Chapter 33
Preliminary Evaluation of Seismic Capacity and Torsional Irregularity of Uto City Hall Damaged in the 2016 Kumamoto Earthquake

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Abstract In this paper, the seismic capacity and torsional irregularity of the main building of Uto City Hall are evaluated by using a simple method based on the building's structural drawing. The simplified evaluation method of seismic capacity, which was proposed by Shiga in the 1970s, is based on the wall-area index and the average shear stress in walls and columns. For evaluation of its seismic capacity, the following two cases are considered: the building is assumed to behave as a unit building, and each of the structural blocks responding independently. The evaluation of the torsional parameters, stiffness eccentricity and radius of torsional stiffness with respect to the center of stiffness are based on the sectional area of the columns and walls, which is presented in the Japanese Standard for the seismic evaluation of existing reinforced concrete (RC) buildings. The main findings of this paper are as follows. (a) The seismic capacity of the main building of Uto City Hall is insufficient to survive severe earthquakes. However, the evaluated results of both cases cannot explain the damage observed in upper stories. (b) The ratio of the stiffness eccentricity to radius of torsional stiffness evaluated in each story exceeds 0.15, while the radius ratio of the torsional stiffness with respect to center of stiffness to the gyration of the whole mass above the considered story is smaller than 1. Therefore, the main building of Uto City Hall is sensitive to torsional response: it may be classified as a "torsionally flexible building".

Keywords Seismic capacity evaluation · 2016 Kumamoto Earthquake · Damage · Torsional irregularity · Wall-area index · Column-area index

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33.1 Introduction

The main building of Uto City Hall, a five-story reinforced concrete building constructed in 1965, was severely damaged in the 2016 Kumamoto Earthquake. As reported in reference (Fujii et al. 2017), most of the structural damage to this building was concentrated in the upper stories. External observation of the main damage to this building was limited to the third to fifth stories on the south and west elevations. From this point, the following questions arise. (i) Had this building structure had enough seismic capacity to withstand severe earthquake? (ii) Why was most of the structural damage concentrated in the upper stories? (iii) From the damage observation, the torsional response might be significant. Had this building been sensitive to torsional response?

In this paper, the seismic capacity and torsional irregularity of the main building of Uto City Hall are evaluated by using a simple method based on its structural drawing. The simplified evaluation scheme of seismic capacity, which was proposed by Shiga in the 1970s, is based on the wall-area index and the average shear stress in walls and columns (Shiga 1977). Evaluating the torsional parameters, stiffness eccentricity and radius of torsional stiffness with respect to the center of stiffness, is based on the sectional area of the columns and walls, which is presented in the Japanese Standard for the seismic evaluation of existing RC buildings (The Japan Building Disaster Prevention Association 2001).

33.2 The Main Building of Uto City Hall

Figure 33.1 shows the structural plan of the main building of Uto City Hall. The structure of this building can be divided into two structural blocks (office block and stair block). The two blocks are connected only by a concrete slab (thickness: 110 mm).

As shown in this figure, all the structural walls are concentrated in the stair block, whereas in the office block concrete columns are the only vertical members to resist lateral loads. Is should be also noted that in the office block not all frames are oriented in X- or Y-directions: frames $A_1 - A_3$ lie on the axis rotated 45° counter-clockwise from the X-axis, and frames $B_1 - B_3$ are orthogonal to frames A_1.

In the fourth and fifth story, the floor slab between frames Y_4 and Y_5, the border of two blocks, was severely damaged because of this earthquake, as described in reference (Fujii et al. 2017).

Figure 33.2 shows the simplified structural elevation of frame Y_4 and A_2. The height of the first story is different in zones (I) and (II) in the office block: in zone (I), where the number of stories is 5, the story height is 4.4 m, while it is 3.1 m in zone (II), where the number of stories is 1. Note that the story height in the stair block is the same as frame A_2.

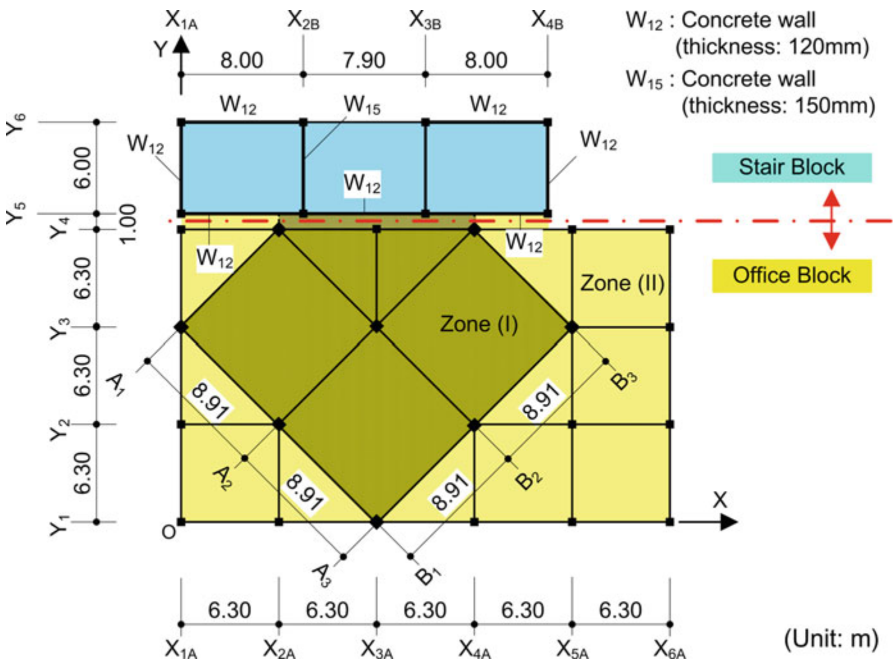


Fig. 33.1 Structural plan of the main building of Uto City Hall

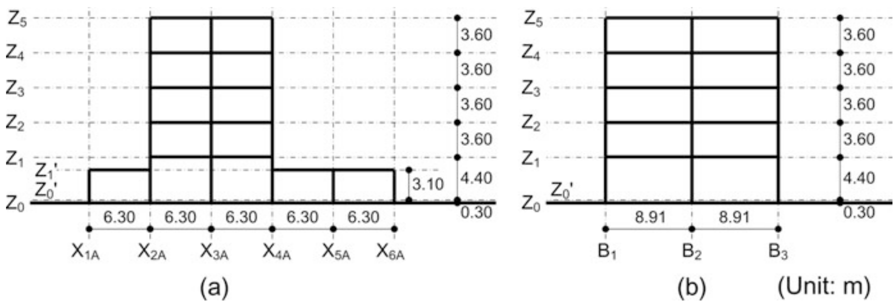


Fig. 33.2 Simplified structural elevation of the main building of Uto City Hall. (a) frame Y_4, (b) frame A_2

Figure 33.3 shows the sections of column A_1B_1, A_2B_1 and A_2B_2. As shown in this figure, the sectional area of column is drastically reduced from the lower stories to upper stories. This is very common in reinforced concrete buildings constructed before 1981, because at that time the design seismic force in upper stories is smaller than that in the current seismic code of Japan (BCJ 2016).

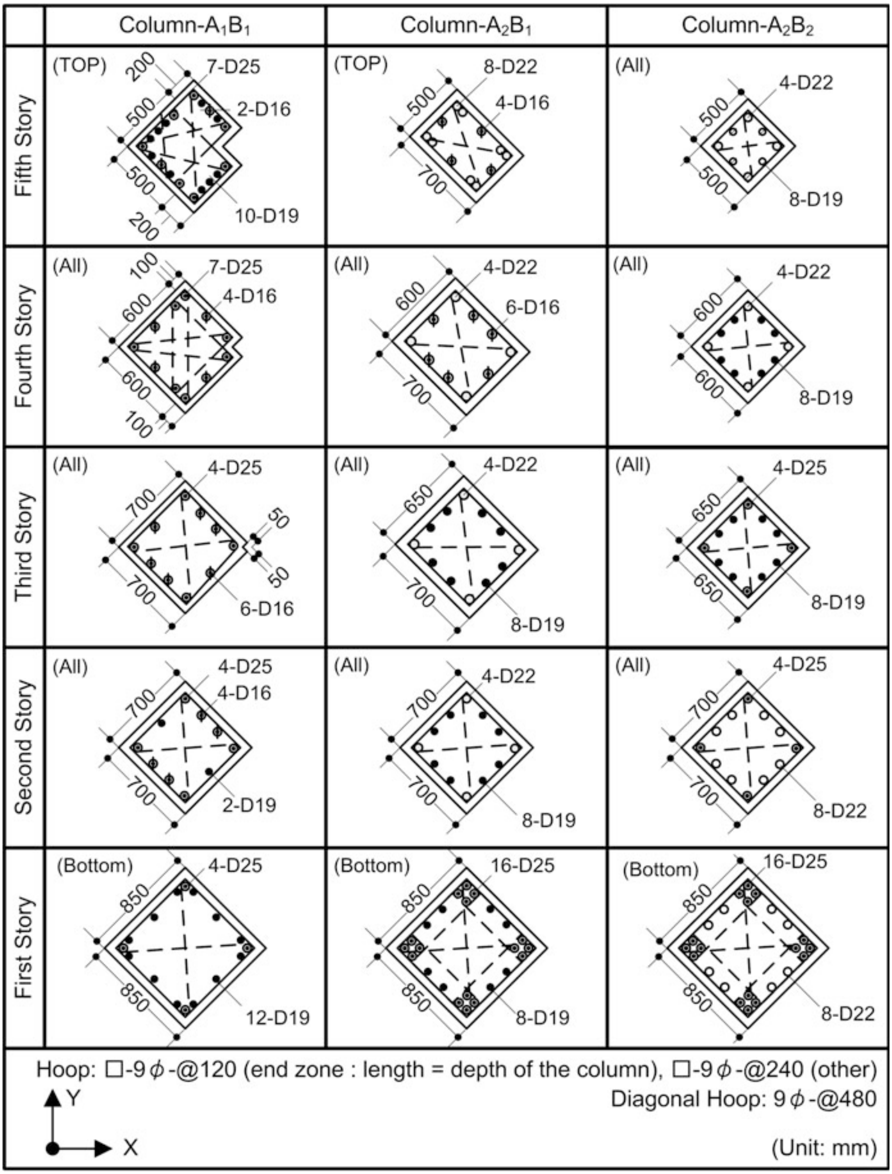


Fig. 33.3 Sections of column A_1B_1, A_2B_1 and A_2B_2

33.3 Seismic Capacity Evaluations

33.3.1 Description of the Simplified Evaluation Method

Shiga investigated low-rise reinforced concrete buildings damaged in the 1968 Tokachi-oki Earthquake (Shiga 1977). He explored the relation of earthquake damage and the following parameters, which can be easily obtained from drawings: wall-area index, column-area index, and average shear stress in walls and columns. He had concluded that damaged and undamaged buildings could be significantly distinguished between two parameters, wall-area index and average shear stress in walls and columns. In this study, the seismic capacity evaluation of the main building of Uto City Hall is carried out according to Shiga's method, with some modifications.

In the present study, wall-area index and column-area index of the i-th story, α_{Wi} and α_{Ci}, respectively, are defined by Eq. (33.1).

$$\alpha_{Wi} = \frac{A_{Wi}}{A_i \sum_{j=i}^{N} A_{fj}} \left(\text{unit} : \text{mm}^2/\text{m}^2\right), \alpha_{Ci} = \frac{A_{Ci}}{A_i \sum_{j=i}^{N} A_{fj}} \left(\text{unit} : \text{mm}^2/\text{m}^2\right). \quad (33.1)$$

In Eq. (33.1), A_{Wi} (unit: mm^2) and A_{Ci} (unit: mm^2) are the sum of the sectional area of the walls and columns in the i-th story, respectively, and A_{fj} (unit: m^2) is the area of the j-th floor. Th coefficient A_i is calculated from Eq. (33.2), which is used in the current seismic design code in Japan (BCJ 2016).

$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i\right) \cdot \frac{2T}{1 + 3T}, \alpha_i = \sum_{j=i}^{N} w_j / \sum_{j=1}^{N} w_j. \quad (33.2)$$

In Eq. (33.2), w_j (unit: kN) is the weight of the j-th floor, and T is the natural period of the building that is calculated as a function of the building height H (unit: m).

$$T = 0.02H. \quad (33.3)$$

The average shear stress in walls and columns in the i-th story, τ_{avei}, is calculated from Eq. (33.4), assuming that weight per unit floor area of the building is 10 kN/m^2 and base shear coefficient is 1.0.

$$\tau_{avei} = \frac{A_i \cdot \sum_{j=i}^{N} w_j}{A_{Wi} + A_{Ci}} = 10^4 \times \frac{A_i \cdot \sum_{j=i}^{N} A_{fj}}{A_{Wi} + A_{Ci}} \left(\text{unit} : \text{N}/\text{mm}^2\right). \quad (33.4)$$

In the present study, two modifications are made to Shiga's original method. One is that the wall-area index and column-area index are extended for the upper stories in a multi-story building: both indices are divided by A_i coefficient to consider the vertical distribution of lateral seismic forces. The other is that the weight per unit floor area of the building is changed from 1000 kgf/m^2 to 10 kN/m^2, to adjust the SI unit.

In Shiga's investigation, he had concluded that buildings that satisfy either of two conditions, that the wall-area index α_{Wi} is larger than 30×10^2 mm^2/m^2 or the average shear stress in walls and columns τ_{avei} is less than 1.2 N/mm^2, correspond to those that were undamaged or very slightly damaged in the 1968 Tokachi-oki Earthquake. He had also concluded that the buildings within zone A, which is defined by the condition shown as Eq. (33.5), correspond to those whose walls were heavily cracked columns were heavily damaged in shear in case columns were short and shear failure preceded bending failure in 1968 Tokachi-oki Earthquakes (Shiga 1977).

$$1.2A_{Ci} + 3.3A_{Wi} \leq 10^4 \times A_i \cdot \sum_{j=i}^{N} A_{fj}. \tag{33.5}$$

Note that in Eq. (33.5), the average ultimate shear stress of the column is assumed to be 1.2 N/mm^2, while that of wall is assumed to be 3.3 N/mm^2.

33.3.2 Evaluation Cases

In this study, the following two cases are considered for the seismic capacity evaluation of the main building of Uto City Hall. In Case 1, the building is assumed to behave as a unit building, and the evaluation is carried out as if for a single building. In contrast, in Case 2, the stair and office blocks are assumed to behave independently, and the evaluation is carried out as if for two independent buildings. In each case, the X- and Y-directions shown in Fig. 33.1 are evaluated.

33.3.3 Evaluation Results

Figures 33.3 and 33.4 show the evaluation results in each case. In these figures, the zone A is the area corresponding to the most of buildings were heavily damaged while zone C is the area corresponding to the most of buildings were not damaged or only slightly damaged in the 1968 Tokachi-oki Earthquake.

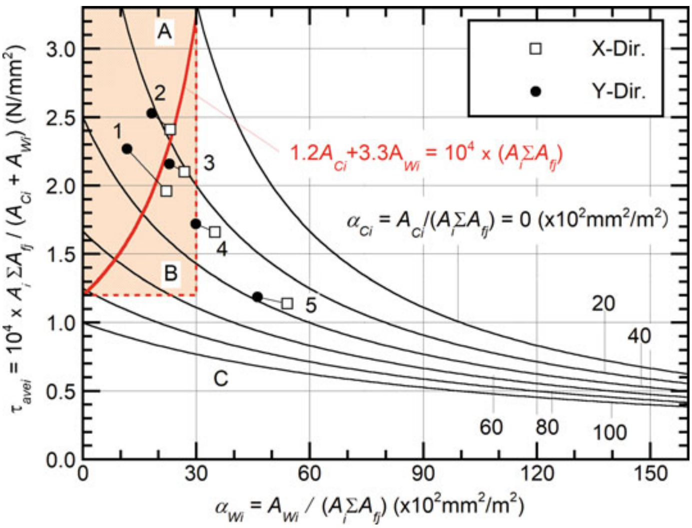


Fig. 33.4 Evaluation results in case 1

33.3.4 Discussions

In Case 1 (Fig. 33.3), the plots of Y-direction in the first and second stories are within zone A, while the plots of the upper stories are in zone B or C. Therefore, it may be concluded that if this building behaved as a united single building, the seismic capacity of this building is insufficient to survive strong earthquakes. However, this result cannot explain the fact that most damage in this building is in the upper stories.

In Case 2 (Fig. 33.4) the plots of office blocks in all stories are within zone A, whereas the plots of stair block in all stories are within zone C. Therefore, it may be concluded that the seismic capacity of the office block is insufficient while that of the stair block is sufficient, under the condition that the two blocks of this building behaved as two independent buildings. However, in the damage observation of this building (Fujii et al. 2017), it was found that the walls in the fifth story of frame Y_5 (stair block) were severely damaged. The results shown in Fig. 33.5 cannot explain this damage. Therefore, the assumption that the stair and office blocks behave independently appears invalid, even though the floor slab at the border of two blocks in the fourth and fifth floors were severely damaged (Fujii et al. 2017).

In conclusion, the seismic capacity of the main building of Uto City Hall is insufficient to survive strong earthquakes. However, neither results can explain the damage of this building observed. The reasons why this simplified evaluation method fails to explain the observed damage are (i) the lateral force distribution coefficient, A_i, is smaller in upper stories because the A_i coefficient cannot reflect the drastic reduction of the sectional area in upper stories, and (ii) the effect of torsion is not considered in this simplified method.

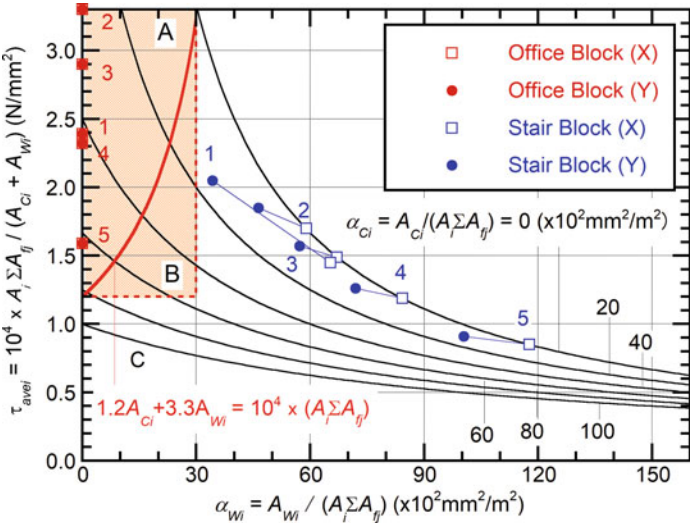


Fig. 33.5 Evaluation results in case 2

33.4 Evaluation of Torsional Irregularity

33.4.1 Description of Calculation Method

In this study, the parameters of torsional irregularity, eccentricity ratio, ratio of gyration of story torsional stiffness with respect to the center of mass, and eccentricity index are calculated according to the standard for seismic evaluation of existing reinforced concrete buildings (The Japan Building Disaster Prevention Association 2001). In this study, those parameters are calculated based on the sectional area of columns and walls as below.

The stiffness index of the j-th frame, S_j, is calculated by Eq. (33.6).

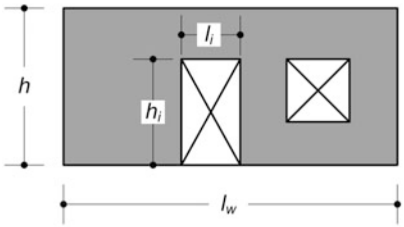
$$S_j = \sum_k a_{Cjk} + \sum_k \alpha_{jk}\left(1 - \eta_{jk}\right) a_{Wjk}. \tag{33.6}$$

In Eq. (33.6), a_{Cjk} is the sectional area of the k-th column in the j-th frame, and a_{Wjk}, α_{jk}, η_{jk} are the sectional area, stiffness modification factor considering the proportion of wall, and opening ratio, respectively, of the k-th wall in the j-th frame. Figure 33.5 shows the definition of α_{jk}, η_{jk} (Fig. 33.6).

The location of the center of stiffness of each story (x_{Si}, y_{Si}), and the radius of gyration of story torsional stiffness with respect to the center of stiffness, j_{Xi}' and j_{Yi}', respectively, are calculated by using stiffness index S_j.

Let m_i and I_i be the mass and mass moment of inertia of the i-th floor, respectively, and the location of the center of mass of i-th floor is expressed as (x_{Gfi}, y_{Gfi}).

(a)



(b)

h / l	α	
	Wall within frame	Independent wall
$3.0 \le h / l_w$	1.0	0.3
$2.0 \le h / l_w < 3.0$	1.5	0.5
$1.0 \le h / l_w < 2.0$	2.5	0.8
$h / l_w > 1.0$	3.5	1.2

(c)

$$\eta = \max\left(\sqrt{\frac{\sum_i h_i l_i}{h l_W}}, \frac{\sum_i l_i}{l_W}\right)$$

Note:
If η is larger than 0.4, wall with openings should be modeled as separated members.

The case $\eta > 0.4$:

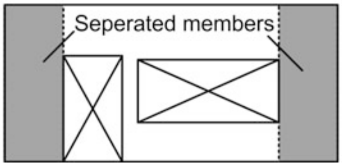


Fig. 33.6 Definition of α_{jk}, η_{jk} for wall. (**a**) Elevation of wall considered, (**b**) definition of α_{jk}, (**c**) definition of η_{jk}

The location of the center of total mass above the i-th story $(\widehat{x}_{Gi}, \widehat{y}_{Gi})$is calculated from Eq. (33.7).

$$\widehat{x}_{Gi} = \sum_{j=i}^{N} m_j x_{Gfj} / \sum_{j=i}^{N} m_j, \widehat{y}_{Gi} = \sum_{j=i}^{N} m_j y_{Gfj} / \sum_{j=i}^{N} m_j. \tag{33.7}$$

The radius of gyration of mass above the i-th story, r_i, is calculated from Eq. (33.8).

$$r_i = \sqrt{\sum_{j=i}^{N} \left[I_j + m_j \left\{ \left(x_{Gfj} - \widehat{x}_{Gj} \right)^2 + \left(y_{Gfj} - \widehat{y}_{Gj} \right)^2 \right\} \right] / \sum_{j=i}^{N} m_j}. \tag{33.8}$$

The stiffness eccentricity of the i-th story, e_{Xi} and e_{Yi}, are calculated by Eq. (33.9).

$$e_{Xi} = x_{Si} - \widehat{x}_{Gi}, e_{Yi} = y_{Si} - \widehat{y}_{Gi}. \tag{33.9}$$

The eccentricity indices of the i-th story defined in the current seismic design code of Japan, R_{eXi} and R_{eYi}, respectively, are calculated by Eq. (33.10).

$$R_{eXi} = |e_{Yi}/j_{Xi}'|, R_{eYi} = |e_{Xi}/j_{Yi}'|. \tag{33.10}$$

According to Hejal and Chopra (Hejal and Chopra 1987), the classification of systems as either torsionally stiff (TS) or torsionally flexible (TF) systems is based on the ratio of the uncoupled torsional mode to the lateral frequencies $\Omega_{\theta X}$, $\Omega_{\theta Y}$ of the corresponding torsionally balanced system, defined by Eq. (33.11).

$$\Omega_{\theta X} = \omega_{0\theta}'/\omega_{0X}, \Omega_{\theta Y} = \omega_{0\theta}'/\omega_{0Y}. \tag{33.11}$$

In Eq. (33.11), $\omega_{0\theta}'$ is the uncoupled natural circular frequency of rotational oscillation with respect to the center of stiffness. The system $\Omega_{\theta X}$, $\Omega_{\theta Y} > 1$ is classified as a TS system in both the X- and Y-directions (Hejal and Chopra 1987).

For the single-story asymmetric building system (mass: m, mass moment of inertia I, lateral stiffness of system in X- and Y-direction, K_X and K_Y, torsional stiffness with respect to the center of stiffness K_θ'), $\Omega_{\theta X}$, $\Omega_{\theta Y}$ are equal to the radius ratios of gyration of the story torsional stiffness with respect to center of stiffness, j_X'/r and j_Y'/r, as shown in Eq. (33.12).

$$\Omega_{\theta X} = \frac{\omega_{0\theta}'}{\omega_{0X}} = \frac{\sqrt{K_\theta'/I}}{\sqrt{K_X/m}} = \frac{j_X'}{r}, \Omega_{\theta Y} = \frac{\omega_{0\theta}'}{\omega_{0Y}} = \frac{\sqrt{K_\theta'/I}}{\sqrt{K_Y/m}} = \frac{j_Y'}{r}. \tag{33.12}$$

In this study, the system classification as either TS or TF is made based on j_X'/r and j_Y'/r for each direction in each story: the i-th story is classified as TS in X-direction if the ratio j_{Xi}' / r_i is larger than 1, whereas it is classified as TF if j_{Xi}' /r_i is smaller than 1. The i-th story in Y-direction is also classified in the same manner.

33.4.2 Calculated Results

Figure 33.7 shows the location of the center of total mass above the considered story and the center of stiffness of the same, and Fig. 33.8 shows the vertical distribution of three parameters of torsional irregularity.

33.4.3 Discussions

From Fig. 33.7, the center of total mass above the story, G, and the center of stiffness of each story, S, almost lie on the axis of frame X_{3A}; however, the location of S is closer to the stair block than G. This is because all of the walls are in the stair block. Therefore, the eccentricity ratio in X-direction $|e_X/r|$ is small (0.009–0.030), whereas the eccentricity ratio in Y-direction $|e_Y/r|$is relatively large (0.219–0.306), as shown in Fig. 33.8a.

The radius ratios of gyration of the story torsional stiffness with respect to S, j_X'/r and j_Y'/r, are smaller than 1, except j_Y'/r in the first story (Fig. 33.8b). In addition, the

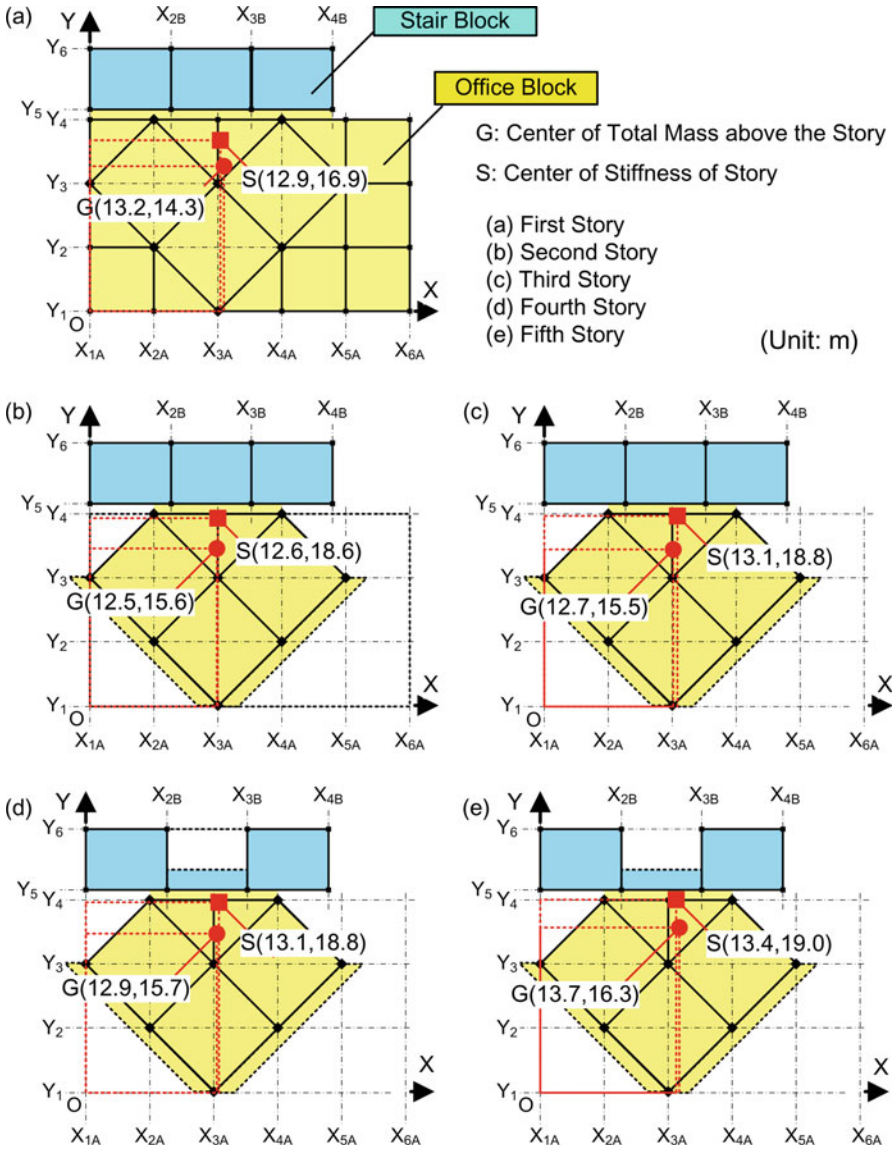


Fig. 33.7 Location of the center of total mass above the considering story and the center of stiffness of the considering story

eccentricity index in X-direction, R_{eX}, is larger than 0.15 in all stories: in particular, R_{eX} is larger than 0.3 in the second to fourth stories (Fig. 33.8c).

Therefore, this building is sensitive to torsional response and is classified as a TF system in all stories in X-direction and the second to fifth stories in Y-direction.

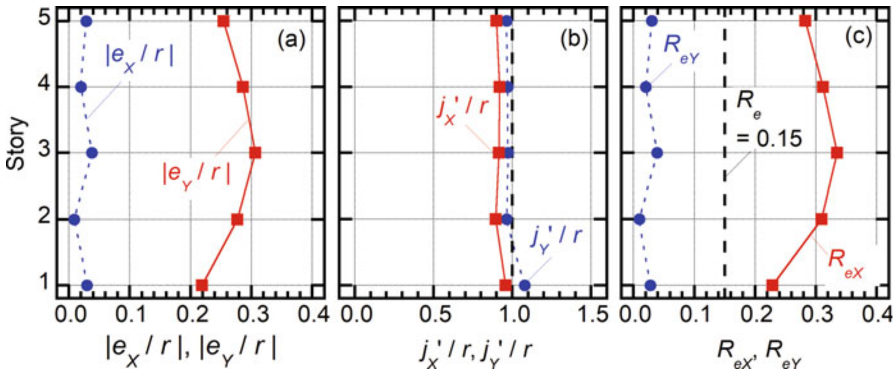


Fig. 33.8 Distribution of parameters of torsional irregularity. (**a**) Eccentricity ratio, (**b**) radius ratio of gyration of story torsional stiffness with respect to the center of stiffness, (**c**) eccentricity index

33.5 Discussions and Conclusions

In this paper, the seismic capacity and torsional irregularity of the main building of Uto City Hall were evaluated by using a simple method based on structural drawings. The main findings of this paper are as follows.

(a) The seismic capacity of the main building of Uto City Hall is insufficient to survive severe earthquakes. However, the evaluated results of both cases cannot explain the damage observed in upper stories.
(b) The ratio of the stiffness eccentricity to radius of torsional stiffness evaluated in each story exceeds 0.15, whereas the radius ratio of the torsional stiffness with respect to center of stiffness to the gyration of whole mass above the considered story is smaller than 1. Therefore, the main building of Uto City Hall is sensitive to torsional response: it may be classified as a "torsionally flexible building."

Note that further detailed investigations, such as a nonlinear time-history analysis of the frame building model, are needed to explain the seismic behavior of the main building of Uto City Hall during sequential seismic events. Seismic response evaluation of this building by using several nonlinear static procedures is also attractive for the validation of these procedures.

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References

BCJ (2016) The building standard law of Japan on CD-ROM, The Building Center of Japan, Tokyo

Fujii K, Yoshida T, Nishimura T et al (2017) Observation of damage to Uto City Hall in the 2016 Kumamoto Earthquake. In: 8th European workshop on the seismic behaviour of irregular and complex structures, Bucharest, Romania, 19–20 October 2017 (submitted)

Hejal R, Chopra AK (1987) Earthquake response of torsionally-coupled buildings. Earthquake Engineering Research Center, report no. UCB/EERC-87/20, College of Engineering, University of California at Berkeley

Shiga T (1977) Earthquake damage and the amount of walls in reinforced concrete buildings. In: 6th world conference on earthquake engineering, New Delhi, India, 9–14 January 1977

The Japan Building Disaster Prevention Association (2001) Standard for seismic evaluation of existing reinforced concrete buildings (in Japanese)