Bull. ERS, No. 25(1992)

SHAKING TABLE TESTS OF REINFORCED CONCRETE SMALL SCALED MODEL STRUCTURE (Part 2)

by

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INTRODUCTION

Recently, a size of scaled model specimens for structural tests tends to become larger and larger. A large scaled model test makes possible to obtain data similar to real structures. However, since it requires large size testing facilities and large amount of research funds, it makes difficult to execute parametric tests.

In order to establish a testing technique using extremely small scaled model structures to investigate the seismic behavior of reinforced concrete structures, trials to fabricate 1/15 scaled reinforced concrete structures and to conduct shaking table tests were made.

This paper describes the fabrication of the model structures and the response characteristics of scaled model structures [Refs. 1-2].

OUTLINE OF TESTS

MODEL STRUCTURES

The test structures are 1/15 scaled eleven-storied models with two dwelling units at each story as shown in Photo. 1 and Fig. 1. The number of specimens is two with the test parameter of the shape of the plan as shown in Fig. 2. Non-shifted type specimen is named as 'STANDARD', and the other is 'SHIFTED'. The story height is 20.0cm in each story and the overall height is 240cm including basement. Dimensions of columns and beams are shown in Fig. 3. Vertical reinforcing bars in columns and transverse walls are continuous from the basement to the top.

The mass of the model structures was increased by adding lead blocks at each floor as shown in Fig. 2. Sixteen blocks were placed at each floor level; i.e., eight blocks were at the top and bottom of a slab at each story. The attached total weights were 2.58tonf in the STANDARD and 2.90tonf in the SHIFTED.

The model structures were designed so that a yield hinge mechanism of strong columns-weak beams could be developed, base shear capacity would be small enough to be compared with the capacity of the shaking table, and bar arrangement was modified properly [Ref. 3]. In the case of the STANDARD, the estimated base shear coefficient at the ultimate stage is 0.275, when concrete and reinforcement in slabs and transverse walls within a range regulated in the Code [Ref. 4] are assumed effective to the stiffness and ultimate

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Note; Main part of this paper will be presented at the Tenth World Conference on Earthquake Engineering, Madrid, Spain, July 1992.

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strength. When those within slabs and the wall are fully effective, the coefficient is 0.42.

LAW OF SIMILARITY

Law of similarity is shown in Table 1. Lead blocks were tried to attach at the slabs to satisfy the weight similarity. The normal stress of columns that is $9.08\mathrm{kgf/cm^2}$ at the first story is, however, a half of the target due to the space limitation. The natural periods of the model structure, therefore, were actually $1/\sqrt{2}$ times of the target; i.e., the actual scaling factor of the natural periods was $1/\sqrt{30}$. Hence, the shaking table test was performed under a compressed time scale of $1/\sqrt{30}$. The scaling factor of shear force coefficients was 2.0. The ratio of shear force coefficient to input acceleration, however, was 1.0 because the actual scaling factor of input acceleration was twice of the target.

MATERIAL

Deformed reinforcing bars and micro concrete was used in the small scaled model structures. Deformed reinforcing bars, D1, D2 and D3; D denotes nominal diameter and the unit of the numbers is mm, were specially rolled for these test series.

i) Deformed reinforcing bars

The deformed bars were produced by rolling a wire through a pair of grooved metal rolls as shown in Photo. 2. The process to roll was cold drawing. The quality of the wire, of which the mechanical characteristics satisfied JIS G3112; the Japanese Industrial Standard, was optimum to the cold working. The bars were annealed before being deformed, and only D2 bars were annealed after being deformed, too. Configuration of the bars was proportional to that defined in the JIS. Stress-strain relationships and the average tensile strength are shown in Fig. 4.

ii) Micro concrete

The mixture of micro concrete was decided after several trials. Design specified strength is $150\mathrm{kgf/cm^2}$ and the water-cement ratio is 78.0%. Portland cement, coarse and fine aggregate, and water were mixed in the proportions as shown in Table 2. To reduce the amount of water in the unit volume, to raise workability of concrete and to increase strength at an early stage, AE (Air-Entraining) water reducing agent was used. Compressive test results of concrete are shown in Table 3. The particle size distribution of coarse aggregate after mixture was within the allowable range defined in JASS 5 specifications [Ref. 5]. The nominal diameter of fine aggregate was generally twice as large as the desired.

Concrete, which was cast vertically at every story, was very carefully cured by wet blanket, and no shrinkage cracks were, therefore, found.

SHAKING TABLE

A shaking table driven and controlled by an electro-hydraulic servo system was used, which is installed at the Chiba Experiment Station in Chiba Prefecture, Institute of Industrial Science, University of Tokyo. Dimension of the table is a square of 300cm, and loading capacity is 7.0tonf. The test platform can be actuated to a maximum acceleration of 3.0G and 1.5G in horizontal and vertical direction, respectively, without any additional weight, and 2.0G and 1.1G with 7.0tonf additional weight, respectively.

TEST PROGRAM AND MEASURING

The model structures were subjected to the east-west component of the earthquake record obtained at the Hachinohe Harbor in Aomori Prefecture, Japan during the Tokachi-Oki Earthquake in 1968, scaled to the peak acceleration of 40gals, 200gals, 400gals, 600gals and 800gals. Each test is referred to as 'G40', 'G200', 'G400', 'G600' and 'G800', respectively. Time scale was reduced to $1/\sqrt{30}$ of the original record to conform with the similarity law. Finally, the model structures were also subjected to excitation with peak acceleration of 800gals and reduced time scale of $2/\sqrt{30}$ to observe an ultimate behavior of the structure; G800-2. The input acceleration and the test program are shown in Fig. 5 and Table 4, respectively.

Absolute accelerations were measured at each floor level in the direction of excitation, at every third floor level in the transverse direction, and at the base and top floor levels in the vertical direction. Relative displacements of each story to the basement in the direction of excitation and the basement to the shaking table in the direction of excitation were measured. As was the case of the SHIFTED, relative displacements of the top to the basement and inter-story displacement in the transverse direction were measured. Strain gages were installed to reinforcing bars at 28 locations in the STANDARD and at 31 locations in the SHIFTED.

The measured data were recorded continuously throughout the tests on a magnetic tape with a sampling rate of 1/200sec. in the all runs.

TEST RESULTS

Final crack patterns and hysteresis loops at the first story are shown in Figs. 6 and 7, respectively. Final cracks at the first story of the both models are shown in Photos. 3 and 4, respectively. The maximum responses are shown in Table 5.

Damage Procedure

G40; Although small cracks were observed in the case of the STANDARD, the response ranges of both specimens were almost within elastic ranges.

G200; As was the case of the STANDARD, a few cracks were observed.

G400; Although the input acceleration level was about 70% of the target in the case of the SHIFTED, several cracks were observed.

G800; As was the case of the STANDARD, the response range was similar to that of G600.

G800-2; Flexural cracks were developed at the ends of almost all beams and bottom reinforcing bars in beams were broken off at intermediate stories. Shear cracks were observed in column-beam joints at lower stories. At lower stories, cracks due to punching shear were also observed at the intersection of the transverse wall and interior beams. Severe damages were observed in columns at the bottom of the first story; i.e., concrete crushed and reinforcing bars buckled in the case of the SHIFTED, and were broken off in the case of the STANDARD which transverse walls could sustain axial force and avoid collapse.

Story Distribution of Maximum Response

Story distributions of maximum responses; absolute acceleration, relative displacement to the basement, inter-story displacement and story shear force of both specimens, are shown in Figs. 8 through 11, respectively.

At the final run, it was impossible to measure the maximum response displacement of the STANDARD by the reason that the response exceeded the capacity of transducers.

Acceleration Response Spectrum

Relationships of changes of fundamental period and the maximum response acceleration on response acceleration spectra of command acceleration, which is similar to those observed at the first floor during the tests, are shown in Fig. 12. The ordinate gives a magnification factor of the response acceleration, and the abscissa gives period. Circles in this figure indicate the predominant period during early 2.5sec. (5.0sec. in G800-2) of testing that response relative displacement became maximum approximately. The period was from the ratio of Fourier spectra of response acceleration at the top floor to those at the first floor. It is recognized that the fundamental periods after testing became over three times as long as initial those.

It is very interested that the magnification factors of response acceleration of testing were nearly equal to the elastic response acceleration corresponding to response fundamental period in the region of the maximum response displacement.

Story Shear Coefficient and Distribution of Shear Force

Distributions of maximum shear coefficient ratios to maximum base shear coefficient are shown in Fig. 13, and Fig. 14 shows distribution of lateral force ratios to first story shear force at the time with maximum base shear.

At elastic stage; G40 run, distribution of the ratios is very close to the inverted triangular force distribution as shown in Fig. 13. At upper stories, the ratios decrease at slightly damaged stage; G200 and G400 runs, and increase at moderately damaged stage; G600 and G800 runs. The distribution at lower stories is, however, similar to the inverted triangular force distribution through all runs.

The larger input acceleration level becomes, the more high order fundamental periods become effective as shown in Fig. 14.

CONCLUDING REMARKS

Shaking table tests of 1/15 scaled model structure used micro concrete and scaled deformed reinforcing bars are effective enough to simulate the earthquake response.

Response characteristics of model structure depended upon changes of fundamental period due to stiffness deterioration. The maximum response amplitude could be assumed from response acceleration spectrum of input acceleration.

The distribution of story shear force coefficients is similar to the inverted triangular force distribution at elastic stage. The inverted triangular force distribution, however, underestimates the distribution of story shear force coefficients at upper stories in plastic stage.

ACKNOWLEDGMENTS

Deformed reinforcing bars, D1, D2 and D3 were specially rolled for the small scaled model structure with cooperation of Professor Kiuchi Manabu; Institute of Industrial Science, University of Tokyo, and Aichi Steel Works, Ltd.. Metal form for the model structure was designed and produced by Central Workshop in Institute of Industrial Science, University of Tokyo. The small scaled model structures were produced on the efforts of many colleagues in

Okada laboratory. The authors are grateful for their cooperation. To perform the shaking table test, the authors also thanks to the members of ERS; Earthquake Resistant Structure Research Center, Institute of Industrial Science, University of Tokyo.

This investigation on the seismic behavior of small scaled model structures was performed as a part of the project on "Seismic Performance of Reinforced Concrete High-Rise Frame Structure with Wall Columns" initiated by the Architectural Institute of Japan, and the Building Center of Japan.

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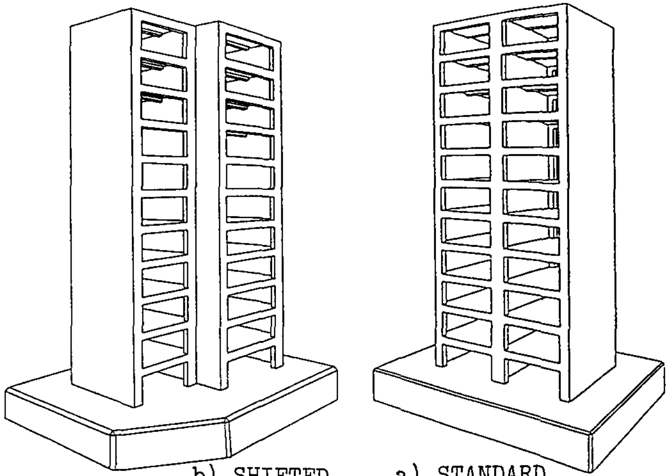
[3] "Recommendation for Detailing and Placing of Concrete Reinforcement," the Architectural Institute of Japan, 1986 (in Japanese).

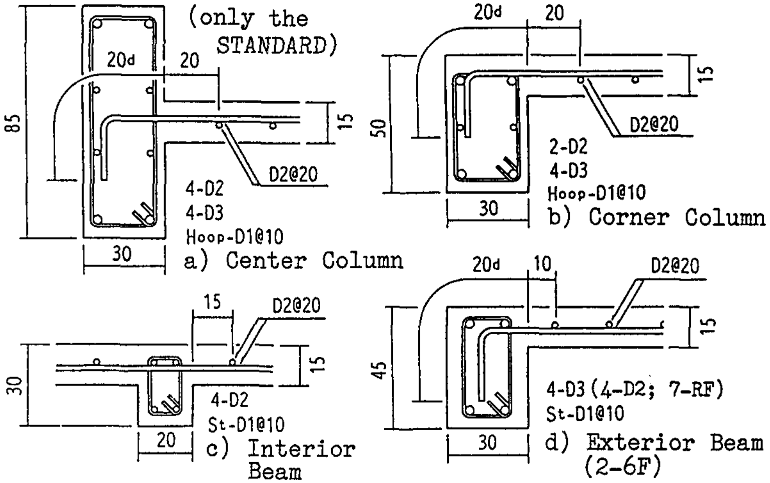
[4] "Design Guidelines for Reinforced Concrete Medium-/High-Rise Frame Structure with Wall Columns," the Building Center of Japan, 1987 (in Japanese).

[5] "Japanese Architectural Standard Specification, No.5, Reinforced Concrete Work," the Architectural Institute of Japan, 1986 (in Japanese).



b) SHIFTED a) STANDARD

Fig. 1 General Views of Model Structures



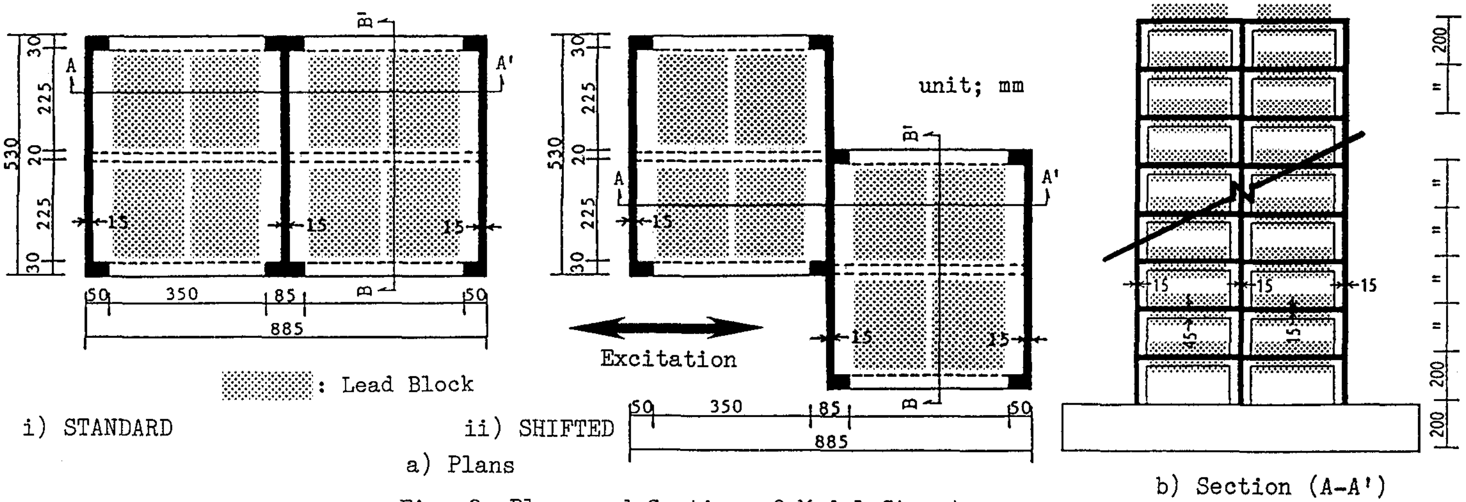
a) Center Column

b) Corner Column

c) Interior Beam

d) Exterior Beam (2-6F)

Fig. 3 Dimensions of Columns and Beams



▨ : Lead Block

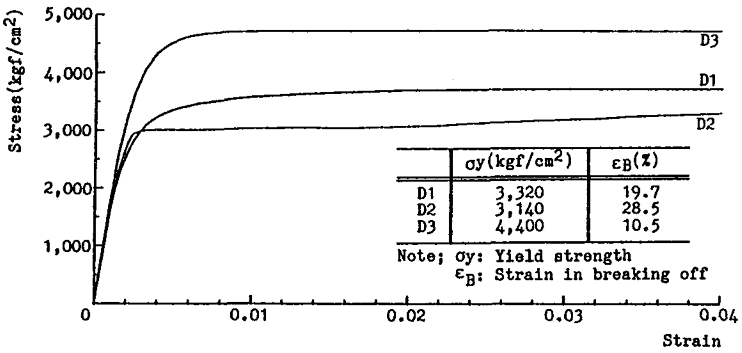
i) STANDARD

ii) SHIFTED

a) Plans

b) Section (A-A')

Fig. 2 Plans and Section of Model Structures



	σy(kgf/cm^2)	ε_B(%)
D1	3,320	19.7
D2	3,140	28.5
D3	4,400	10.5

Note; σy: Yield strength
ε_B: Strain in breaking off

Fig. 4 Stress-Strain Relationships of Re-bars (for the STANDARD)

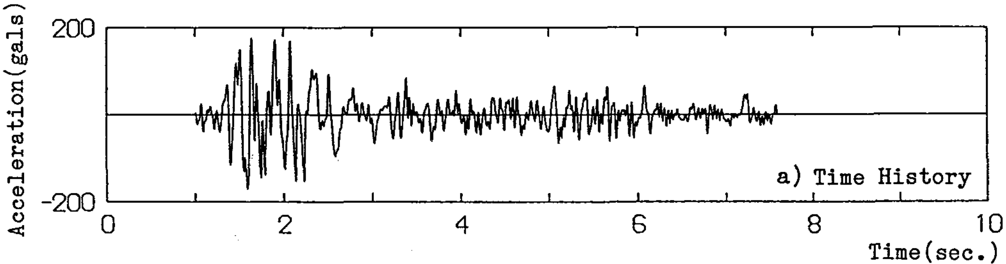
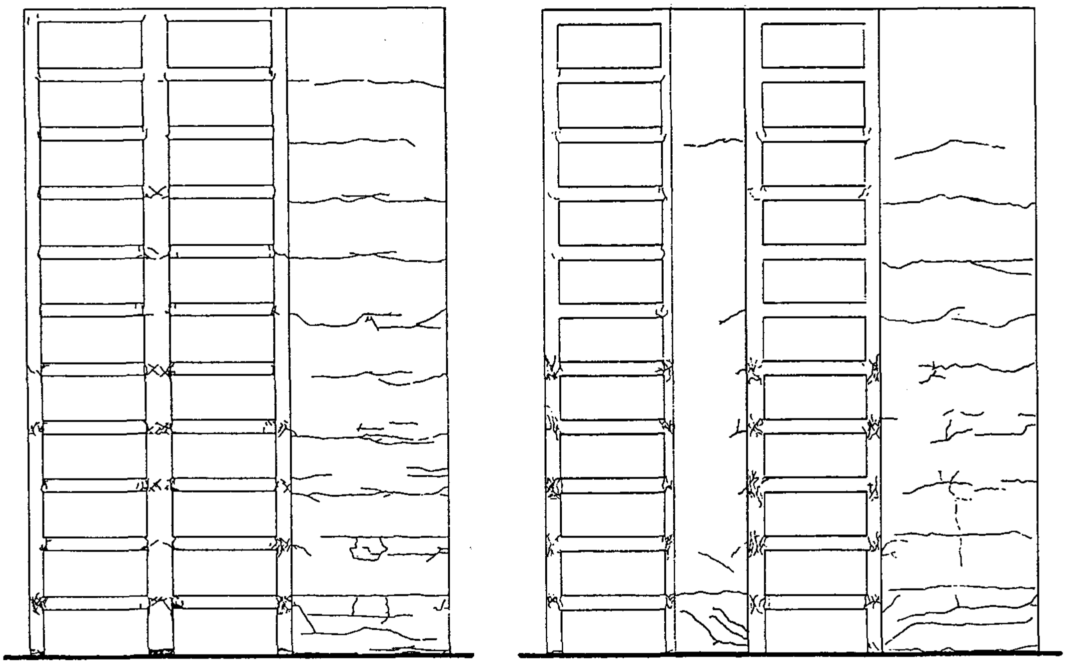


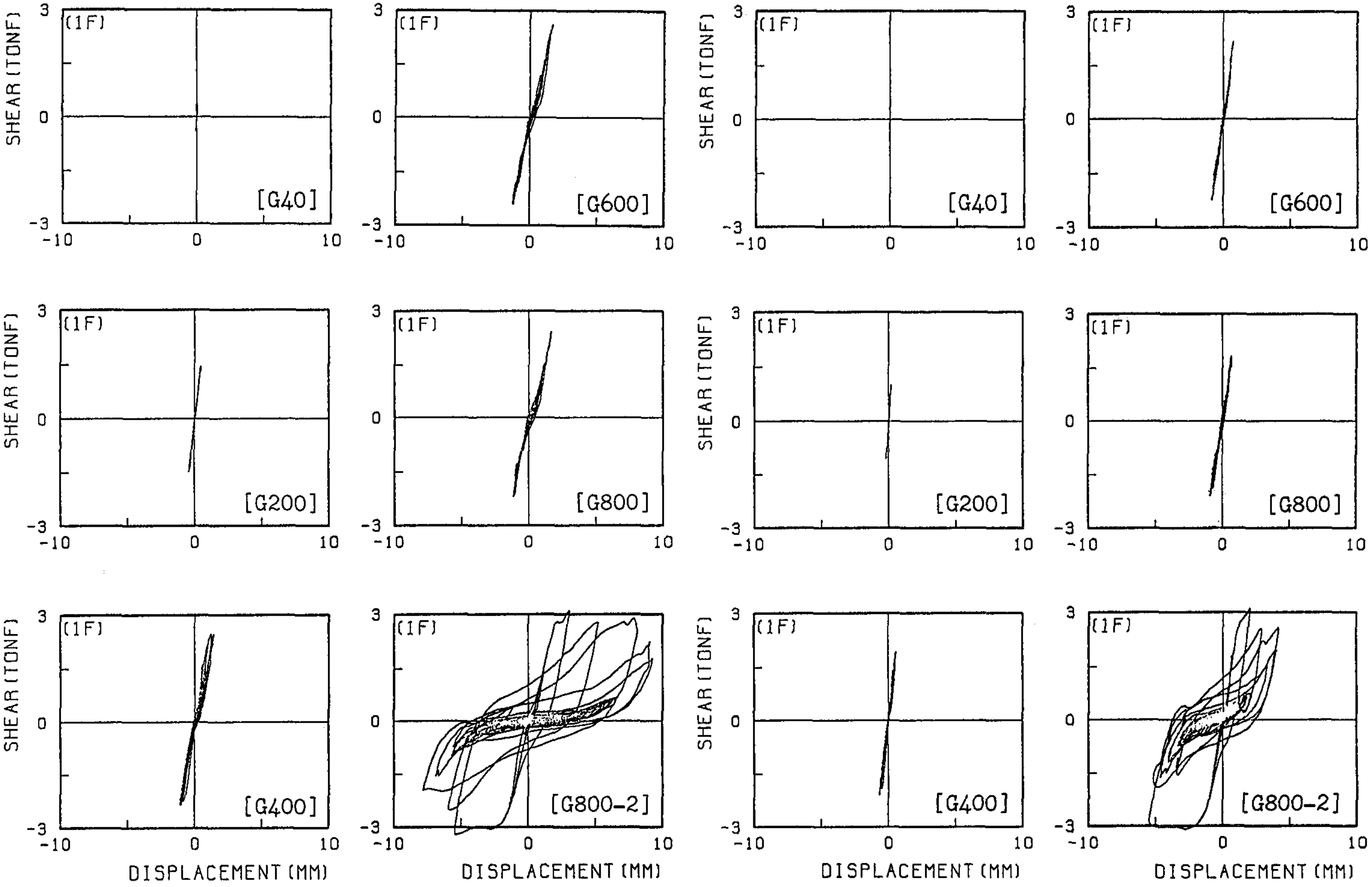
Fig. 5 Time History of Input Acceleration



a) STANDARD

b) SHIFTED

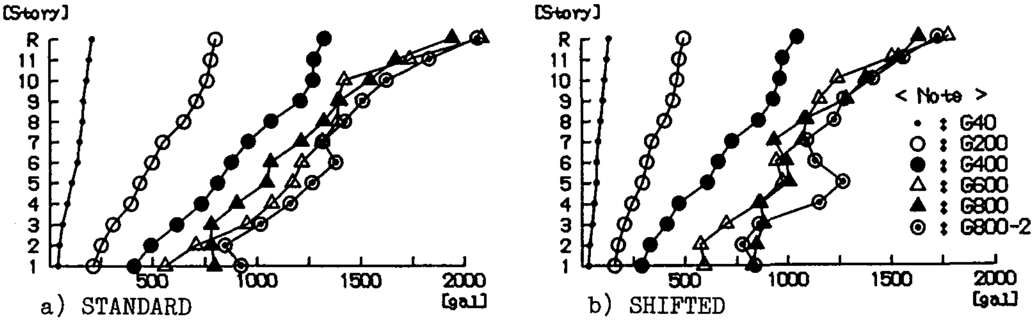
Fig. 6 Final Crack Patterns



a) STANDARD

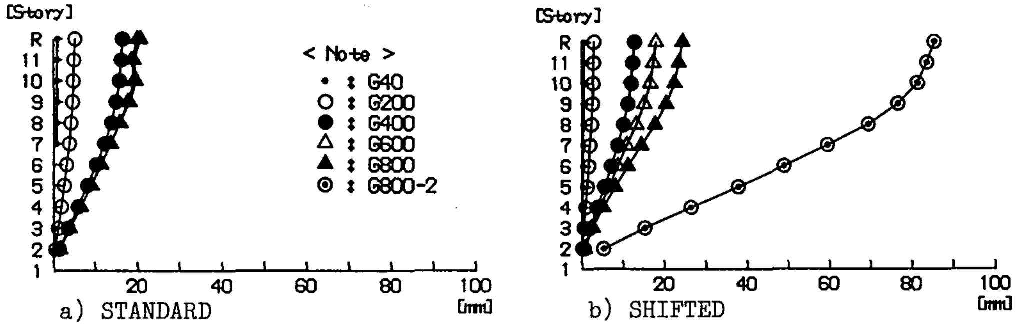
b) SHIFTED

Fig. 7 Hysteresis Loop (First Story)



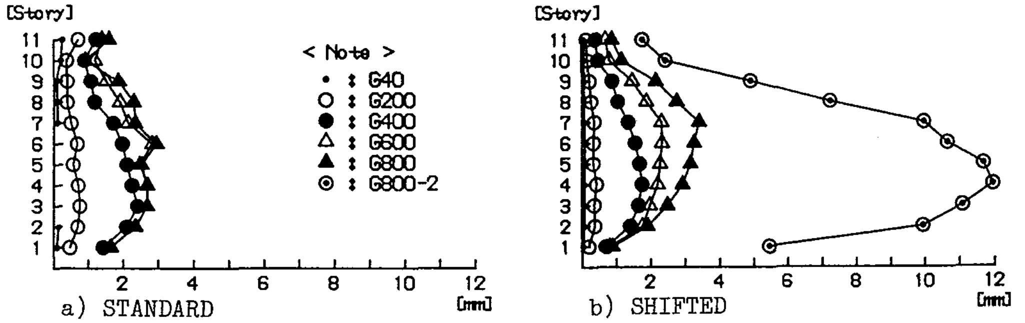
a) STANDARD b) SHIFTED

Fig. 8 Maximum Absolute Acceleration



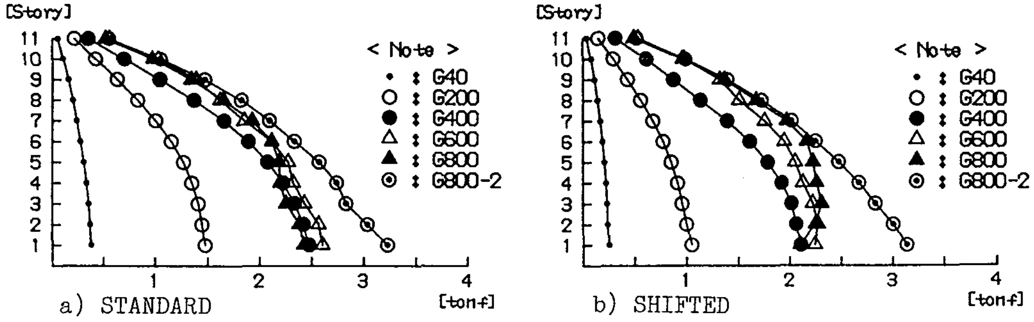
a) STANDARD b) SHIFTED

Fig. 9 Maximum Relative Displacement



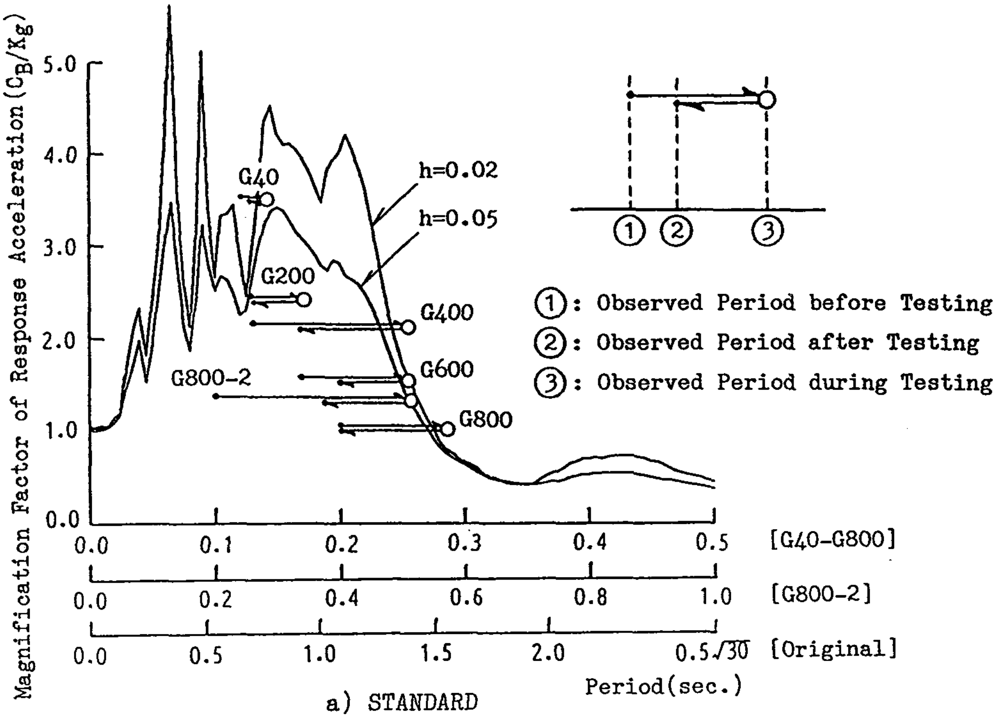
a) STANDARD b) SHIFTED

Fig. 10 Maximum Inter-Story Displacement

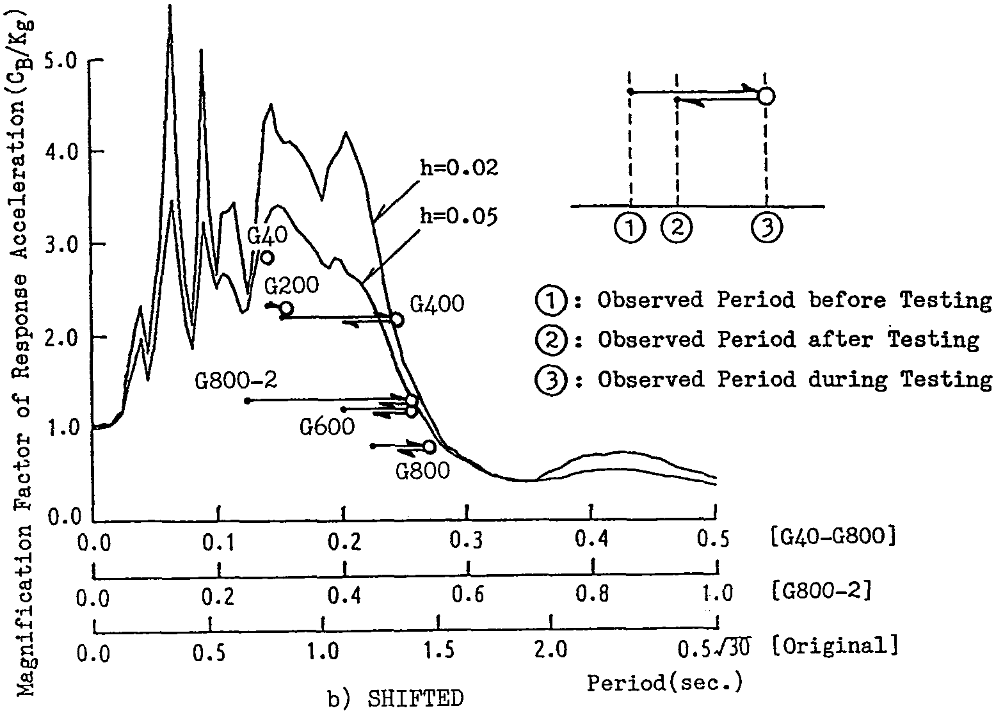


a) STANDARD b) SHIFTED

Fig. 11 Maximum Story Shear Force

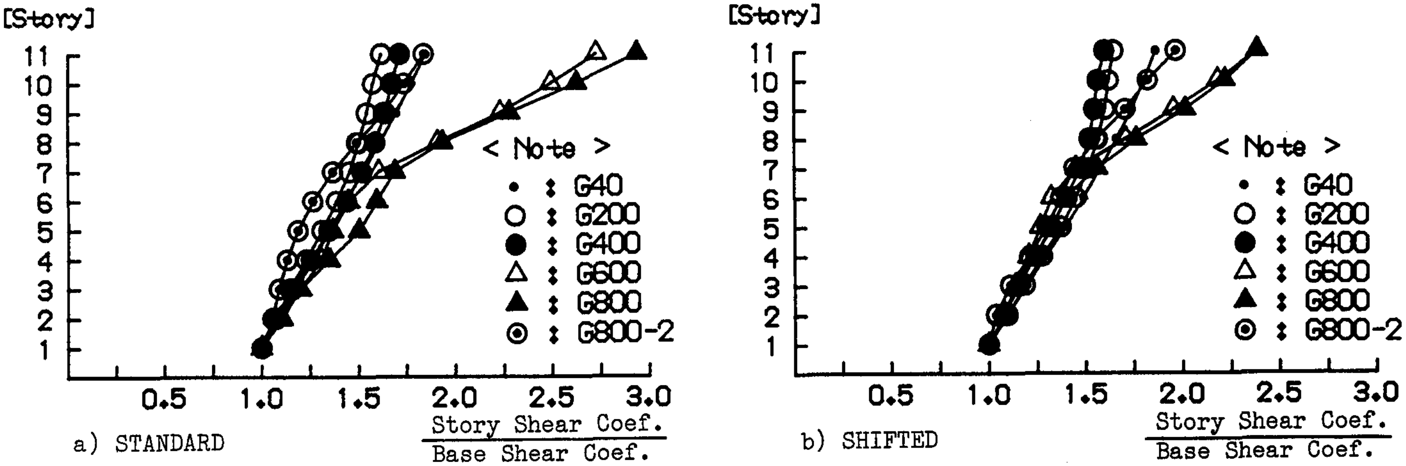


a) STANDARD



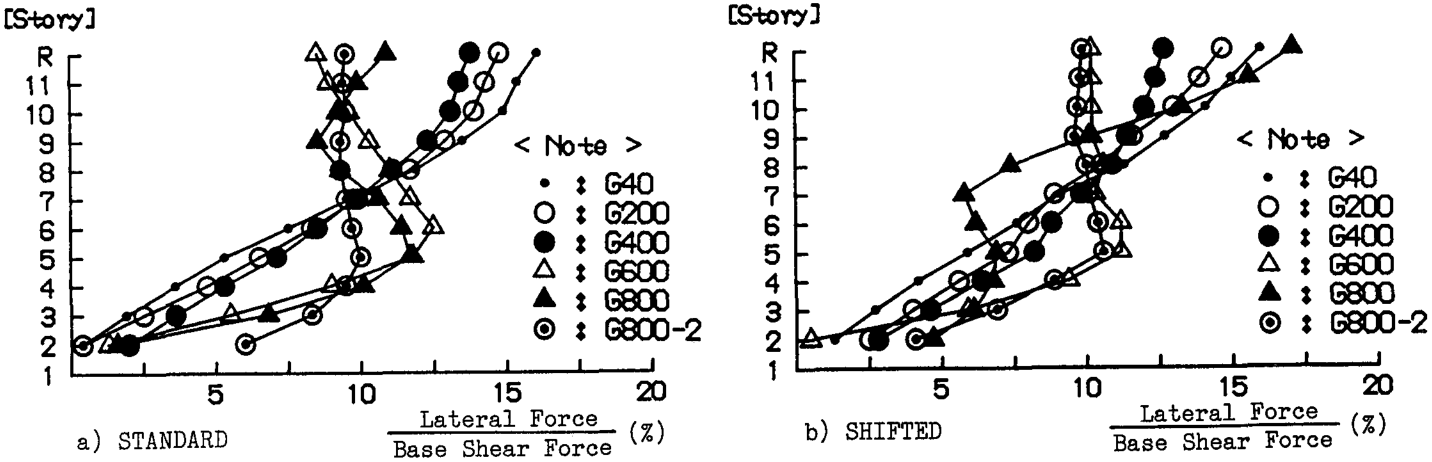
b) SHIFTED

Fig. 12 Maximum Acceleration Response Magnification Factors vs. Fundamental Periods



a) STANDARD b) SHIFTED

Fig. 13 Distribution of Story Shear Coefficients in Positive Direction
(each story shear is the maximum)



a) STANDARD b) SHIFTED

Fig. 14 Distribution of Lateral Force
(at the time when base shear is the maximum in positive direction)

Table 1 Law of Similarity

	Target	Actual
Length	1/15	1/15
Stress	1	1[*1]
Strain	1	1
Time	$1/\sqrt{15}$	$1/(\sqrt{15}\text{x}\sqrt{2})$
Weight[*2]	$1/15^2$	$1/(15^2\text{x}2)$
Deformation	1/15	1/15
Deflection Angle	1	1
Acceleration	1	2
Force of Inertia	$1/15^2$	$1/15^2$
Shear Force Coef.	1	2
Fundamental Period	$1/\sqrt{15}$	$1/(\sqrt{15}\text{x}\sqrt{2})$

Note; [*1] Actual axial stress is 1/2 of the target value.
[*2] Total weight including additional lead blocks

Table 4 Test Program

Run Steps	Maximum Accel. (gal)		
	Target	Observed	
		STANDARD	SHIFTED
G40	40	39.3 -36.7	25.9 -33.2
G200	200	202 -213	160 -137
G400	400	408 -371	282 -289
G600	600	560 -556	593 -569
G800	800	782 -796	827 -778
G800-2	800	922 -810	839 -715

Table 2 Micro Concrete Mixture

Water-Cement Ratio (%)	Unit Weight (kg/m^3)				AE Water Reducing Agent (cc/m^3)
	Water	Cement	Fine Aggre.	Coarse Aggre.	
78	292	372	583	861	3,724

Table 3 Compressive Tests of Concrete

Story	STANDARD		SHIFTED	
	Slump (cm)	Strength[*1] (kgf/cm^2)	Slump (cm)	Strength[*1] (kgf/cm^2)
Base	14.5	232.8	——	——
1	25.5	370.4	22.0	392.3
2	20.0	348.5	20.0	309.7
3	9.0	369.7	20.0	298.0
4	13.0	353.3	22.0	272.1
5	5.5	417.1	23.0	302.7
6	20.0	408.1	22.0	363.7
7	19.5	352.7	23.0	231.0
8	16.0	377.4	22.0	294.3
9	20.5	409.4	23.0	305.1
10	20.5	339.8	22.0	313.4
11	19.5	351.2	21.5	339.2

Note; [*1] Average of three cylinders

Table 5 Maximum Responses

	STANDARD			SHIFTED		
	C_B	R_1	R	C_B	R_1	R
G40	0.13	1/1960	1/2160	0.08	1/4130	1/4250
G200	0.50	1/422	1/418	0.32	1/912	1/732
G400	0.84	1/139	1/132	0.64	1/283	1/171
G600	0.89	1/119	1/109	0.69	1/240	1/121
G800	0.83	1/121	1/105	0.64	1/219	1/90
G800-2	1.10	1/22	———	0.96	1/37	1/26

Note; C_B : Base Shear Coefficient
R_1 : Drift Angle at the First Story
R : Overall Drift Angle

Photo. 1 Sight of Testing

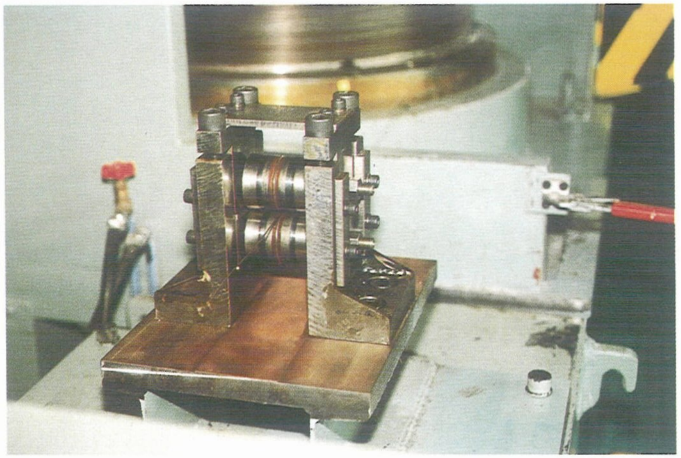


Photo. 2 Deforming Rolls

Photo. 3 Cracks at the Bottom (the STANDARD)

Photo. 4 Cracks at the First Story (the SHIFTED)
(Plastic models are 1/20 scales)