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RESPONSE CHARACTERISTICS OF REINFORCED CONCRETE STRUCTURES UNDER BI-DIRECTIONAL EARTHQUAKE MOTIONS

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ABSTRACT

The purpose of this study is to investigate the elasto-plastic response characteristics of reinforced concrete structures under horizontal bi-directional earthquake motions. In this study, the behavior of reinforced concrete columns failing in flexure was evaluated by means of two-way shaking table tests and response analyses. Furthermore, the response characteristics of reinforced concrete structures where columns dominate the behavior under bi-directional earthquake motions were verified from a comparison between uni-directional response and bi-directional response.

KEYWORDS

Bi-directional earthquake motion; response characteristic; reinforced concrete column; shaking table test; response analysis; bi-axial interaction; flexural failure; energy response.

INTRODUCTION

In reinforced concrete (hereafter, refers to as "R/C") structures under horizontal bi-directional earthquake motions, vertical elements such as columns must resist bending moments and shearing forces in two directions, in addition to vertical load. Under bi-directional excitation, elasto-plastic behaviors of R/C columns are more complex than those under uni-directional one, and it is noted that the behaviors have significant influence on response characteristics of structures. However, in the past experimental studies, the behaviors of R/C columns under bi-directional excitation have been scarcely investigated under the dynamic load. And in the past analytical studies, fundamental response characteristics have not been verified although the increase and decrease of response values have been discussed. Furthermore, although asiesmic performance of R/C structures are dependent on strength and deformability such as the performance of energy dissipation, either only the strength or deformability is often evaluated and the response characteristics under bi-directional earthquake motions have been scarcely evaluated from the point of view of energy balance.

In this study, first, the shaking table tests of R/C columns failing in flexure were performed under uni-directional and bi-directional input excitations. The effects of bi-directional earthquake motions on elasto-plastic behaviors of R/C columns were evaluated from the comparison between the results of two-way and one-way shaking table tests. Next, an analytical procedure which can simulate the elasto-plastic behaviors of R/C columns under bi-directional dynamic load was developed, and its validity verified from the comparison with the test results. Furthermore, the parametrical response analyses were conducted, and the fundamental response characteristics of R/C structures under bi-directional earthquake motions were verified from the point of view of energy balance. In this paper, the response characteristics under bi-directional earthquake motions which were evaluated from the results of shaking table test and parametric response analyses were investigated.

OUTLINE OF TWO-WAY SHAKING TABLE TESTS

The two-way shaking table, which can simultaneously move horizontally in two directions, was used in order to reproduce bi-directional earthquake motions. The test equipment is schematically shown in Fig. 1 and the configuration and bar arrangement of specimens are shown in Fig. 2. The specimens were the 1/9 scaled R/C columns failing in flexure which have square section and symmetrical bar arrangement. The shear-span ratios(M/QD) of R/C columns are equal to 2.0 and/or 3.0. The tests were carried out under uni-directional and bi-directional excitation. The input earthquake motions used in the tests were the Hachinohe NS(North-South) and EW(East-West) ground acceleration recorded in the 1968 Tokachi-oki earthquake. The input excitations were obtained by modifying the original excitations, that is, the time duration of input signals was reduce to 1/3 of the actual according to the similitude law. The detail of the test equipment, specimens, measurements and test results were presented in previous publication(Kitajima *et al.*, 1994a).

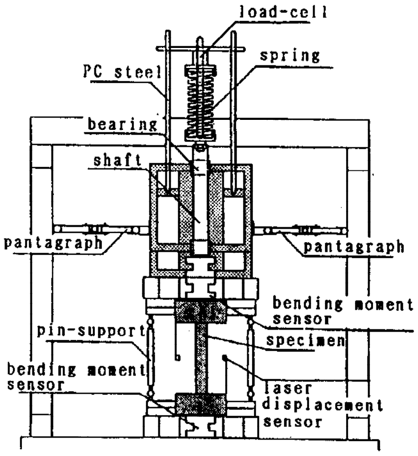
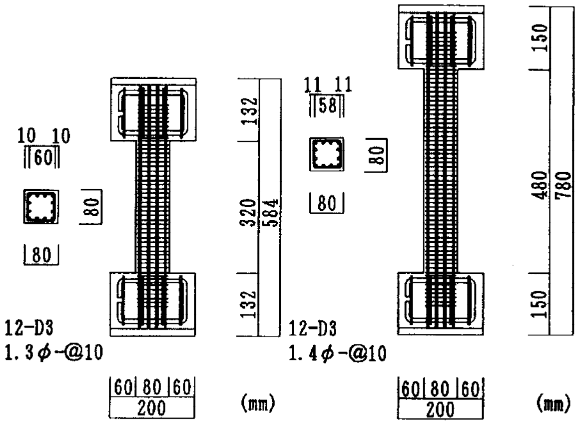


Fig. 1. Shaking table test equipment



(M/QD=2.0) (M/QD=3.0)

Fig. 2. Test specimen

ANALYTICAL STUDY

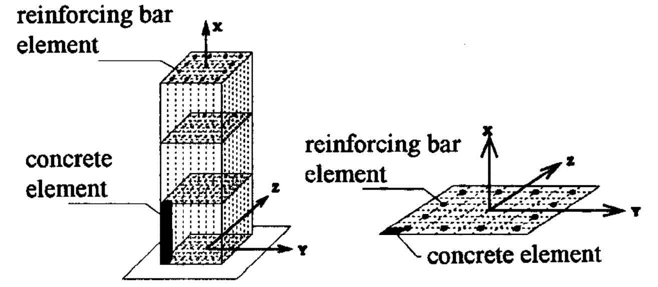
In order to investigate the validity of the findings obtained by the shaking table tests, response analyses of single mass system were conducted on 112 cases, by taking into account of the natural frequency of analytical models, the input earthquake waves and the input conditions (uni-directional or bi-directional) as variables.

Outline of Analytical Procedure

The analytical procedure which combines the restoring force calculation by the fiber method (Fig. 3) with the response calculation by the Newmark explicit method was developed (Figs. 4 and 5). The details of this analytical procedure can be found on the references Kitajima *et al.*(1991, 1992).

Analytical Valuable

The parametrical response analyses were curried out with 4 models. The natural frequency of each model is shown in Table 1. Those analytical models were based on the tests specimen of M/QD=3.0 series. The elastic natural frequency of model 1 was the same as the test specimen and the natural frequencies of the other



(a) Discretization of member (b) Discretization of section

Fig. 3. Discretization in fiber method

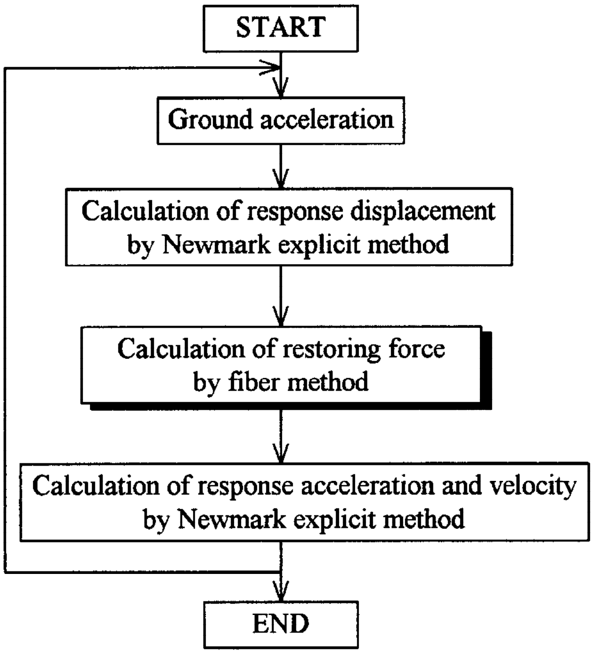


Fig. 5. Flow of analysis

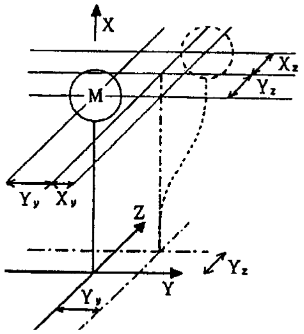


Fig. 4. Analytical model in response analysis

three models were varied by changing the mass. The acceleration wave measured in the two-way shaking table, Elcentro, Taft and Hachinohe were used for the input excitations in analysis. The time duration of Elcentro, Taft and Hachinohe, as well as the test wave, were reduced to 1/3. The maximum input acceleration was modified to correspond to the same level of the elastic response under NS uni-directional excitation in model 1. The input excitation is shown in Table 2. The response analyses were curried out under NS or EW uni-directional excitation and under bi-directional, one for each case. Furthermore, in order to investigate the relationship between the bi-directional response and the uni-directional response with previously reduced strength, the uni-directional analysis were curried out by reducing the strength to $1/\sqrt{2}$ or 1/1.2. The reason why the strength is reduced will be explained later. The combination of analytical variables is shown in Table 3. The viscous damping factor in the analysis using the test wave was assumed 1.0% in proportion to the initial stiffness. In the analysis using the Elcentro, Taft and Hachinohe for input excitations, it was assumed to be non-damping in order to make the difference between the uni-directional response and the bi-directional response more pronounced.

Table 1. Natural frequency of analytical model

	Natural Frequency
Model 1	4.1 Hz
Model 2	2.6 Hz
Model 3	2.2 Hz
Model 4	6.7 Hz

Table 2. Input earthquake motion

Input Wave		Max. Acc. (cm/sec^2)	Amplitude
Shaking Table wave	NS	167.3	1.0
	EW	119.6	
El centro	NS	239.2	0.7
	EW	147.1	
Taft	NS	168.0	1.1
	EW	193.5	
Hachinohe	NS	202.5	0.9
	EW	164.5	

Table 3. Combination of analytical valiables

Input Wave	Input Direction		Strength Ratio
Shaking Table wave El centro Taft Hachinohe	Uni-direc.	NS	1.0, 1/1.2, $1/\sqrt{2}$
		EW	1.0, 1/1.2, $1/\sqrt{2}$
	Bi-direc.	NS-EW	1.0

EVALUATION OF TEST AND ANALYTICAL RESULT

The equation of motion of single mass system under bi-directional excitation is given as follows :

$$M\ddot{x}_i + D_i + Q_i = -M\ddot{y}_i \tag{1}$$

where, M indicates the mass, Di indicates the i-directional damping force, Qi indicates the i-directional restoring force, $\ddot{x}$i indicates the i-directional relative acceleration of mass, $\ddot{y}$i indicates the i-directional ground acceleration, i indicates the NS or EW direction.

If the viscous damping forces Di are assumed to be independent for each direction, the eq. (1) is same as under uni-directional case except for the restoring force Qi which is influenced by the effect of bi-axial interaction. This means the one-directional restoring force is effected by the transverse displacement, that is, the difference of the restoring force properties of NS or EW direction under uni or bi-directional excitation makes the difference in the response values. Therefore, in this study, the response characteristic of NS or EW direction under bi-directional excitation were evaluated by correlating the response under uni-directional one.

Test Result

The response hysteresis curves (load-displacement relationships), the trace of displacement and the trace of shearing force observed in the shaking table tests are shown in Figs. 6 and 7. The early steps of the records are shown in the figures, which shows the difference between uni and bi-directional response. The test results show that the behaviors of R/C column under bi-directional excitation are more complex than those under uni-directional one. The strength and stiffness under bi-directional excitation are smaller in comparison with those under uni-directional one, and the maximum displacement under bi-directional excitation is larger than those under uni-directional one.

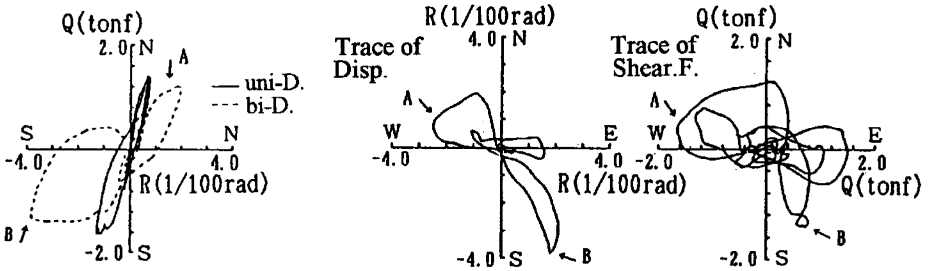


Fig. 6. Hysteresis curve and trace of displacement and shearing force (M/QD=2.0)

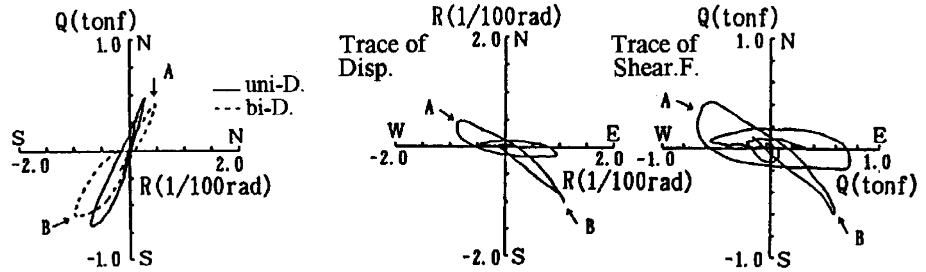


Fig. 7. Hysteresis curve and trace of displacement and shearing force (M/QD=3.0)

Comparison Between Test and Analytical Results

The comparison between the test and analytical results of the specimen of M/QD=3.0 series are shown in Figs. 8 and 9. The analytical results agreed with the test results, and it is verified that the analytical procedure can simulate the behaviors of R/C column under bi-directional dynamic load. The detail of comparison can be found in the reference (Kitajima *et al.*, 1994b), which reports the comparison about the strain level and the strain rate of reinforcing bars.

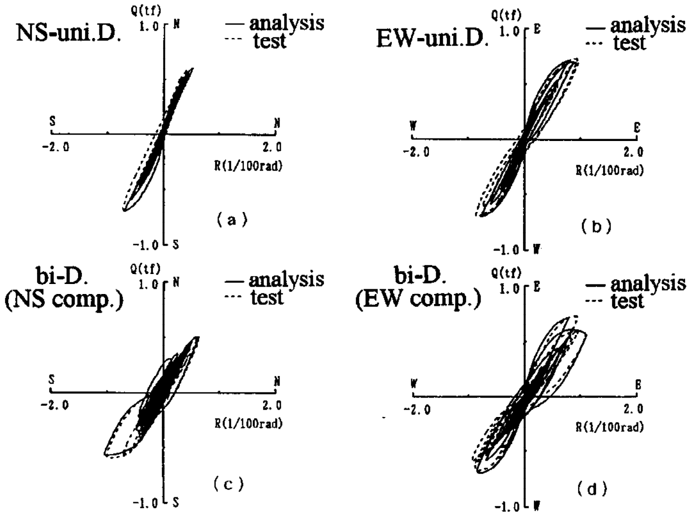


Fig. 8. Hysteresis curve

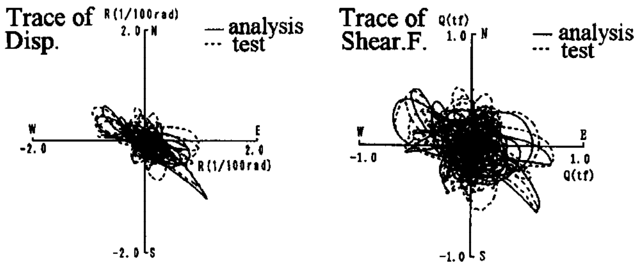


Fig. 9. Trace of displacement and shearing force

Relationship Between Elastic Response Spectra and Test and Analytical Results

It was pointed out from the past analytical study (Ishimaru. 1982) that the elasto-plastic response characteristics of single mass system under uni-directional excitation reflect the elastic response spectral characteristics between the elastic natural frequency and equivalent frequency which is the decreased frequency due to plastification. In this paper, it is verified that the uni-directional and bi-directional responses reflect the elastic response spectral characteristics in both cases. The decreased frequency due to the decrease of the strength and stiffness of R/C columns was evaluated by using the equivalent frequency which is determined from the relationship between the mass and the equivalent stiffness. The equivalent stiffness was defined by using the maximum shearing force and the maximum displacement obtained from the test and analytical results. The maximum displacement and the total energy input (Akiyama. 1980) due to earthquake, obtained from the test and analysis, were plotted on the elastic response spectra, which correspond with the equivalent frequency as shown in Figs. 10~14. The total energy input due to earthquake were calculated by integrating form time 0 to time t_0 (time of ending input excitation) of the right term of eq. (1) times ($\dot{x}_i \cdot dt$) as in eq. (2), and converted to equivalent velocity as eq. (3).

$$E_i = -M\int_0^{t_0} \ddot{y}_i \cdot \dot{x}_i \cdot dt \qquad (2)$$

$$V_{E_i} = \sqrt{\frac{2 \cdot E_i}{M}} \qquad (3)$$

where, E_i indicates the i-directional energy input due to earthquake, $\dot{x}_i$ indicates the i-directional relative velocity of mass, dt indicates the time interval, V_{E_i} indicates the i-directional equivalent velocity of energy input due to earthquake.

Figure 10 shows that the bi-directional responses reflect the elastic response spectral characteristics similar to that of the uni-directional response. If the column performed the elastic behavior, the bi-directional responses were the same as the uni-directional response. But the maximum displacement and the energy input under bi-directional excitation are greater than those under uni-directional excitation, because the natural frequency under bi-directional excitation is smaller than those under uni-directional excitation. In addition, the plastification of specimen under bi-directional excitation is greater than those under uni-directional excitation. Also, it is found that this tendency is verified during all of parametrical frequency in Figs. 11~14, and does not occurd at a specific frequency only. It is noticed that the response characteristics under bi-directional excitation can be explained by the elastic response spectra of NS and EW direction, if the decresed natural frequency of each direction are evaluated appropriately. This phenomenan is similar to that of uni-directional excitation.

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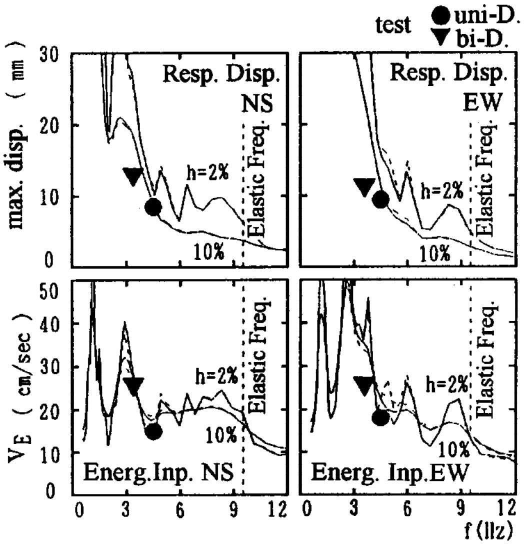
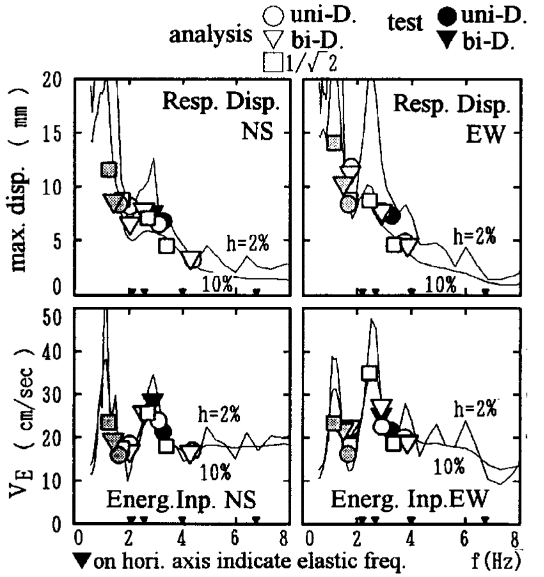
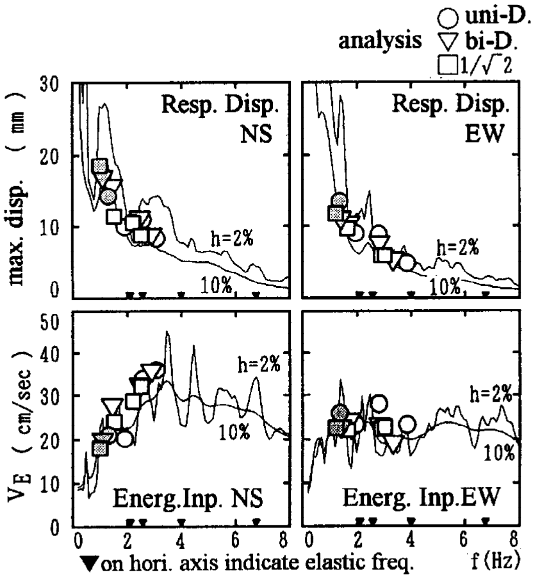


Fig. 10. Response spectra and test results (M/QD=2.0)



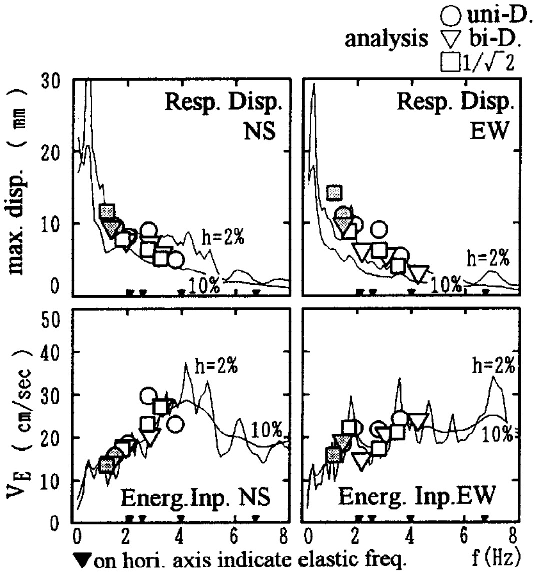
▼on hori. axis indicate elastic freq.

Fig. 11. Response spectra and analytical results (Shaking table wave)



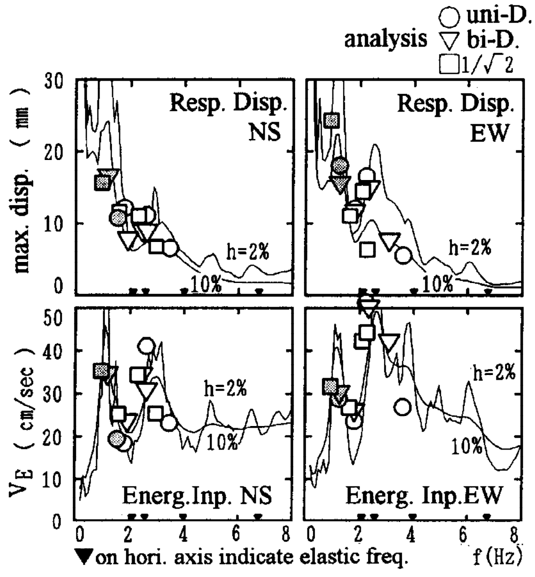
▼on hori. axis indicate elastic freq.

Fig. 12. Response spectra and analytical results (Elcentro)



▼on hori. axis indicate elastic freq.

Fig. 13. Response spectra and analytical results (Taft)



▼on hori. axis indicate elastic freq.

Fig. 14. Response spectra and analytical results (Hachinohe)

As for the two-way shaking table tests, the R/C columns performed complex behaviors, the response shearing force reached the strength envelop toward about 45 degree direction and the maximum displacement is larger. It was verified from the uni-directional response analysis using the prereduced strength(Kitajima *et al.*, 1994a) that the maximum displacement increased under bi-directional excitation becaused the shearing force that is projected on the NS or EW direction is reduced. This tendency can be seen in Figs. 11～14. The response displacement and energy input under bi-directional excitation (▽) in Figs. 11～14 are located in between the response with 1.0 strength under uni-directional excitation(○) and the response with strength previously reduced to $1/\sqrt{2}$ under uni-directional one(□). It is noticed that the response characteristics which will be incresed or decreased can be predicted by the uni-directional response analysis using the previously reduced strength. The relationship between the bi-directional response and the uni-directional response using the prereduced strength are shown in Figs. 15 and 16. The horizontal axis in the figures indicate the ratio of uni-directional response against the uni-directional response using the prereduced strength. And the vertical axis in the figures indicate the ratio of the bi-directional response against the uni-directional response. Figure 15 shows the uni-directional case with prereduced strength to $1/\sqrt{2}$. Figure 16 shows the uni-directional case with prereduced strength to 1/1.2. The assumption of the previously reduced strength to $1/\sqrt{2}$ means that the projected shearing force on the NS or EW direction stops increasing at $1/\sqrt{2}$ strength when the shearing force reached the 45 degree direction of the assumed circular strength envelop as shown in Fig. 17. The assumption of the prereduced strength to 1/1.2 means that the projected shearing force on the dominative direction stops increasing at 1/1.2 strength when the shearing force reached the 30 degree direction of the assumed circular strength envelop. In this assumption, it is considered that 50% of the response dominate in the perpendicular direction. In Figs. 15 and 16, each point is located at the first and the third quadrant. It means that the bi-directional response also increase (decrease), if the uni-directional response using the previously reduced strength increase (decrease). Therefore, it is found out that the bi-directional response is significantly influenced by the reduced shearing force projected on NS or EW direction, which means the virtual reduction of strength in NS or EW direction.

r : correlation coefficient, n : number of data, ave : average, σ : standard deviation

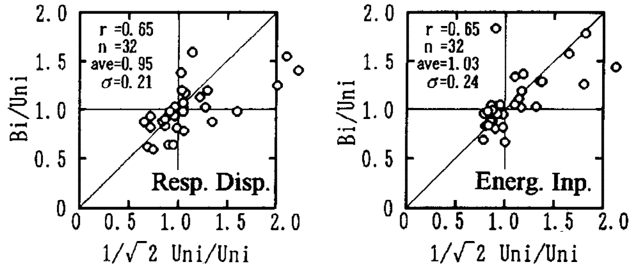


Fig. 15. Relationship between bi-direc. response and uni-direc. response with prereduced strength ($1/\sqrt{2}$)

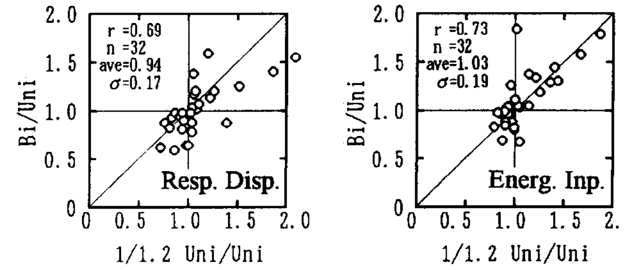
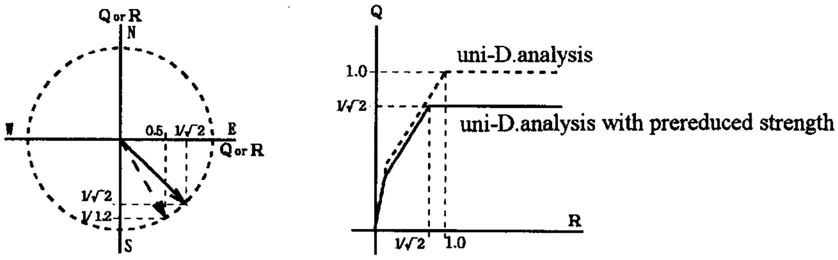


Fig. 16. Relationship between bi-direc. response and uni-direc. response with prereduced strength (1/1.2)



(a)correlation curve (strength envelop) (b)skeleton curve

Fig. 17. Concept of uni-direc. analysis with prereduced strength ($1/\sqrt{2}$ or 1/1.2)

CONCLUSIONS

In this study, the behavior of R/C columns failing in flexure was evaluated by means of shaking table tests and response analyses. The response characteristics of R/C structures where column behaviors are dominant under bi-directional earthquake motions were verified. The conclusions obtained through this study can be summarized as follows:

(1) The bi-directional responses (maximum displacement and total energy input due to earthquake) on NS or EW direction reflect the elastic response spectral characteristics on each direction, if the decrease of natural frequencies under bi-directional excitation are evaluated on the response spectra of each direction. This phenomenon is similar to that of uni-directional excitation.

(2) The shearing forces under bi-directional excitation are reduced virtually due to bi-axial interaction of R/C column, if the shearing forces are projected on the NS or EW direction. And this virtual reduction of strength on NS or EW direction causes the difference between the bi-directional response and uni-directional response. Also, the increase or decrease of response effected bi-directional input can be predicted from the uni-directional response analysis of a column with reduced strength.

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