EFFECT OF COLUMN-TO-BEAM STRENGTH RATIO ON MAXIMUM STORY DRIFT ANGLE RESPONSE OF STEEL FRAMES SUBJECTED TO HORIZONTAL BIDIRECTIONAL GROUND MOTION

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ABSTRACT:

In this research, the authors investigate the effect of the column-to-beam strength ratio on the seismic response of 3D frames. Analyses were carried out by using bidirectional ground motion transformed into the directions of strong and weak axes. The maximum value concerning all the stories of the maximum story drift angle caused in an arbitrary direction when bidirectional ground motion was inputted along all the directions can be almost approximated by the maximum value among the responses when only the strong-axis ground motion was inputted along the direction of the structural plane and the response when only the strong-axis ground motion was inputted along the direction of 45° from the structural plane, in the range where the column-to-beam strength ratio is greater than $\sqrt{2}$.

KEYWORDS: Column-to-Beam Strength Ratio, Maximum Story Drift Angle, Bidirectional Ground Motion

1. INTRODUCTION

Many researches have been conducted investigation on the effect of the column-to-beam strength ratio on the seismic response of 2D frames, as well as researches on the quantification of the column-to-beam strength ratio necessary to prevent the damage concentration at a particular story [e.g., Nakashima and Sawaizumi 2000]. However, there have been a few researches on the effect of the column-to-beam strength ratio on the maximum story drift angle response of steel frames subjected to bidirectional ground motion. In the case of a 3D multistory frame consisting of similar orthogonal planar multistory frames and a column used as rectangular hollow section members, the column strength in the direction of 45° from the principal axis of the section is almost equal to that in the direction along the axis. On the other hand, when a lateral force is applied along the direction of 45° from the structural plane, two orthogonal beams connected to the column resist the load. Therefore, the loading capacity of the frame is $\sqrt{2}$ times greater than that in the direction of the structural plane. As a result, the column-to-beam strength ratio becomes small, and it is supposed that the seismic behavior of the frame would be worse than that in the case of the in-plane load. It has been reported that when the column-to-beam strength ratio in the direction of the structural plane is smaller than 1.5, the collapse mechanism characteristic changes in a complicated manner according to the column-to-beam strength ratio and the input direction to the frame of the ground motion [Wada and Hirose 1989]. However, the column-to-beam strength ratio of a realistic steel frame is generally greater than approximately 1.5 [Kawashima and Ogawa 2007].

The seismic response such as the maximum story drift angle of a multistory frame can be approximated by a fishbone-shaped model [Nakashima, Ogawa, and Inoue 2002]. In this research, a fishbone-shaped model having beams in two orthogonal directions (Figure 1) is used in the analysis, and the effect of the column-to-beam strength ratio on the maximum story drift angle response of the steel frames subjected to horizontal bidirectional ground motion is examined.

2. ANALYSIS MODEL

The analysis object is a fishbone-shaped model having beams in two orthogonal directions, as shown in Figure 1. The number of stories (N) is 4 and 8. The story height (h_i) is 4 m, and the story weights are the same for all the stories. The stiffness and strength of both the beams in the same story are equal, and the stiffness and strength of the column are equal in all the directions. The yield surface of the column subjected to a bidirectional bending moment is assumed to be a circle.
The stiffness and strength of the members were set as follows.
The design story-shear force (Q_i) at the i-th story can be derived from Eqn. (2.1).

$$Q_i = C_0\, R_t\, A_i\, \alpha_i\, W_T = C_0\, R_t \sqrt{\alpha_i}\, W_T \tag{2.1}$$

where W_T is the full weight of the frame and α_i is the ratio of the partial weight from the top to the i-th story and the full weight of the frame. R_t is determined using the standard design procedures stipulated in the seismic code of Japan. R_t is 1.000 for the 4-story frame and 0.928 for the 8-story frame.
The story-shear force coefficient follows A_i, as shown in Eqn. (2.2).

$$A_i = \frac{1}{\sqrt{\alpha_i}} \tag{2.2}$$

When it is assumed that the position of the inflection points in the column is at the center of a member and the story-shear force that corresponds to a standard shear force coefficient (C_0) of 0.2 is applied along the direction of the structural plane, the rotation 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 frame for which the column-to-beam strength ratio is 1.0, when a story-shear force that corresponds to a C_0 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 full plastic moment of the other beams is the same as the standard frame. Analyses were carried out while changing the column-to-beam strength ratio from 1.0 to 3.0. The full plastic moments of the column and beam at the i-th story of the frame ($C_{p,i}$ and $B_{p,i}$) are shown in Eqn. (2.3).

$$\begin{aligned} C_{p,i} &= \gamma \frac{Q_i\, h_i}{2} \\ B_{p,N} &= \gamma \frac{Q_N\, h_N}{2} \\ B_{p,i} &= \gamma \frac{Q_i\, h_i + Q_{i+1}\, h_{i+1}}{2} \end{aligned} \tag{2.3}$$

Table 1 shows the ultimate base shear coefficient (C_B) and primary natural period (T_1) in the analysis frames for which the column-to-beam strength ratio is 1.0. In this analysis, the beam is modeled as an elasto-plastic spring that restrains the in-plane node rotation, and the column is modeled by using a general plastic hinge method [Bruinette and Fenves 1966] 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. (2.3) was adopted for the load versus

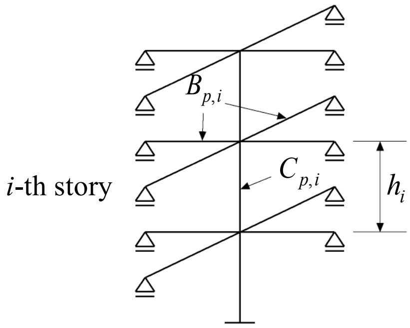


Figure 1: Analysis frame

Table 1: Outline of analysis frames

N	C_B	T_1 (s)
4	0.300	0.95
8	0.278	1.37

deformation relationship of the columns and beams, and the strain-hardening coefficient is assumed to be 0.02. The reduction in the bending stiffness of the columns subjected to an axial force, vertical displacement of the node, and torsional deformation of the columns are neglected. The $P-\Delta$ effects are considered. The analysis was carried out with stiffness-proportional damping for which the damping ratio of the first mode is 0.02.

3. INPUT GROUND MOTION

3.1 Directivity of Bidirectional Ground Motion

Four bidirectional ground motion records, as listed in Table 2, were used in the analysis. These records indicate the north–south and east–west directions, and it does not reveal the direction in which the strength is the strongest or the weakest. Therefore, the consideration of this result becomes complex. To more concisely examine the seismic response of the frame subjected to bidirectional ground motion, the ground motion in the direction where the strength was the strongest and weakest was used as the input ground motion.

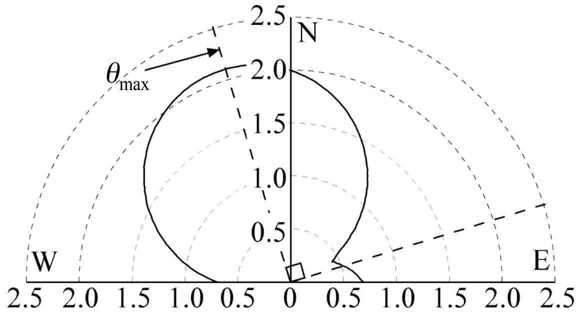


Figure 2: Distribution of maximum velocity response; NTT Kobe, T = 1.00 (s)

Table 2: Ground motions

Seismic Records	Duration Time (s)	Maximum Acceleration (m/s^2)		θ_S (°)
		N–S	E–W	
El Centro, 1940	53.47	3.42	2.10	127
Taft, 1952	54.36	1.53	1.75	31
JMA Kobe, 1995	30.00	8.21	6.19	121
NTT Kobe, 1995	50.54	3.31	1.53	107

Figure 2 shows the maximum velocity response in each direction of a single-mass system subjected to bidirectional ground motion using a polar display. Since this figure is symmetric about the origin, the lower half is omitted. The orthogonal axes E, W, and N in the figure indicate the direction of the input ground motion record. The natural period (T) of the single-mass system and input ground motion are shown in the figure. This analysis was carried out by using a damping ratio of 0.02. As for the maximum velocity response in each direction for each value of T, the directions where the strengths are the strongest and weakest are almost orthogonal, as shown in Figure 2. Figure 3 shows the relation between the direction where the strength of the ground motion is the strongest (θ_{max}) and T. θ_{max} fluctuates when T changes. Moreover, θ_{max} changes by changing the damping ratio, and fluctuations of θ_{max} by changing T are inactive in large values of the damping ratio [Wada and Hirose 1989]. Therefore, in consideration of the influence of a higher mode and change of the apparent natural period along with yielding of the members, it was suggested that setting the θ_{max} direction corresponding to T as the strong-axis direction was unsuitable. In this paper, the direction where the spectrum intensity (SI) [Housner 1959] (Eqn. (3.1)) became the maximum (θ_S) was adopted as the strong-axis direction of ground motion, independent of T.

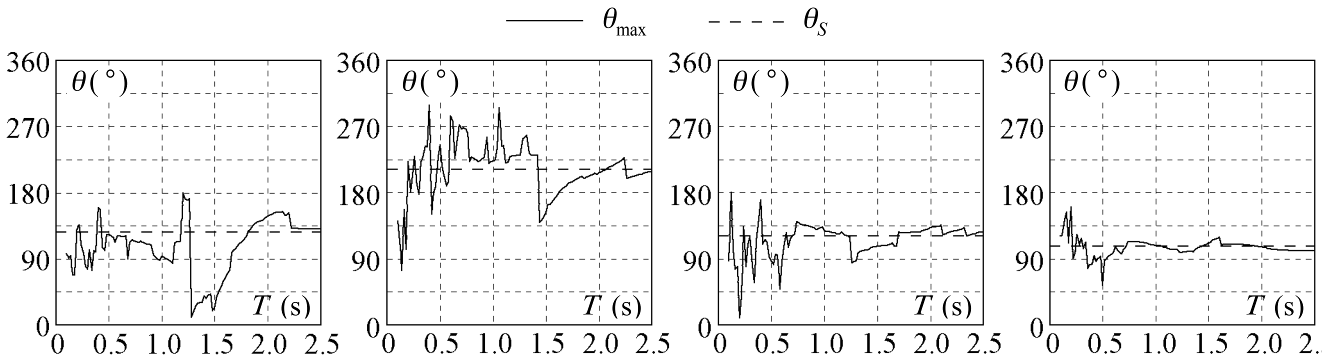


Figure 3: Relationship between $\theta_{max}-T$

$$SI = \int_{0.1}^{2.5} S_v(T)\,dT \qquad (3.1)$$

The broken line in Figure 3 shows the θ_S direction. For most values of T, $\theta_{\max}$ and θ_S become almost similar. Based on this discussion, the direction of the principal axis of the ground motion was set to be independent of T. The direction where the spectrum intensity became the maximum was set as the strong-axis direction, and the direction orthogonal to the strong axis was set as the weak-axis direction. In this research, the analyses were carried out by using seismic waveforms that were converted into these two directions as the input ground motion. Angles of the strong-axis direction from the E–W axis (θ_S) of each ground motion are listed in Table 2.

3.2 Input Level of Ground Motion

In the input ground motions, to make the levels of the responses of the frames uniform, two types of levels were set by using the value (V_{dm}) that converted the earthquake input energy causing damages into an equivalent velocity. They were V_{dm} = 1.5 m/s and V_{dm} = 2.25 m/s. When only the strong-axis ground motion was inputted along the direction of structural plane of the frame with a column-to-beam strength ratio of 1, the maximum acceleration of the ground motion is adjusted in order for V_{dm} to attain these values. Table 3 shows the maximum acceleration of each ground motion that was adjusted.

Table 3: Maximum accelerations of ground motions ($\mathrm{m/s^2}$)

Seismic Records	$N = 4$				$N = 8$			
	$V_{dm} = 1.50$ m/s		$V_{dm} = 2.25$ m/s		$V_{dm} = 1.50$ m/s		$V_{dm} = 2.25$ m/s	
	Strong Axis	Weak Axis	Strong Axis	Weak Axis	Strong Axis	Weak Axis	Strong Axis	Weak Axis
El Centro	5.57	3.58	8.14	5.23	7.17	4.60	9.56	6.13
Taft	6.65	4.38	9.85	6.49	7.51	4.95	10.1	6.68
JMA Kobe	4.39	2.50	7.51	4.27	5.72	3.26	8.75	4.98
NTT Kobe	2.58	1.24	3.61	1.73	1.95	0.94	3.41	1.64

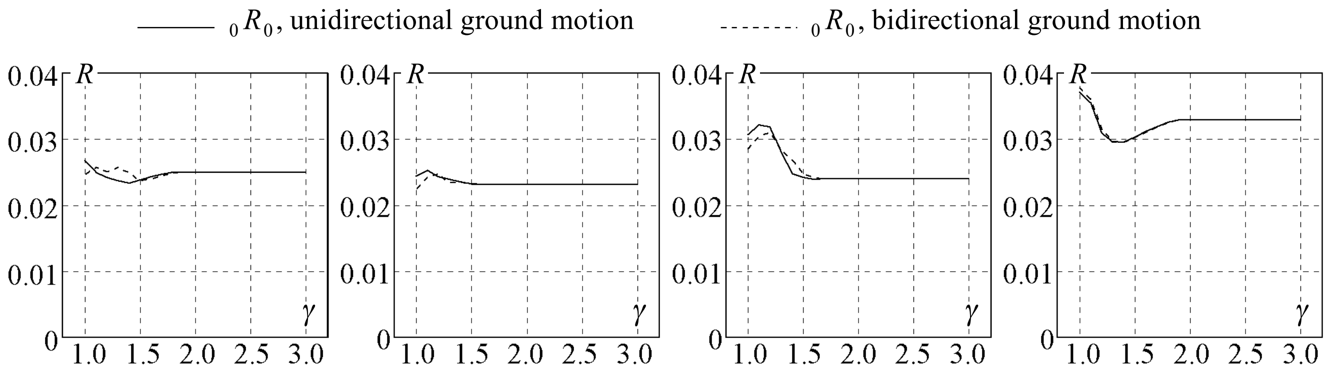
4. ANALYSIS RESULTS

Here, the relation between the column-to-beam strength ratio (γ) of the frame and the maximum value concerning all the stories of the maximum story drift angle (R) is shown. In this research, the analysis was carried out by using two types of input levels and number of stories, but the analysis results for the 8-story frame for which V_{dm} = 2.25 m/s is the input level is expanded because they all have similar results.
Because the seismic response changes according to the direction where the ground motion is inputted to the frame and the response of all the directions is targeted in this research, many response values are obtained. At first, the analyses are carried out by inputting the ground motion along the direction of the structural plane and along the direction of 45° from the structural plane. Then, the analyses are carried out by inputting the ground motion along all the directions, and the maximum response value is examined. In this paper, R shows the maximum value concerning all the stories of maximum story drift angle, and the left subscript shows the direction where the strong-axis ground motion was inputted and the right subscript shows the direction where the maximum story drift was obtained.

4.1 Input along the Direction of Structural Plane

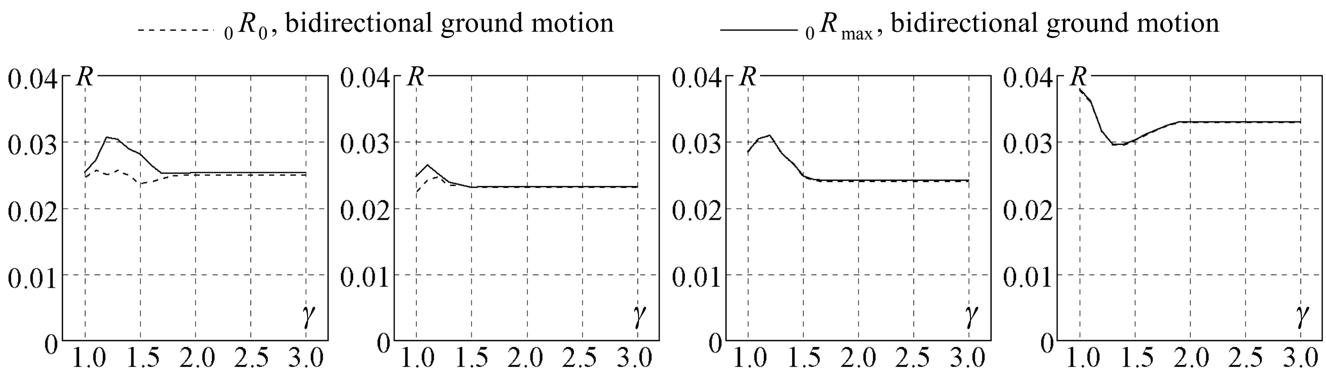
Figure 4 shows the relation between the maximum value concerning all the stories of the maximum story drift angle in the direction where the strong-axis ground motion was inputted (${}_0R_0$) and the column-to-beam strength ratio (γ), concerning the analysis in which only the strong-axis ground motion was inputted along the direction of the structural plane and the analysis in which bidirectional ground motion was inputted adding the weak-axis ground motion. The number of stories of an analysis frame (N), input ground motion, and input level of the ground motion (V_{dm}) are shown in the figure. The solid line in the figure shows ${}_0R_0$ when unidirectional ground motion was inputted, and the broken line shows ${}_0R_0$ when bidirectional ground motion was inputted. ${}_0R_0$ when unidirectional ground motion was inputted is the same as the analysis result of the 2D frame.
Because the weak-axis ground motion influences ${}_0R_0$ when bidirectional ground motion was inputted, it might be different from the response when unidirectional ground motion was inputted. However, the influence of the

weak-axis ground motion is considerable only in the range where the column-to-beam strength ratio is smaller than approximately $\sqrt{2}$. In the range where the column-to-beam strength ratio is greater than $\sqrt{2}$, the influence of the weak-axis ground motion is marginal, and ${}_0R_0$ for both unidirectional and bidirectional ground motions became almost similar.



(a) El Centro (b) Taft (c) JMA Kobe (d) NTT Kobe

Figure 4: ${}_0R_0$ when unidirectional ground motion was inputted and ${}_0R_0$ when bidirectional ground motion was inputted; $N = 8$, $V_{dm} = 2.25$



(a) El Centro (b) Taft (c) JMA Kobe (d) NTT Kobe

Figure 5: ${}_0R_0$ and ${}_0R_{max}$ when bidirectional ground motion was inputted; $N = 8$, V_{dm} =2.25 m/s

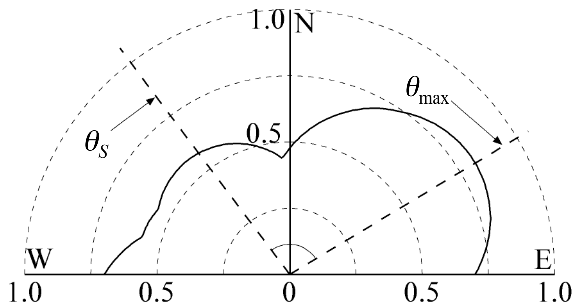


Figure 6: Distribution of maximum velocity response; El Centro, $T = 1.37$ (s)

Figure 5 shows ${}_0R_0$ when bidirectional ground motion was inputted and the maximum value concerning all the stories of the maximum story drift angle (${}_0R_{max}$) caused in an arbitrary direction when bidirectional ground motion was inputted. The solid line in this figure shows ${}_0R_{max}$ when bidirectional ground motion was inputted, and the broken line shows ${}_0R_0$ when bidirectional ground motion was inputted. When bidirectional ground motion was inputted, the story drift angle in the direction of the orthogonalization was caused at the same time as that when ${}_0R_0$ occurs in the direction where the strong-axis ground motion was inputted. Therefore, the maximum response value was obtained in the direction that is not the direction where the strong-axis ground motion was inputted. This is represented by the right subscript "max." In Figure 5 (a), ${}_0R_{max}$ is considerably greater than ${}_0R_0$ in the range where γ = 1.1–1.5. Figure 6 shows the maximum velocity response value in each direction of the single-mass system with $T = 1.37$ s for the 8-story frame subjected to the ground motion at El Centro. In this example, the maximum value of the maximum velocity response is obtained in an almost orthogonal direction to θ_S that was set as the strong axis of the ground motion. Therefore, ${}_0R_{\max}$ is caused in the direction that is not the direction where the strong-axis ground motion was inputted, and it assumes a value that is considerably greater than ${}_0R_0$. In a part of this example, because the influence of the weak-axis ground motion is large, ${}_0R_{\max}$ is approximately 30% greater than ${}_0R_0$ in the range where the column-to-beam strength ratio is smaller than $\sqrt{2}$. However, both these values are almost the same in the range where the column-to-beam strength ratio is greater than $\sqrt{2}$.

4.2 Input along the Direction of 45° from Structural Plane

Figure 7 shows the relation between the maximum value concerning all the stories of the maximum story drift angle in the direction where the strong-axis ground motion was inputted (${}_{45}R_{45}$) and the column-to-beam strength ratio (γ), concerning the analysis in which only the strong-axis ground motion was inputted along the direction of 45° from the structural plane and the analysis in which bidirectional ground motion was inputted adding the weak-axis ground motion. The solid line in this figure shows ${}_{45}R_{45}$ when unidirectional ground motion was inputted, and the broken line shows ${}_{45}R_{45}$ when bidirectional ground motion was inputted. Because the two orthogonal beams resist the lateral force along the direction of 45° from the structural plane, the strength of the beam is $\sqrt{2}$ times greater than that in the direction of the structural plane. That is, in the frame for which the column-to-beam strength ratio is $\sqrt{2}$, the strengths in the column and beam against the ground motion along the direction of 45° from the structural plane are equal. Therefore, in the range where the column-to-beam strength ratio is smaller than $\sqrt{2}$, the columns tend to yield earlier than the beams. Further, when the column-to-beam strength ratio increases, there are many cases in which the ${}_{45}R_{45}$ values tend to increase because the story drift angle at the elastic limit increases.

In most of the results, the ${}_{45}R_{45}$ values when bidirectional ground motion was inputted are almost the same or smaller than the ${}_{45}R_{45}$ values when unidirectional ground motion was inputted. When the ground motion is

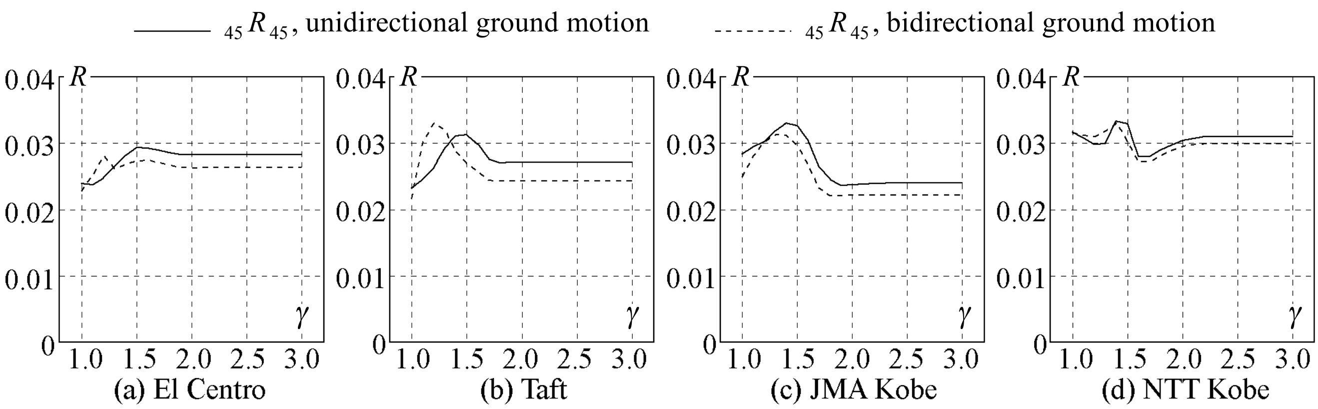


Figure 7: ${}_{45}R_{45}$ when unidirectional ground motion was inputted and ${}_{45}R_{45}$ when bidirectional ground motion was inputted; $N = 8$, V_{dm} = 2.25 m/s

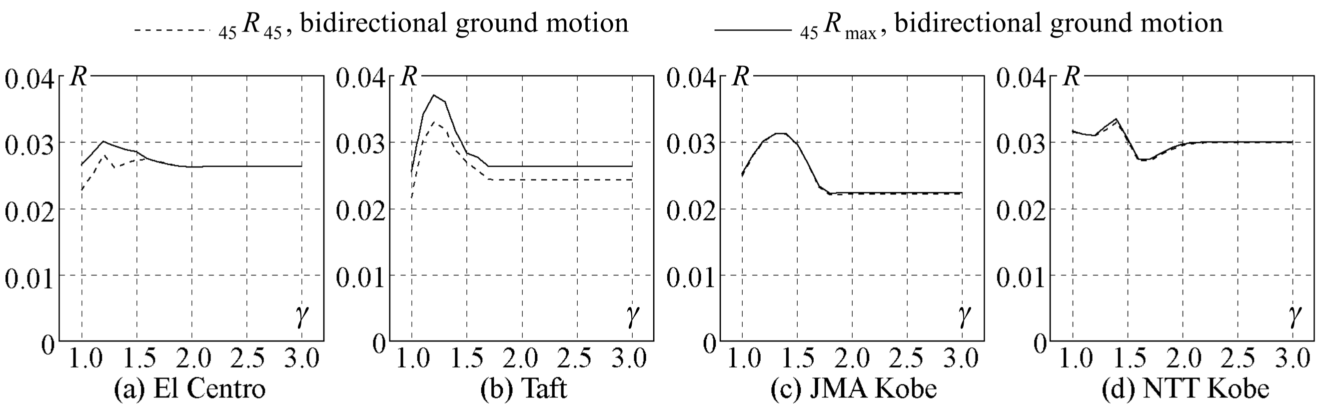


Figure 8: ${}_{45}R_{45}$ and ${}_{45}R_{\max}$ when bidirectional ground motion was inputted; $N = 8$, V_{dm} = 2.25 m/s

inputted along the direction of the structural plane of the frame in which the column is sufficiently strong and only the beam yields, the responses when unidirectional and bidirectional ground motions are inputted are equal, because the weak-axis ground motion influences only the orthogonal beam. In contrast, when the ground motion is inputted along the direction of 45° from the structural plane of the frame in which the column is sufficiently strong and only the beam yields, the responses when unidirectional and bidirectional ground motions are inputted are not equal, because the two orthogonal beams resist the strong- and weak-axes ground motions. When unidirectional ground motion is inputted, two orthogonal beams yield at the same time. On the other hand, when bidirectional ground motion is inputted, one of the beams yields early due to the weak-axis ground motion and the strength of the beam becomes small. Because hysteretic damping is caused from a small deformation when the elastic limit of the elasto-plastic system becomes small, the displacement response tends to become small. Accordingly, ${}_{45}R_{45}$ when bidirectional ground motion was inputted tends to become small more than ${}_{45}R_{45}$ when unidirectional ground motion was inputted, as shown in Figure 7.
Figure 8 shows ${}_{45}R_{45}$ when bidirectional ground motion was inputted, and the maximum values concerning all the stories of the maximum story drift angle (${}_{45}R_{max}$) caused in an arbitrary direction when bidirectional ground motion was inputted. The solid line in this figure shows ${}_{45}R_{max}$ when bidirectional ground motion was inputted, and the broken line shows ${}_{45}R_{45}$ when bidirectional ground motion was inputted. As well as the case which ground motion was inputted along the direction of the structural plane, both values are almost the same in the range where the column-to-beam strength ratio is greater than $\sqrt{2}$.

4.3 Maximum Value Caused in an Arbitrary Direction when Ground Motion is Inputted along All Directions
In sections 4.1 and 4.2, the direction where the ground motion was inputted to the frame was limited along the direction of the structural plane and the direction of 45° from the structural plane; these results were examined. As a result, it was shown that the maximum value concerning all the stories of the maximum story drift angle when only strong-axis ground motion was inputted becomes almost similar to the maximum value concerning all the stories of the maximum story drift angle caused in the direction where the strong-axis ground motion was inputted when bidirectional ground motion was inputted and in an arbitrary direction. In this section, the relationship between the maximum value concerning all the stories of the maximum story drift angle in an

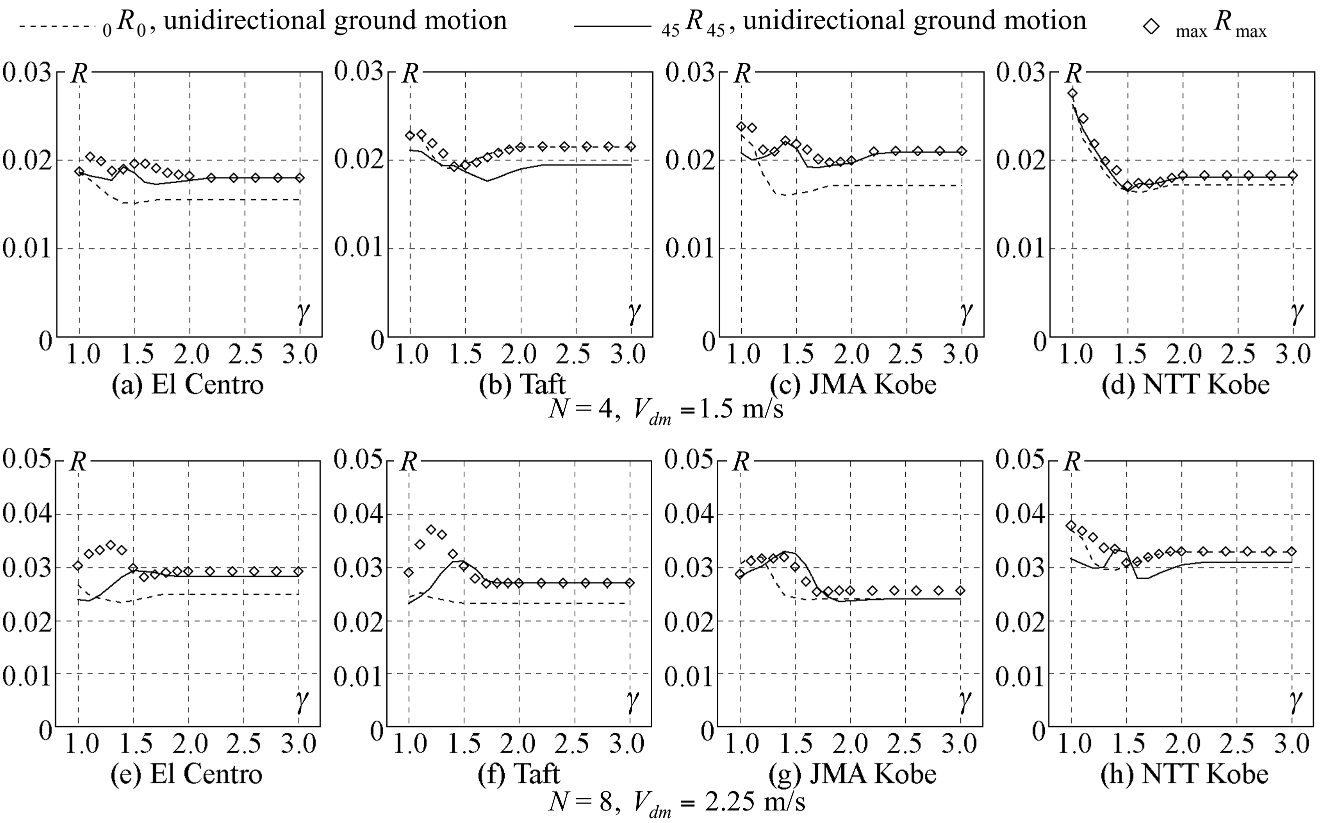


Figure 9: ${}_{0}R_{0}$ and ${}_{45}R_{45}$ when unidirectional ground motion was inputted and ${}_{max}R_{max}$

arbitrary direction when bidirectional ground motion is inputted along all the directions (${}_{\max}R_{\max}$) and the maximum value concerning all the stories of the maximum story drift angle when only the strong-axis ground motion is inputted (${}_{0}R_{0}$ and ${}_{45}R_{45}$) are examined.
Figure 9 shows ${}_{0}R_{0}$ when only the strong-axis ground motion was inputted along the direction of the structural plane, ${}_{45}R_{45}$ when only the strong-axis ground motion was inputted along the direction of 45° from the structural plane and ${}_{\max}R_{\max}$ in an arbitrary direction when bidirectional ground motion was inputted along all the directions. The solid line in this figure shows ${}_{45}R_{45}$, the broken line shows ${}_{0}R_{0}$, and ◇ shows ${}_{\max}R_{\max}$. The results obtained when four ground motions with input levels of V_{dm} = 1.5 m/s were inputted to a 4-story frame are shown in Figure 9 (a)–(d), and the results when four ground motions with input levels of V_{dm} = 2.25 m/s were inputted to an 8-story frame are shown in Figure 9 (e)–(h).
In some examples, ${}_{\max}R_{\max}$ is considerably greater than ${}_{0}R_{0}$ and ${}_{45}R_{45}$ in the range where the column-to-beam strength ratio is smaller than $\sqrt{2}$. This is because the direction of the maximum response might be different from the direction of the strong-axis ground motion, as described in section 4.1, and the influence appears strongly in the range where the column-to-beam strength ratio is smaller than $\sqrt{2}$. However, in most of the examples, the largest value among ${}_{0}R_{0}$ and ${}_{45}R_{45}$ when only the strong-axis ground motion was inputted becomes close to ${}_{\max}R_{\max}$, in the range where the column-to-beam strength ratio is greater than $\sqrt{2}$.

5. CONCLUSION

In this paper, the direction where the spectrum intensity became the maximum (θ_S) was set as the strong-axis direction, and the orthogonal direction to this strong axis was set as the weak-axis direction; the relationship between the column-to-beam strength ratio and the maximum story drift angle of the multistory steel frame subjected to ground motion was examined.
As a result, it was clarified that the maximum value concerning all the stories of the maximum story drift angle in an arbitrary direction when bidirectional ground motion was inputted along all the directions (${}_{\max}R_{\max}$) can be almost approximated by the largest value among ${}_{0}R_{0}$ when only the strong-axis ground motion was inputted along the direction of the structural plane and ${}_{45}R_{45}$ when only the strong-axis ground motion was inputted along the direction of 45° from the structural plane, in the range where the column-to-beam strength ratio was greater than $\sqrt{2}$.
The authors have investigated the column-to-beam strength ratio of 30 frames designed according to Japanese Building Code; many examples exceed a value of 1.5 [Kawashima and Ogawa 2007]. When assuming that the column-to-beam strength ratio is greater than 1.5, the maximum story drift angle response subjected to bidirectional ground motion is obtained from the analysis result in which only the strong-axis ground motion is inputted along the direction of the structural plane and 45° from the structural plane.

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