maximum story shear, the torsional moment distribution also changes. There is no evident tendency for the torsional moment to increase or decrease in the story having eccentricity. Thus, even if which story has eccentricity, torsion moment is shown the same-like distribution. However, on the frames having eccentricity near the top story (10th, 9th, 8th and 7th), the tendency is shown that the torsional moment becomes small in near the intermediate stories.

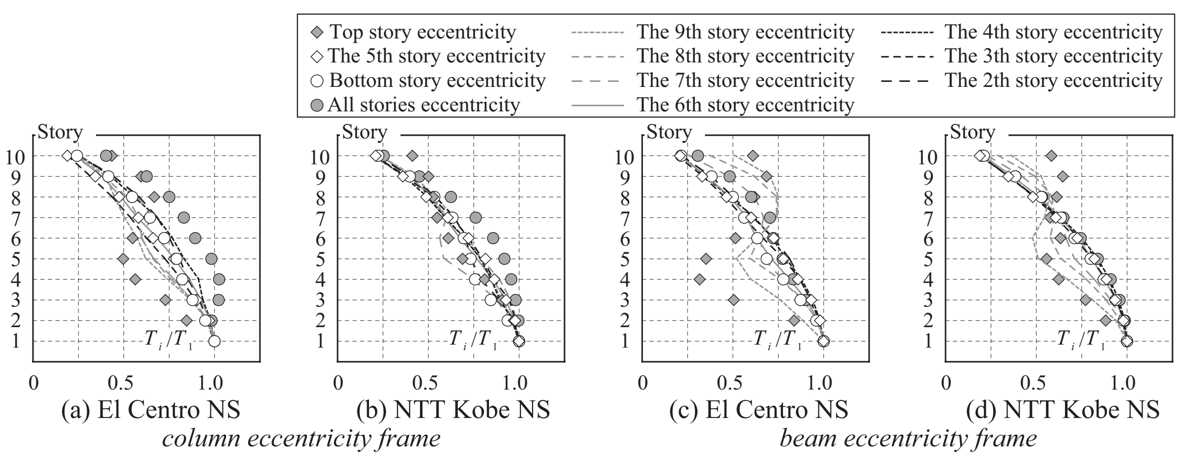


Figure 5.2. Maximum torsional moment distribution

5.3. Equivalent Bending Moment Taken Account of Torsion

In this section, the influence, which the torsional vibration by eccentricity causes the bending moment of each structural member, is considered.

The yield surface (F) about the center of strength on the column used by the simplified dynamic model assumes that it is a rotational ellipse. In consideration of this yield surface, the equivalent bending moment ($M_{T,c,i}$) which the following equation defines is used as an index showing the size of the end stress of a column.

$$M_{T,c,i} = \sqrt{{C_{Y,i}}^2 + {C_{Z,i}}^2 + \left(\frac{S_{c,i}}{{}_R r_{c,i}} \right)^2} \tag{5.1}$$

where $C_{Y,i}$ and $C_{Z,i}$ are the bending moment of each direction on columns ($M_{Y,i}$ and $M_{Z,i}$). $S_{c,i}$ is the bending moment due to the torsional deformation of the floor (S_i) on columns.

The following equation is defined as the equivalent bending moment ($M_{T,b,Y,i}$) similarly for the beam.

$$M_{T,b,Y,i} = \sqrt{{B_{Y,i}}^2 + \left(\frac{S_{b,i}}{{}_R r_{b,Y,i}} \right)^2} \tag{5.2}$$

where $B_{Y,i}$ is the bending moment of Y-direction on beams ($M_{Y,i}$). $S_{b,i}$ is the bending moment due to the torsional deformation of the floor (S_i) on beams. In addition, when the each above-mentioned equivalent bending moment reaches the full plastic moment of the column and beam, each member yields.

Fig. 5.3 shows the ratio of the maximum equivalent bending moment ($M_{T,c,i}$, $M_{T,b,Y,i}$) and the maximum bending moment ($C_{Y,i}$, $B_{Y,i}$) for the column (at the capital and bottom) and the beam on *column eccentricity frame* of each story. In Fig. 5.3, the increase rate of the stress of the columns is larger than the beam on *column eccentricity frame* near the story having eccentricity under the influence of the torsion. Therefore, the columns yield easier than the beams, and it causes the story collapse on *column eccentricity frames*.

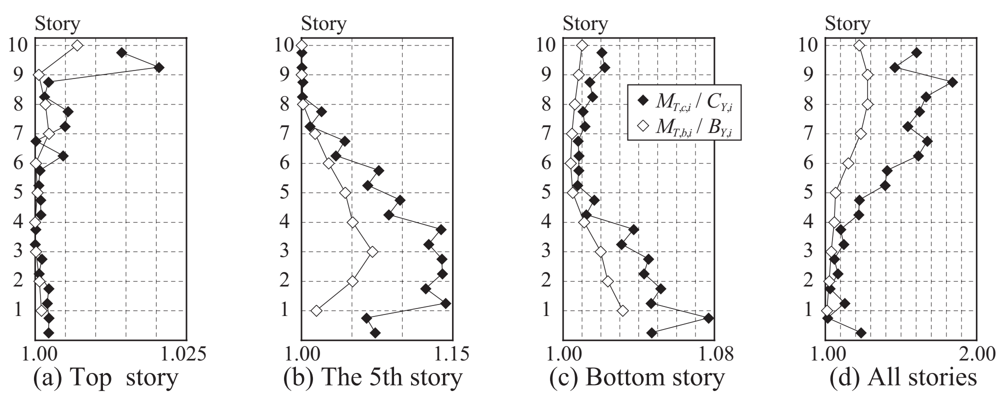


Figure 5.3. The ratio of the maximum equivalent bending moment and the maximum bending moment on *column eccentricity frame*

Fig. 5.4 shows the ratio of the maximum equivalent bending moment ($M_{T,c,i}$, $M_{T,b,Y,i}$) and the maximum bending moment ($C_{Y,i}$, $B_{Y,i}$) for the column (at the capital and bottom) and the beam on *beam eccentricity frame* of each story. In Fig. 5.4, the increase rate of the stress of the beams is larger than the columns on *beam eccentricity frame* in the story having eccentricity under the influence of the torsion. Therefore, the stress of the beam having eccentricity increases, the beams of the upper and lower stories yield easily relatively, and it has become a factor in which the story collapse covering two stories.

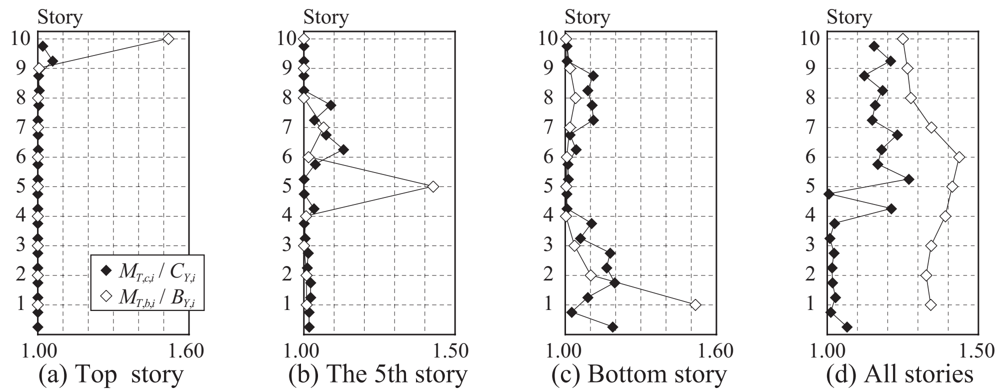


Figure 5.4. The ratio of the maximum equivalent bending moment and the maximum bending moment on *beam eccentricity frame*

As results, the columns stress and the beams stress become larger than the frame of non-eccentricity under the influence of the torsion on the frame having eccentricity. The column-to-beam strength ratio serves as a small frame relatively. The frame having small column-to-beam strength ratio become the cause of carrying out damage concentration and causing the story collapse. Therefore, in consideration of the influence of the torsion, it is necessary to set up the column-to-beam strength ratio appropriately.

6. CONCLUSION

On the frame with floor eccentricity, it becomes easy to cause the story collapse near the story having eccentricity. The tendency is that *column eccentricity frames* are more remarkable than *beam eccentricity frames*. The cause was examined also from the stresses which arise to the frame. The stresses change intricately by the story having eccentricity, the members having eccentricity, and the eccentricity ratio etc. Therefore, it is necessary to set up the column-to-beam strength ratio of the frame appropriately according to the earthquake level and the eccentricity ratio to assume. About quantification of the strength required of each member in the frame having eccentricity, it is a future examination subject.

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