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# OBSERVATION OF NONLINEAR EARTHQUAKE RESPONSE OF REINFORCED CONCRETE WEAK BUILDING MODEL STRUCTURES

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## SUMMARY

Since August in 1983, earthquake response observation on reinforced concrete weak model structures have been carried out at the Chiba Experimental Field Station of the Institute of Industrial Science, University of Tokyo. More than one hundred sets of records were obtained by February in 1988. The strongest record was obtained on December 17 1987. The response of weak model structures exceeded the yielding points. This paper describes the response due to this earthquake and the result of analysis.

## WEAK MODEL STRUCTURES AND INSTRUMENTATIONS

The dimensions of the weak model structures are shown in Fig. 1, and column and beam sections are shown in Fig. 2. A couple of 1/4 scaled five-story building model structures were constructed. One is a weak column-strong beam structure and the other is a strong column-weak beam structure. Each story height is 100 cm and span length is 250 cm. Cross section of the columns are 10 cm × 10 cm for weak column structure and 15 cm × 15 cm for weak beam structure, and beam are 10 cm × 20 cm for weak column structure and 10 cm × 12 cm for weak beam structure. Design base shear was about a half of that required in Japanese Building Codes. Instrumentations to measure the response accelerations at each floor level to each direction, inter-story displacements at each story to each direction, and strains of some reinforcing bars are ready to start when the accelerometer at 40 meters under the ground catches 1 gal.

## GROUND MOTION

Characteristics of the earthquake, named Chibaken Toho-Oki Earthquake, are summarized in Table 1. Fig. 4 show the locations of the epicenter and the observation station. The epicenter was located about 45 km Southeast from the observation station and the focal depth was about 60 km. J.M.A. Intensity at Chiba was V and IV at Tokyo. The Richter magnitude was estimated as 6.7. The peak acceleration recorded at the depth of 1 meter under ground were 400 gals to N-S direction, 223 gals to E-W direction and 124 gals to vertical direction. Fig. 5 shows time history and acceleration response spectra to N-S component. The spectra have an extremely high peak in the short period between 0.15 and 0.2 seconds. This peak indicates the predominated period of the ground. It is found from the waveform that the duration of large amplitude was rather short.

## OBSERVED RESPONSE CHARACTERISTICS

Both weak model structures had already suffered the damage due to previous earthquakes (for example : October 4, 1985 earthquake). The damage of weak column structure had been between medium and small, and that of weak beam structure had been slight by Japanese classification. However, the weak model structures suffered the severe damage and numbers of cracks occurred due to this earthquake. The response of X direction for both weak model structures were mainly described here. The location of each structure are shown in Fig. 3.

OUTLINE OF RESPONSE AND CRACK PATTERNS Table 2 shows the peaks of acceleration and inter-story displacement recorded at each floor level. An acceleration of 260 gals was recorded at the first floor level of weak column structure and 411 gals at the top floor level. 285 gals was recorded at first floor level of weak beam structure and 542 gals at top floor level. Peak displacement at top floor level were 3.28 cm for weak column structure, 3.45 cm for weak beam structure, and maximum drift angle for both weak model structures were about 1/100 radian. The time history of acceleration and the displacement; the sum of inter-story displacement, at the top floor level are shown in Fig. 6. Fig. 7 show the observed crack patterns after this earthquake. Several flexural cracks at the column end were observed at each story on the weak column structure, and flexural cracks at the beam ends which developed into the floor slab were observed at 2nd,3rd and 4th floor on the weak beam model structure.

INELASTIC BEHAVIOR Fig. 8 shows the base shear vs. inter-story displacement at first story relationship for weak column structure and the base shear vs. the displacement at the top floor level for weak beam structure. The base shear was estimated by accumulating the inertia force at each floor. The response of both weak model structures exceeded its yielding points. Base shear coefficient at yielding points are considered about 0.15 for weak column structure and 0.30 for weak beam structure.

CHANGES OF NATURAL PERIODS The time histories of top floor level acceleration from 5.0 to 25.0 second is devided into five parts, and the Fourier amplitude spectra for each part are shown in Fig. 9. At the beginning of this earthquake, during 5.0 to 10.0 second , the first and second vibration periods for weak column structure is estimated about 0.43 and about 0.17 seconds, respectively. The second vibration period was excited by the predominant period of the ground motion. During the period from 10.0 to 15.0 second, the most predominant component became about 0.7 second, which might correspond to the first period changed by the progress of the damage. An influence of the change of the first period to the response is also seen in the time history of acceleration in Fig. 6(a). The first period of weak beam structure is estimated about 0.3 second at the early stage and 0.5 second during larger response. The first periods at large amplitude during this earthquake was about twice as long as initial elastic one as shown in Table 3.

BIAXIAL RESPONSE Fig. 10 show the relationships of two directional horizontal displacements at the top floor level. The orbit of the weak column structure shows a circular shape indicating a strong coupling of two components of the displacements. on the other hand, the coupling is less effective in the case of the weak beam structure.

## RESPONSE ANALYSIS

METHOD OF ANALYSIS Observed accelerograms at the first floor level was used in this analysis. Weak model structures were idealized as plane structure with rigid floor slabs and sway and rocking springs at the base. Beams and columns were represented by the one-component model with inelastic flexural hinges at both ends and a shear spring at midspan. The moment-rotation hysteretic model assigned to the inelastic spring at member-end of beams and columns was determined on the basis of the observed the story shear vs. inter-story displacement relationships; trilinear line determined on the basis of material properties and member geometry was adopted to backbone curve, and the cracking and yielding resistance of columns were calculated by use of the axial force of gravity loads. As shown in Fig. 11, origin-oriented hysteresis model was used for the stage of cracking to yielding points, and Clough's degrading stiffness model with unloading stiffness degration parameter of 0.5 for the stage of beyond yielding was adopted. Viscous damping was assumed in this analysis. The damping factors was determined on the basis of the observed initial elastic response ; the mode damping factor of 1.0 % to the critical value for first mode and 1.2 % for second mode were used for weak column structure, and 0.9 % and 1.9 % for weak beam structure. Initial stiffness in this analysis was adjusted so that the calculated natural period were close to observed one : as weak column structure had suffered with many damage due to past earthquakes, initial stiffness of inelastic spring at member end was decreased to $K_i$ shown in Fig. 11 with reference to its damage, and the effective slab width of weak beam structure increased to coincide with observed elastic natural periods.

RESULTS OF ANALYSIS Table 4 and Fig. 12 show the calculated peaks and waveforms. The calculated waveform of top floor level displacement of weak column structure is similar to observed one, but the ratio of the calculated inter-story displacement of lower stories to upper stories is greater than that of observation. The calculated top floor level displacement of weak beam structure larger than the observation. This discrepancy between calculated and observed may be caused by lower estimation of the yield resistance and hysteretic energy dissipation of beams. To simulate observed behavior of weak beam structure, the influence by the slabs should be considered.

## CONCLUDING REMARKS

1) The response of both weak model structures during this earthquake exceeded the yielding points, and the fundamental periods of both weak structures became about twice as long as the previous periods.
2) The observed displacements of the weak column structure in the two horizontal directions were indicated a strong coupling of two component, on the other hand, the coupling was less effective in the case of the weak beam structure.
3) The agreements between observed and calculated behaviors was fair for weak column structure and poor for weak beam structure. It is required to estimate the effect of the slabs in the analysis of weak beam structure.

## REFERENCES

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4. Tamura, R. and Okada, T., "Observation of Earthquake Response of Reinforced Weak Model Structures (Part 5)," Proceedings of the Annual Convention of A.I.J., Architectural Institute of Japan, October, (1985).

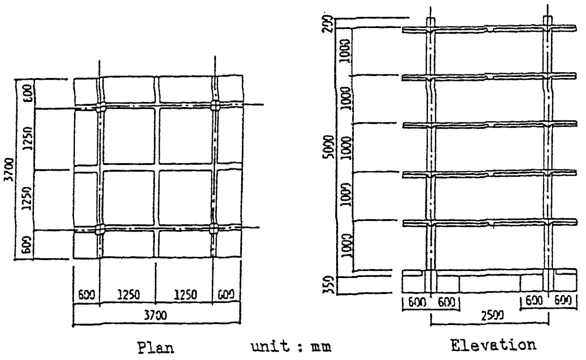


Fig. 1 Plan and Elevation

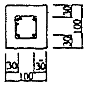
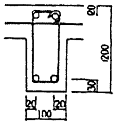
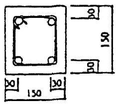
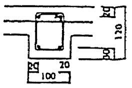
| | Column Section | Beam Section |
|---|---|---|
| Weak Column Structure |  <br>Reinforcement : 4-D6(SD30)<br>Hoop: 2φ @30(SR24) |  <br>Reinforcement : 4-D10(SD30)<br>Stirrup: 2φ @30(SR24) |
| Weak Beam Structure |  <br>Reinforcement : 4-D10(SD30)<br>Hoop: 2φ @30(SR24) |  <br>Reinforcement : 4-D6(SD30)<br>Stirrup: 2φ @30(SR24) |

Fig. 2 Sections of Column and Beam

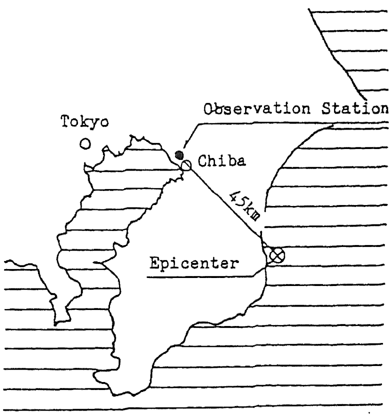


Fig. 4 Locations of Epicenter and Observation Station

Table 1 Characteristics of Earthquake

| | |
|---|---|
| Date | December 17, 1987 |
| Epicenter | N 35° 21'<br>E 140° 29' |
| Magnitude | 6.7 |
| Forcal Depth | 60 km |
| Epicentral Distance | 45 km |
| JMA Intensity at Chiba | V |

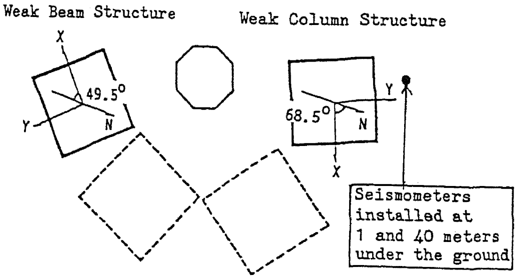
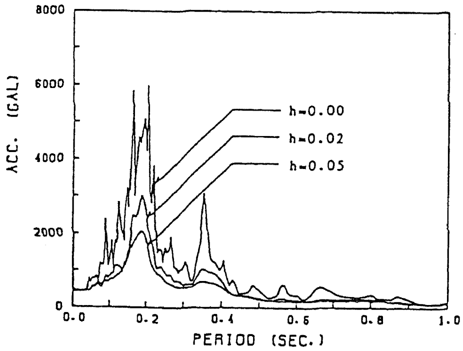
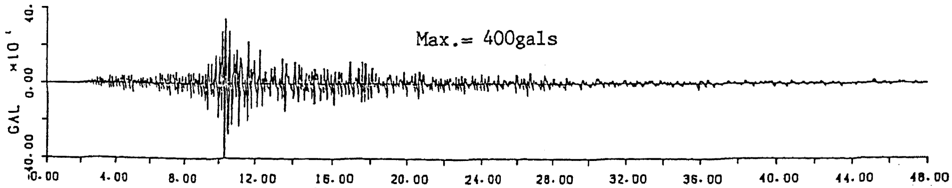


Fig. 3 Layout

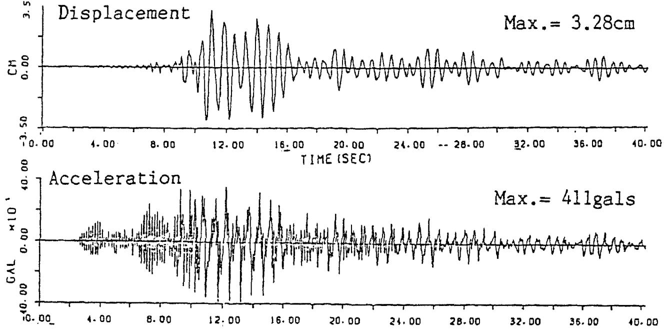


(b) Response Spectra of Acceleration

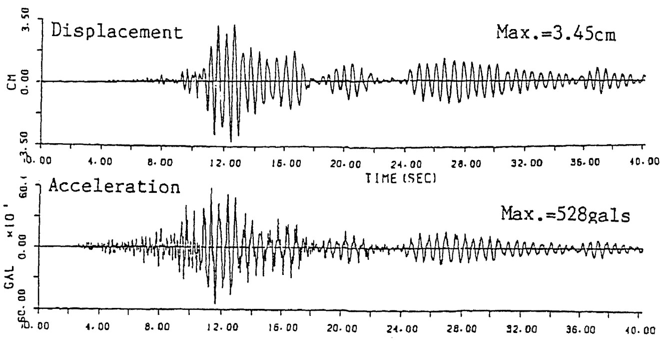


(a) Time History of Acceleration

Fig. 5 Time History and Response Spectra of Ground Motion (N-S component)

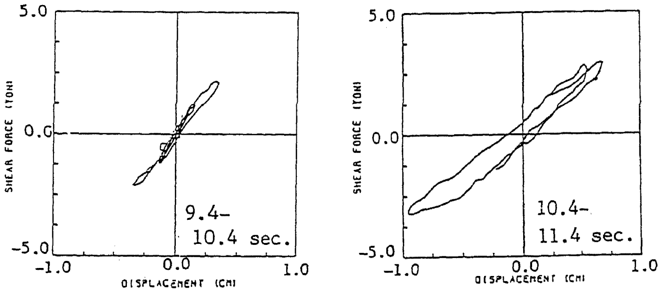


(a) Weak Column Structure



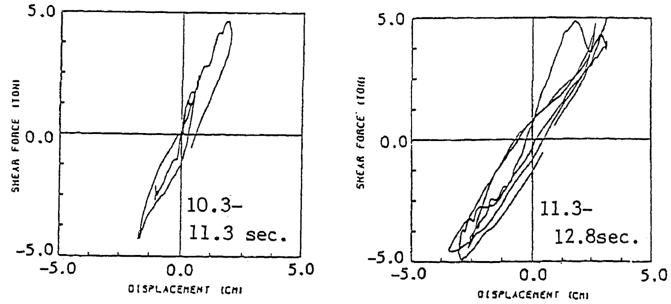
(b) Weak Beam Structure

Fig. 6 Time Histories of Top Floor level



(Cracking to Yielding Points) (Beyond Yielding Point)

(a) Weak Column Structure



(Cracking to Yielding Points) (Beyond Yielding Point)

(b) Weak Beam Structure

Fig. 8 Histeresis Loop

Table 2 Observed Peaks

(a) Weak Column Structure

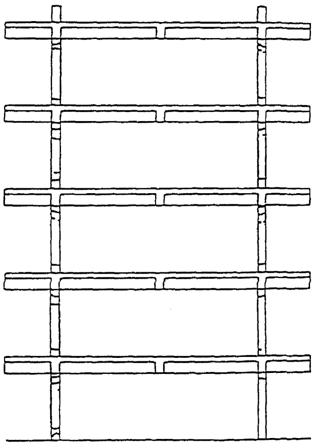
| Acceleration (gal) | |
|---|---|
| Roof | 411.1 |
| 5th | 299.3 |
| 4th | 391.1 |
| 3rd | 387.7 |
| 2nd | 374.0 |
| 1st | 259.8 |

| Inter-story Displ. (cm) | |
|---|---|
| 5th | 0.38 |
| 4th | 0.84 |
| 3rd | 0.86 |
| 2nd | 0.86 |
| 1st | 0.95 |

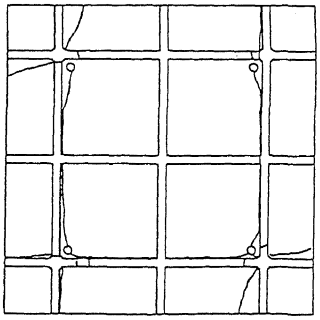
(b) Weak Beam Structure

| Acceleration (gal) | |
|---|---|
| Roof | 582.0 |
| 5th | 511.7 |
| 4th | 488.2 |
| 3rd | 364.3 |
| 2nd | 351.6 |
| 1st | 284.7 |

| Inter-story Displ. (cm) | |
|---|---|
| 5th | 0.17 |
| 4th | 0.63 |
| 3rd | 0.99 |
| 2nd | 1.01 |
| 1st | 0.65 |

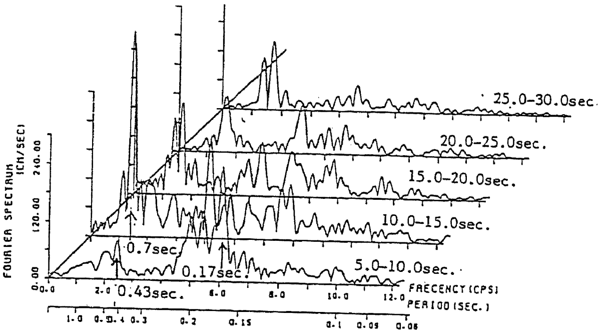


(a) Weak Column Structure

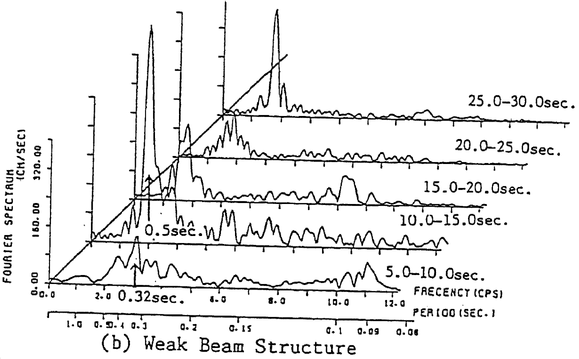


(b) Weak Beam Structure
(Third Floor system)

Fig. 7 Crack Patterns

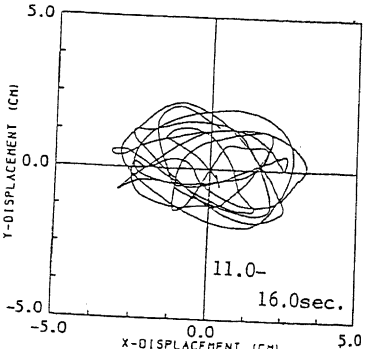


(a) Weak Column Structure

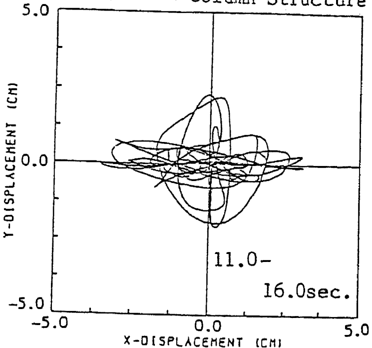


(b) Weak Beam Structure

Fig.9 Fourier Spectra of Top floor Level Acceleration



(a) Weak Column Structure



(b) Weak Beam Structure

Fig. 10 Biaxial Response of Top Floor Level Displacement

Table 3 Changes of Fundamental Periods

| | At Initial Elastic | | '87.12.17 Earthquake |
|---|---|---|---|
| Weak Column Structure | 0.37 | ===> | 0.7 |
| Weak Beam Structure | 0.28 | ===> | 0.5 |

$\alpha$ = unloading stiffness degradation parameter
$D_m$ = previous positive maximam displacement
$D'_m$ = previous negative maximam displacement
$K_y$ = yielding stiffness
$K_i$ = initial stiffness for weak column structure
$K_r$ = unloading stiffness

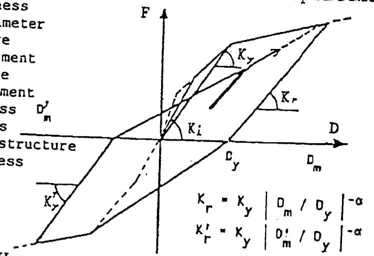


Fig. 11 Hysteresis Model

Table 4 Calculated Peaks

(a) Weak Column Structure

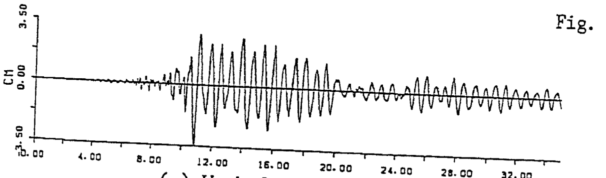
| | Acceleration (gal) |
|---|---|
| Roof | 459.9 |
| 5th | 321.5 |
| 4th | 372.9 |
| 3rd | 429.3 |
| 2nd | 389.7 |
| 1st | 290.5 |

| | Inter-story Displ. (cm) |
|---|---|
| 5th | 0.41 |
| 4th | 0.59 |
| 3rd | 0.65 |
| 2nd | 0.87 |
| 1st | 1.28 |

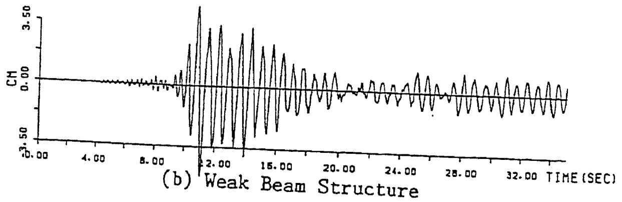
(b) Weak Beam Structure

| | Acceleration (gal) |
|---|---|
| Roof | 625.4 |
| 5th | 415.1 |
| 4th | 443.4 |
| 3rd | 537.2 |
| 2nd | 407.1 |
| 1st | 312.4 |

| | Inter-story Displ. (cm) |
|---|---|
| 5th | 0.52 |
| 4th | 0.87 |
| 3rd | 1.26 |
| 2nd | 1.42 |
| 1st | 1.23 |



(a) Weak Column Structure



(b) Weak Beam Structure

Fig. 12 Calculated Waveforms

(Top Floor Level Displacement)