Bull. ERS, No. 22(1989)

SHAKING TABLE TESTS
OF REINFORCED CONCRETE SMALL SCALED MODEL STRUCTURE

Tsuneo OKADA[1)], Fumitoshi KUMAZAWA[2)], Shoji HORIUCHI[3)]
Masashi YAMAMOTO[4)], Ayumi FUJIOKA[5)]
Kunie SHINOZAKI[6)] and Yoshiaki NAKANO[7)]

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, a trial to fabricate a 1/15 scaled reinforced concrete structure and to conduct a shaking table test was made in 1987 as shown in Photo. 1.

This paper describes the fabrication of the model structure and the response characteristics obtained by the shaking table test [Refs. 1-4].

OUTLINE OF TEST

MODEL STRUCTURE

The test structure was a 1/15 scaled eleven-storied model. A general view of the model, which has two dwelling units at every story, is shown in Fig. 1. The plan and sections are shown in Fig. 2. It has two spans in longitudinal direction; excitation direction, and one span in transverse direction. The story height is 20.0 cm in every story and the overall height is 240 cm including basement. Dimensions of columns and beams are shown in Fig. 3. The center column was 3.0 cm × 8.5 cm; the aspect ratio is 2.83, and the corner column was 3.0 cm × 5.0 cm; the aspect ratio is

1) Professor, Institute of Industrial Science, University of Tokyo.
2) Research Associate, Institute of Industrial Science, University of Tokyo.
3) Technical Stuff, Institute of Industrial Science, University of Tokyo.
4) Research Student, Institute of Industrial Science, University of Tokyo, Engineer, TOBISHIMA Co..
5) Research Student, Institute of Industrial Science, University of Tokyo.
6) Engineer, AXS SATOWINC..
7) Graduate Student, University of Tokyo.

1.67. The exterior beam was 3.0 cm × 4.5 cm and the thickness of transverse walls and slabs was 1.5 cm. Vertical reinforcing bars in columns and transverse walls are continuous from the basement to the top.

The mass of the model structure was increased by adding lead blocks at each floor as shown in Fig. 2. Sixteen blocks of 200 kgf in total were placed at each floor level, i.e. eight blocks; 100 kgf, were at the top and bottom of a slab at each story. The total weight of the model structure was 3.96 tonf including the adding weight; 2.84 tonf, and the basement; 0.72 tonf.

The model structure was designed so that a yield hinge mechanism of strong columns-weak beams could be developed, a base shear capacity would be enough small to be compared with the capacity of the shaking table, and reinforcing bars were arranged properly [Ref. 5]. 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. 6] are assumed effective to the stiffness and ultimate 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 which is 10.0 kgf/cm^2 at the first story is, however, 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 were used in the small scaled model structure. Deformed reinforcing bars, D1, D2 and D3; D denotes nominal diameter, were specially rolled for this test series. The results of the material tests are shown in Table 2.

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. D2 bars were annealed after being deformed, too.

Configuration of the bars was proportional to that defined in the JIS. Design yield strengths were 2,400 kgf/cm^2. Stress-strain relationships are shown in Fig. 4. The average tensile strength of D1, D2 and D3 were shown in Table 2. The standard deviations of strength of the bars; D1, D2 and D3 were 32, 83 and 130 kgf/cm^2, respectively.

ii) Micro concrete

The mixture of micro concrete was decided after several trials. Design strength is 180 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 3. To reduce water in the unit volume, to raise workability of concrete and to increase strength at an early stage, AE (Air-Entraining) water reducing agent; Pozzolith No. 75, high-early type, was used in the ratio of 1 liter to 100 kgf cement weight.

Silica sand with three different particle size distributions was mixed in the proportions of 1:1:1 to produce coarse aggregate with the desired gradation. The particle size distribution of coarse aggregate after mixture was within the allowable range defined in JASS 5 specifications [Ref. 7]. The nominal diameter of fine aggregate was generally twice as large as the desired.

Concrete was cast vertically at every story. Concrete was very carefully cured by wet blanket, and no shrinkage cracks were, therefore, found. Four months were spend to construct the small scaled model structure. Photo. 3 is shown to compare the scale of the model structure with that of a person.

SHAKING TABLE

A shaking table to excite the model structure, which can vibrate in horizontal and vertical directions simultaneously or independently using vibrators controlled by an electro-hydraulic servo mechanism, installed at the Chiba Experiment Station in Chiba Prefecture, Institute of Industrial Science, University of Tokyo. Dimension of the table is a square of 300 cm, and loading capacity is 7.0 ton. 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 7.0 ton additional weight, respectively.

TEST PROGRAM AND MEASURING

The model structure was subjected to the east-west component of the earthquake record obtained at the Hachinohe Harbor in Aomori Prefecture during the Tokachi-Oki Earthquake in 1968, scaled to the peak acceleration of 40 gals, 200 gals, 400 gals, 600 gals and 800 gals. 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 in conformity with the similarity law. The acceleration data were modified through a digital filter to truncate the frequency contents higher than 30 Hz and lower than $1/\sqrt{30}$ Hz as shown in Fig. 5. Finally, the model structure was also subjected to excitation with peak acceleration of 800 gals and reduced time scale of $2/\sqrt{30}$ in order to observe an ultimate behavior of the structure (G800-2 run). The input acceleration and the test program are shown in Fig. 5 and Table 4, respectively.

The locations of measuring instruments are shown in Fig. 6. Absolute Response 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 level in the vertical direction. The number of accelerometers were 12, 10 and 4 in the exciting, transverse and vertical directions, respectively. Relative displacements of each story to the basement at 12 locations and the basement to the shaking table at a location in the direction of excitation were measured. Strains of reinforcing bars at 19 locations were measured, though strain gages were totally put on reinforcing bars at 28 locations.

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

TEST RESULTS

Final crack patterns, strains of reinforcement and story shear force vs. inter-story displacement relationships are shown in Figs. 7, 8 and 9, respectively. Observed response during test runs are shown as follows;

G40; A flexural crack was observed at the end of a beam at the second story.

G200; Flexural cracks were observed at the ends of beams at the intermediate stories.

G400; Many cracks were observed, especially in columns at the first story and beams at intermediate stories, while a few cracks were observed during the past G40 run through G200 run.

G600; Yielding of reinforcement in columns at the first story and beams at the seventh floor were observed.

G800; The response characteristics was similar to that during G600 run and the fundamental period of the test structure was approximately 0.29 sec. after G800 run while 0.12 sec. before G40 run.

G800-2; Lower reinforcing bars in beams broke off at the forth and seventh stories. At intermediate stories, shear cracks were observed in column-beam joints. On the exterior surface of the transverse walls, horizontal cracks along the bottom levels of beams were observed. At the second and third stories, cracks due to punching shear were also observed at the intersection of the transverse wall and beams. Although concrete crushed, reinforcing bars buckled and broke off in columns at the bottom of the first story and yield hinges developed in beams at each floor and columns at the top of the first story, transverse walls could sustain axial force and avoid collapse.

The maximum responses are shown in Table 5. Final crack patterns are shown in Photos. 4, 5, 6 and 7.

ANALYTICAL STUDIES

In order to simulate the test results, ultimate strength and earthquake response were calculated based on non-linearity of members. One component model consisting of series combination of flexural springs at the both ends and a shear spring at the center of the members was considered including rigid zones at the both ends in order to represent the non-linearity. Degrading Tri-linear model was used as hysteresis rule for flexural springs, which was based on fiber model analyses. Origin-oriented Tri-linear model was used for shear springs. The static analysis was based on the gradual increase loading of Ai-distribution in the seismic design code in Japan [Ref. 8], in the following formula (1);

$$Ai = 1 + \left(\frac{1}{\sqrt{\alpha i}} - \alpha i \right) \frac{2T}{1+3T} \qquad \cdots\cdots (1)$$

where, T : fundamental period (sec.)

αi: as follows;

$$\alpha i = \sum_{j=i}^{N} Wj \Big/ \sum_{j=1}^{N} Wj \quad \cdots\cdots (2)$$

N : number of stories

Wj: story weight

to one direction, and the dynamic analysis was based on recorded acceleration at the first floor during every test run. The analytical study follows two different types of procedures. In the Type-A analysis, concrete and reinforcement in slabs and transverse walls within a range regulated in the Code are considered to be effective to the stiffness and ultimate strength and those within slabs and the wall are considered to be fully effective in the Type-B analysis.

TEST RESULTS

Hysteresis Loops

Calculated results are shown in Fig. 10. Initial stiffness, ultimate strength and maximum acceleration observed during the tests are relatively close to those calculated by the Type-B analysis, although relative displacement to base underestimated the test results. This may result from discrepancy related to hysteretic models of members and initial conditions associated with the deterioration of test structure during previous loading history.

Story Distribution of Maximum Response

In three cases; vibration test, and analyses of the Type-A and -B, story distributions of maximum responses; absolute response acceleration, relative displacement to the basement and inter-story displacement, are shown in Figs. 11, 12 and 13, respectively.

i) Absolute Response Acceleration

Although the story distribution calculated by Type-A was similar to that observed during the tests, the absolute response accelerations were underestimated. The absolute response accelerations calculated by Type-B were closer to those observed during the tests.

ii) Relative Displacement

Before G400 run, calculated relative displacements to the basement were underestimated to those observed during the test. Relative displacements at the top level during G600 run were similar to those calculated.

iii) Inter-story Displacement

Observed response during G400 run was remarkably large. During G600 and G800 runs, responses were similar each other. Although the calculated distribution was similar to that observed in G800 run, the concentration of inter-story displacement to upper stories and underestimation were recognized in Type-A analysis.

Acceleration Response Spectrum

Acceleration response spectra observed at the first floor are similar to those of command acceleration as shown in Fig. 14.

Relationships of changes of fundamental period and the maximum response acceleration on response acceleration spectra of command acceleration are shown in Fig. 15. The ordinate gives a magnification factor of the response acceleration, and the abscissa gives period. Circles in Fig. 15 indicate the predominant period during early 2.5 sec. of testing that response relative displacement became maximum approximately.

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

Fundamental Period

Changes of fundamental period during and after the testing, estimated from the ratio of Fourier spectra of response acceleration at the roof floor to those at the first floor during early 2.5 sec. of testing, are shown in Fig. 16. It is recognized that the fundamental period after testing became three times as long as initial that.

Story Shear Coefficient and Distribution of Shear Force

Every story shear coefficient reached maximum approximately at the same time. The distribution is shown in Fig. 17, and Fig. 18 shows distribution of story shear force ratio to first story shear force. From

Fig. 17, the distribution of story shear force coefficient is similar to that by modal analysis until cracking stage (G40 and G200 runs) and not similar to Ai-distribution. With the exception of the top story, Ai-distribution tended to underestimate story shear. At plastic stage (G600, G800 and G800-2 runs) the distribution of story shear coefficient were nearly equal to constant and larger than Ai-distribution at the lower stories.

CONCLUDING REMARKS

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

Model structure with fixed foundation developed to yield mechanism in beams at each story.

During the testing that peak acceleration was 400 gals, the model structure responded to yielding and during the final testing that the peak acceleration was 800 gals ($2/\sqrt{30}$) failed at the bottom of first story columns, however, transverse walls sustained axial force and avoid collapse.

Shear cracks occurred at joints of columns and beams at the final stage, but the joints didn't lead to failure.

Yielding of reinforcing bars were initiated at the beams of intermediate story and the base shear did not increase due to tensile yielding at the bottom of first story columns.

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 coefficient was similar to that by modal analysis until cracking stage and not similar to the distribution of story shear coefficient called as Ai-distribution in the seismic design code in Japan. With the exception of the top story, Ai-distribution tended to underestimate story shear. At plastic stage, the distribution of story shear coefficient were nearly equal to constant and those were larger than Ai-distribution at the lower stories.

Even if concrete and reinforcement in slabs and transverse walls within a range regulated in the Code were considered to be effective to the stiffness and ultimate strength, the calculated strength was lower than the experimental strength. When those within slabs and wall were considered to be fully effective, the calculated strength was nearly equal to the experimental strength but the analytical response displacements were smaller than the experimental values. It is supposed that these discrepancies related to modelings of hysteresis characteristics of members including column-beam joints.

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 Industrial Science, University of Tokyo. The small scaled model structure was produced on the efforts for four months of many colleagues in Okada laboratory, Messrs. NISHIDA Tetsuya and GUAN Baoqi; Graduate Students, University of Tokyo, Mr. YAMADA Hiroshi; SBIC Co., Mr. KOBAYASHI Satoru; Horie Engineering and Architectural Research Institute. 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.

Discussions with Professor H. Krawinkler, Stanford University, have encouraged the authors to perform the test.

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.

REFERENCES

[1] Horiuchi S., Fujioka A., Shinozaki K., Yamamoto M., Kumazawa F. and Okada T.: "Shaking Table Test of Reinforced Concrete One-Fifteenth Scale Model Structures, Part 1. Objectives and Outline of Testing, - Seismic Performance of R/C High-Rise Frame Structure with Wall Columns -," Proceedings of the Annual Convention of the Architectural Institute of Japan, October 1988 (in Japanese).

[2] Fujioka A., Shinozaki K., Yamamoto M., Horiuchi S., Kumazawa F. and Okada T.: "Shaking Table Test of Reinforced Concrete One-Fifteenth

Scale Model Structures, Part 2. Test Results, - Seismic Performance of R/C High-Rise Frame Structure with Wall Columns -," Proceedings of the Annual Convention of the Architectural Institute of Japan, October 1988 (in Japanese).

[3] Kumazawa F., Fujioka A., Shinozaki K., Yamamoto M., Horiuchi S. and Okada T.: "Shaking Table Test of Reinforced Concrete One-Fifteenth Scale Model Structures, Part 3. Analysis, - Seismic Performance of R/C High-Rise Frame Structure with Wall Columns -," Proceedings of the Annual Convention of the Architectural Institute of Japan, October 1988 (in Japanese).

[4] Yamamoto M., Fujioka A., Shinozaki K., Horiuchi S., Kumazawa F. and Okada T.: "Shaking Table Test of Reinforced Concrete One-Fifteenth Scale Model Structures, Part 4. Response Characteristics, - Seismic Performance of R/C High-Rise Frame Structure with Wall Columns -," Proceedings of the Annual Convention of the Architectural Institute of Japan, October 1988 (in Japanese).

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

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

[7] "Japanese Architectural Standard Specification, JASS 5, Reinforced Concrete Work," the Architectural Institute of Japan, 1986 (in Japanese).

[8] "Standard for Structural Calculation of Reinforced Concrete Structures," the Architectural Institute of Japan, 1988 (in Japanese).

[9] B. Wallace and H. Krawinkler: "Small Scale Model Tests of Structural Components and Assemblies," Earthquake Effects on Reinforced Concrete Structures, U.S.-Japan Research, SP 84-11, American Concrete Institute, 1985.

[10] C. Wolfgram, D. Rothe, P. Wilson and M. Sozen: "Earthquake Simulation Tests of Three One-Tenth Scale Models," Earthquake Effects on Reinforced Concrete Structures, U.S.-Japan Research, SP 84-12, American Concrete Institute, 1985.

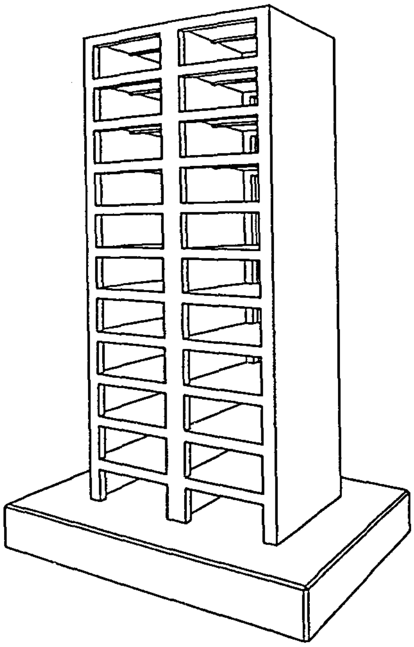
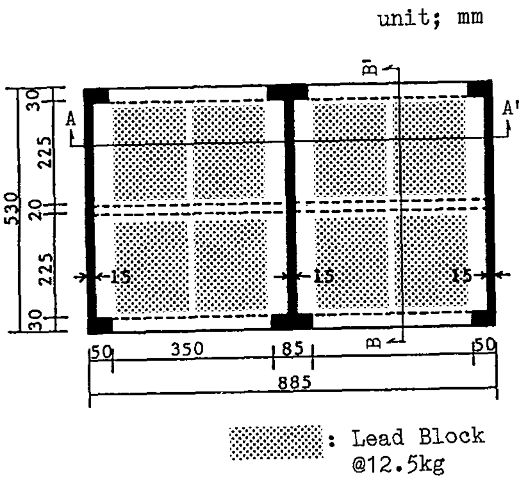
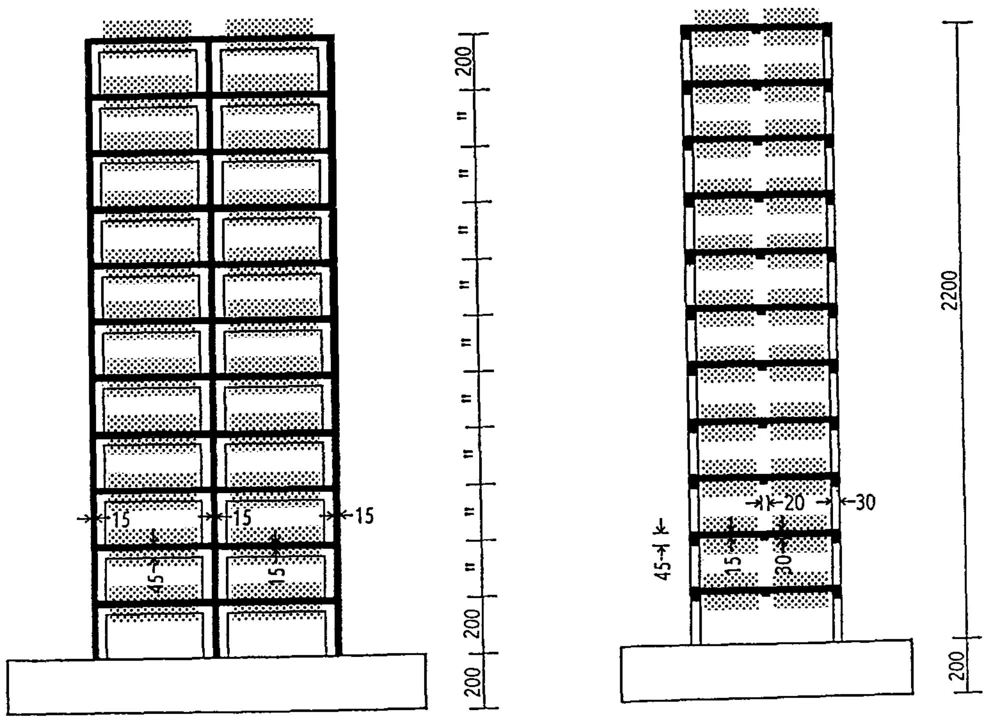


Fig. 1 General View of Model Structure



a) Plan



b) A-A' Section

c) B-B' Section

Fig. 2 Plan and Sections of Model Structure

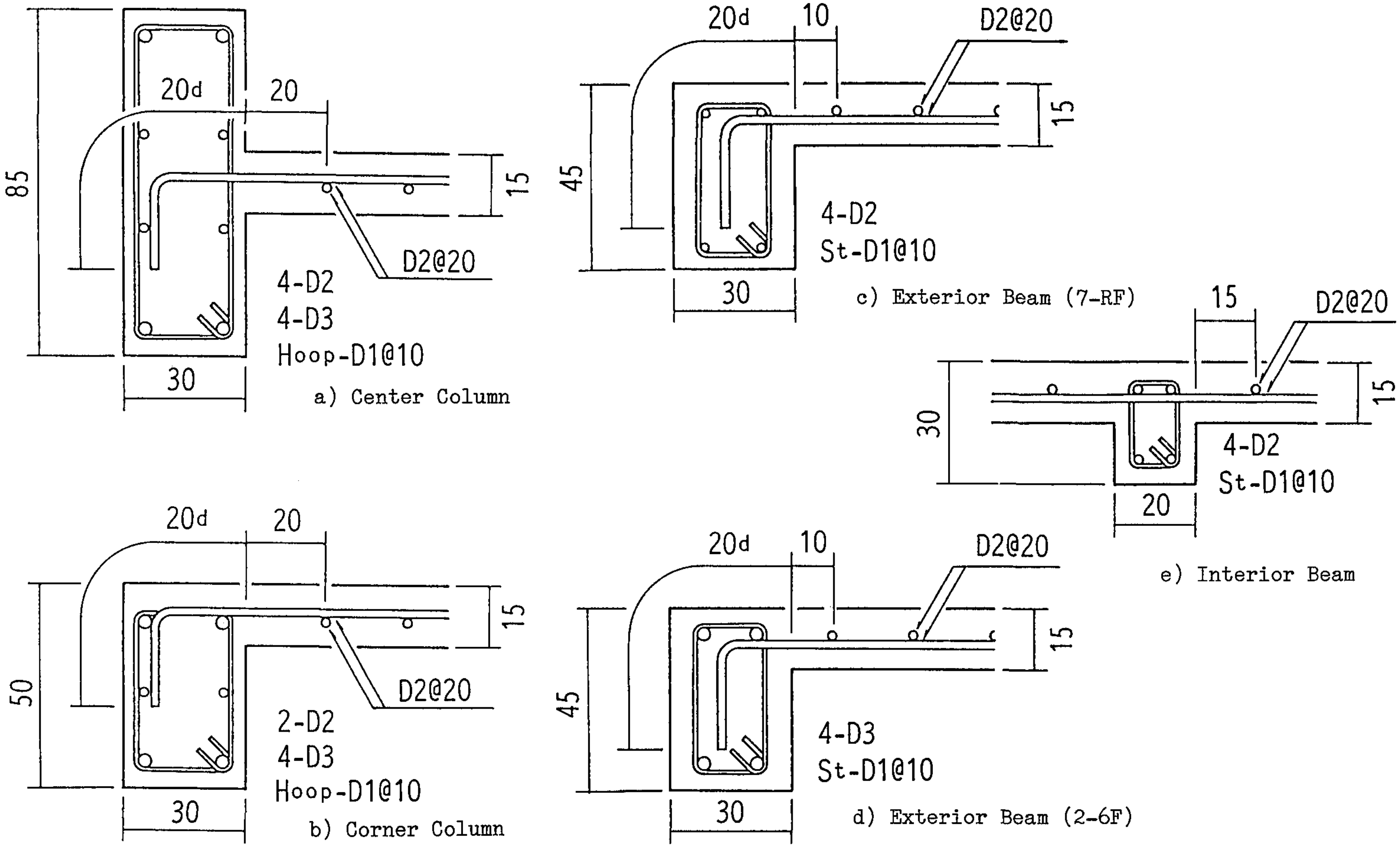


Fig. 3 Dimensions of Columns and Beams

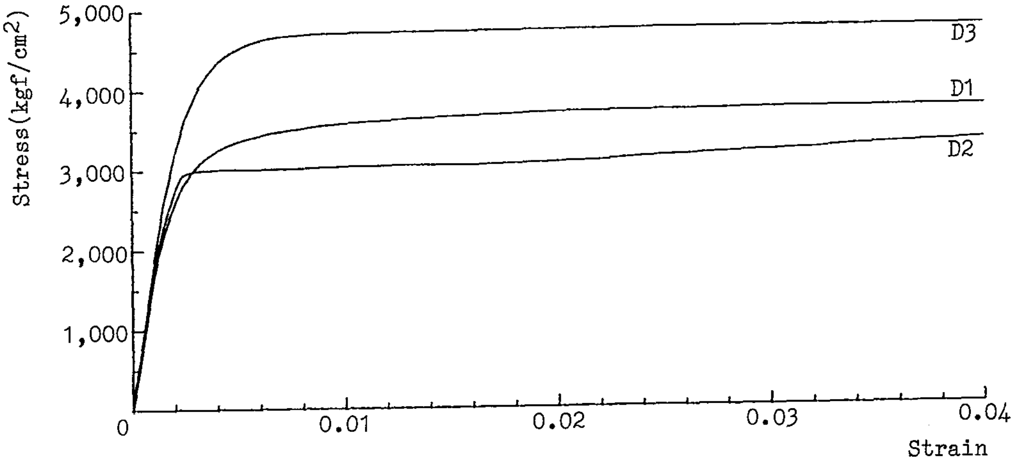


Fig. 4 Stress-Strain Relationships of Reinforcement

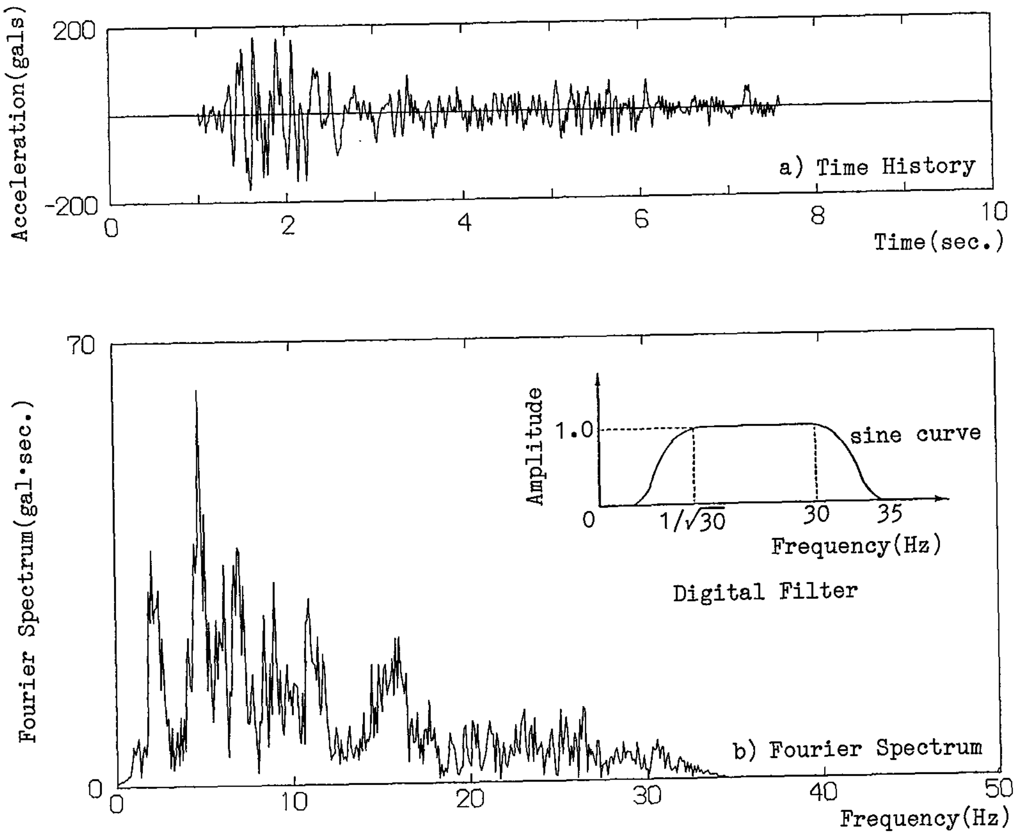
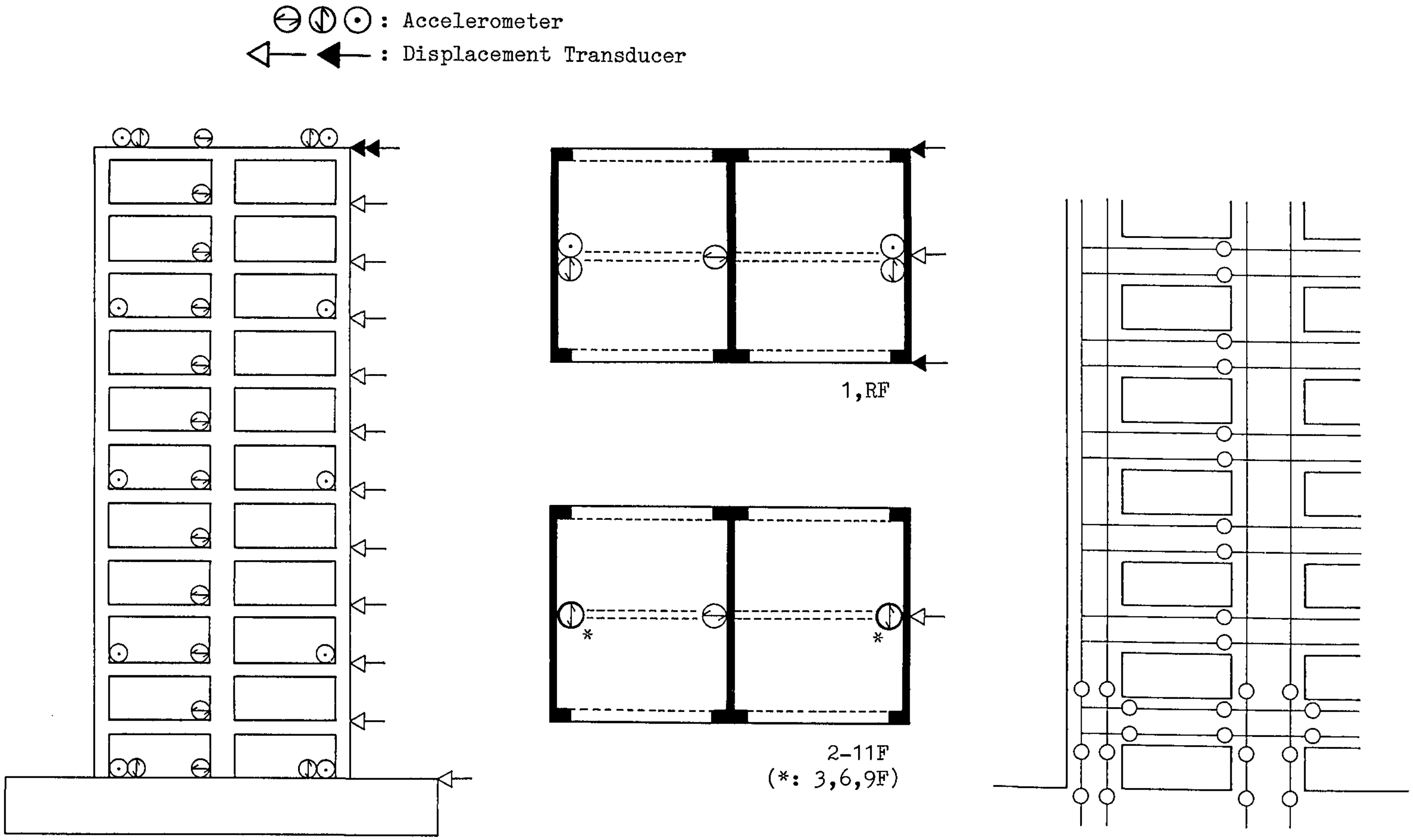


Fig. 5 Input Acceleration



a) Accelerometers and Displacement Transducers

b) Strain Gages

Fig. 6 Locations of Measuring Instruments

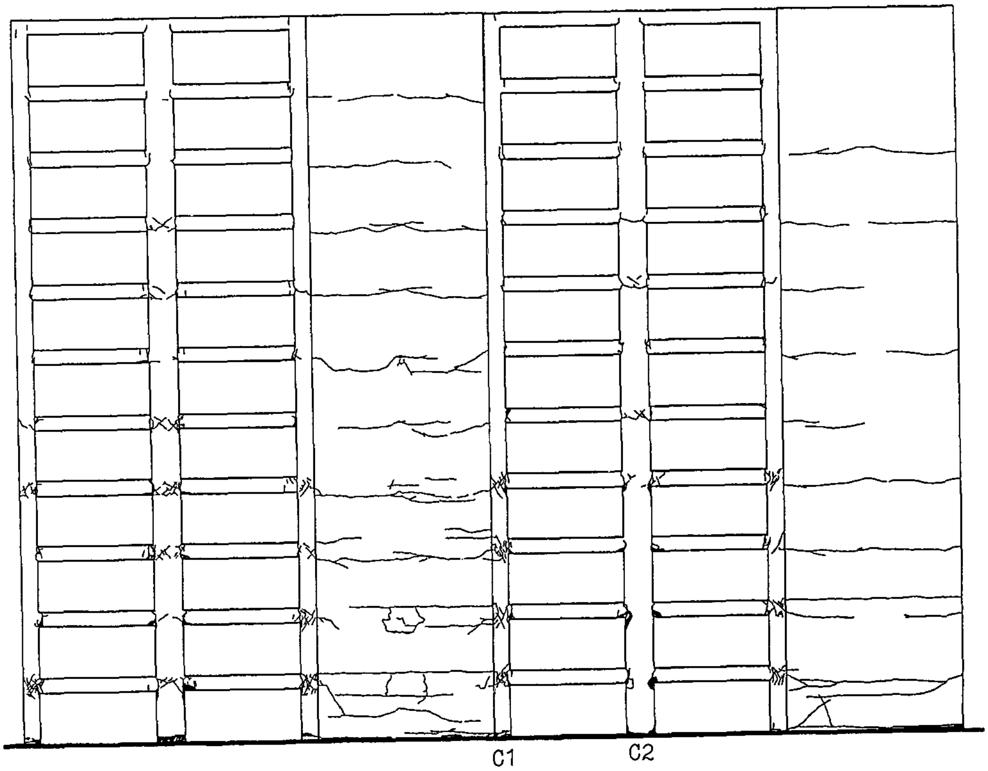


Fig. 7 Final Crack Patterns

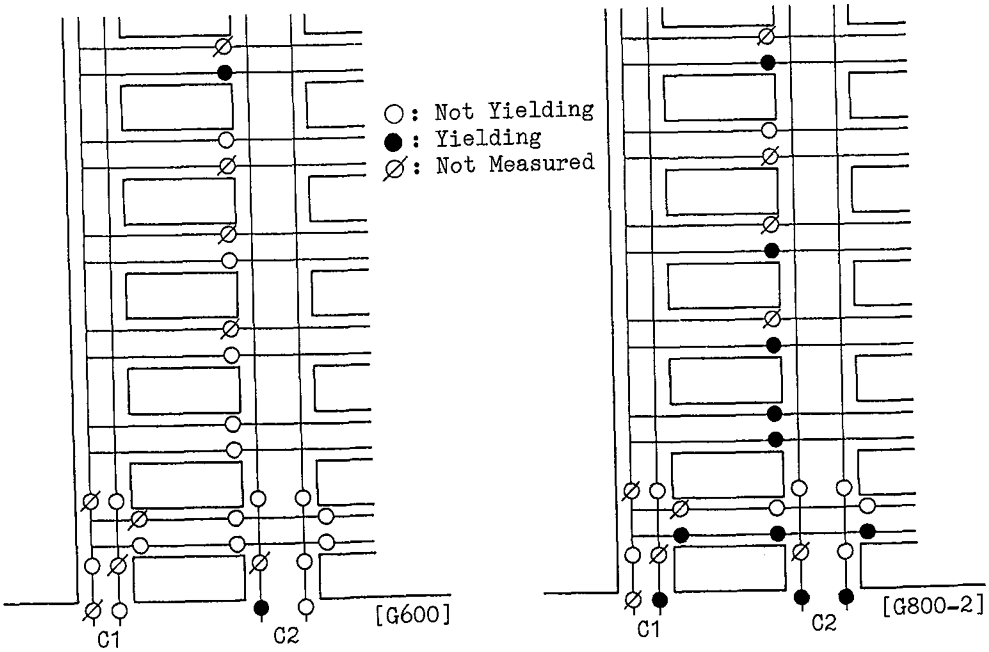


Fig. 8 Yielding of Reinforcement

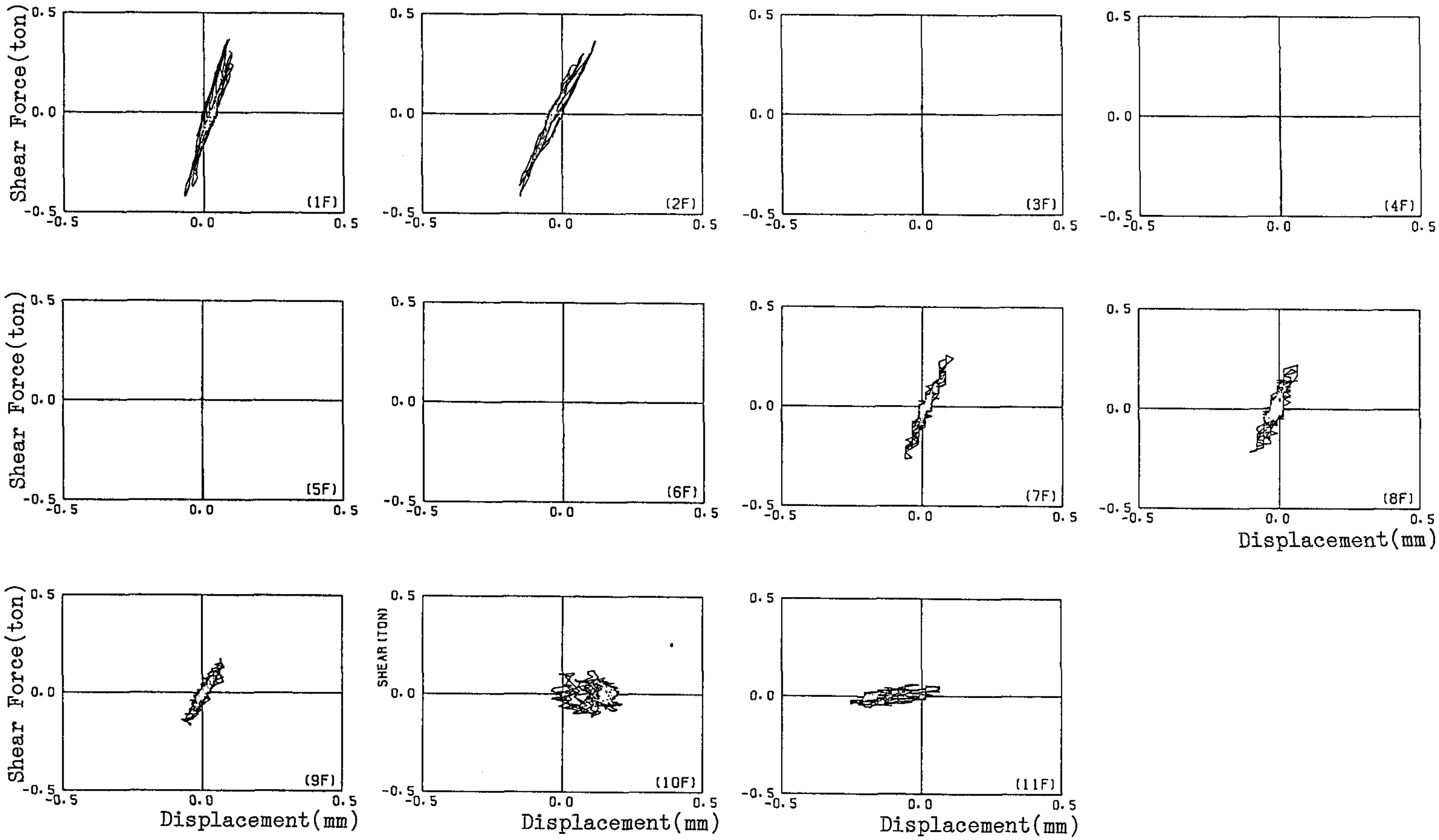


Fig. 9-1 Hysteresis Loops (G40 run)

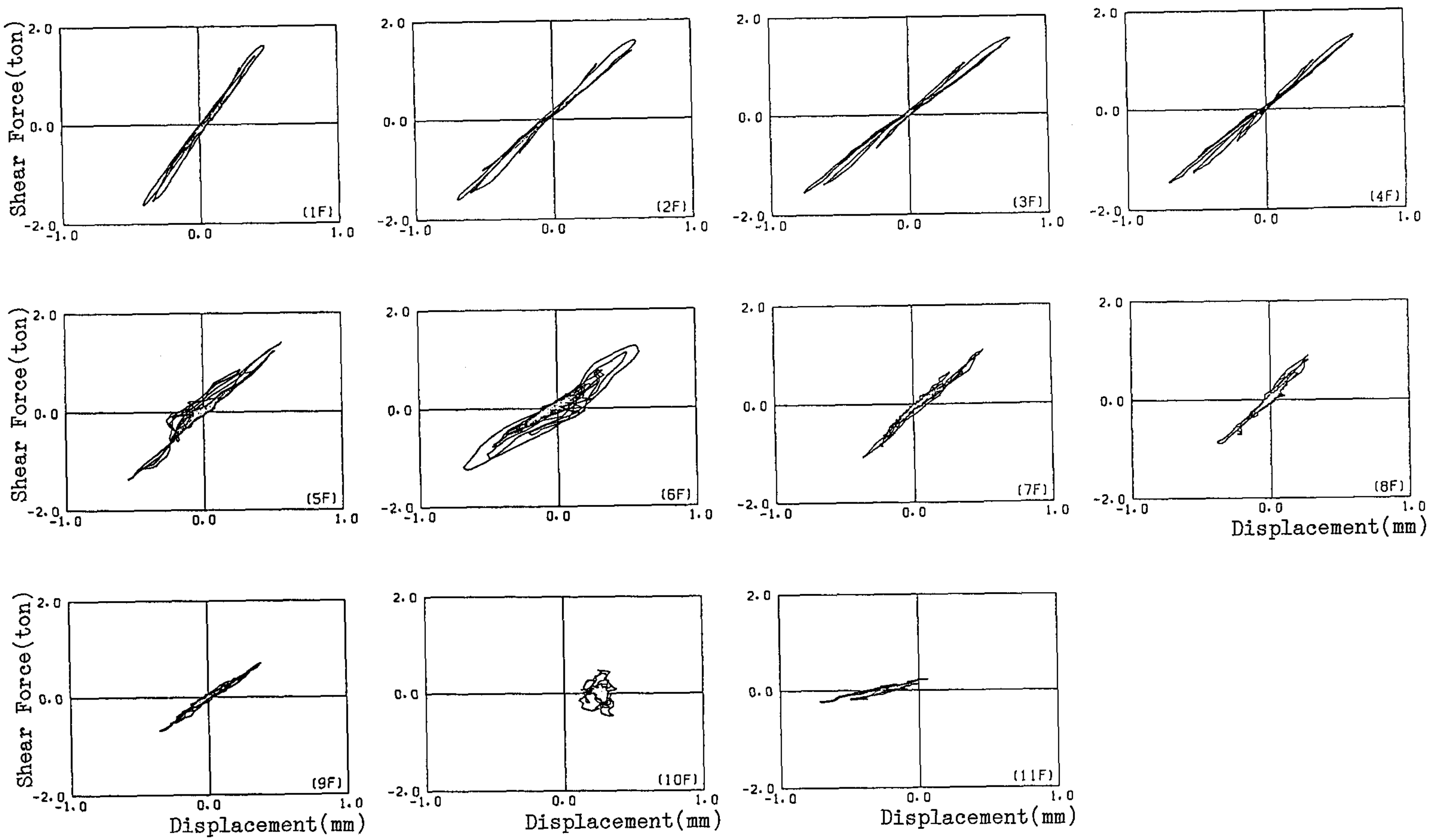


Fig. 9-2 Hysteresis Loops (G200 run)

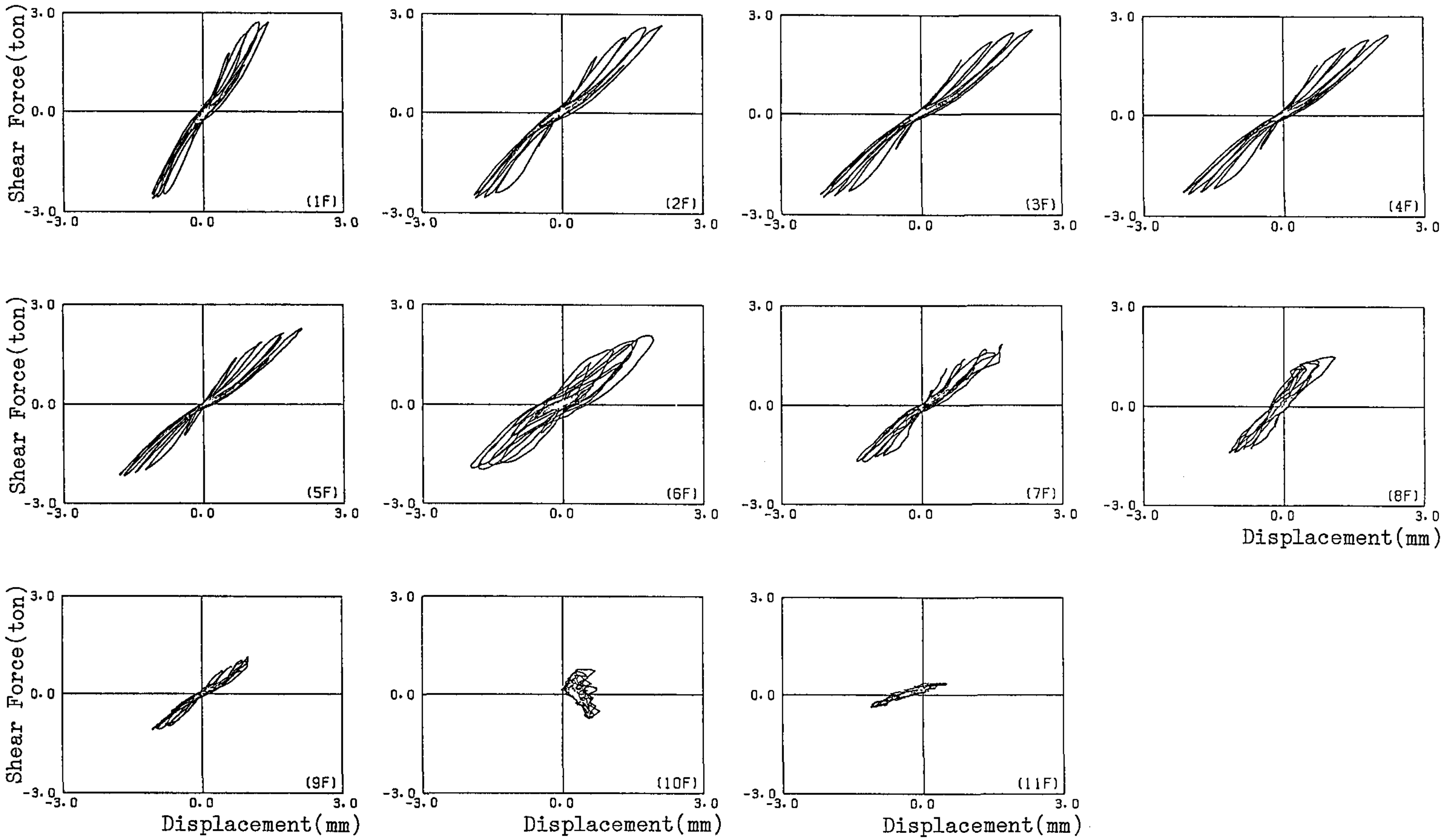


Fig. 9-3 Hysteresis Loops (G400 run)

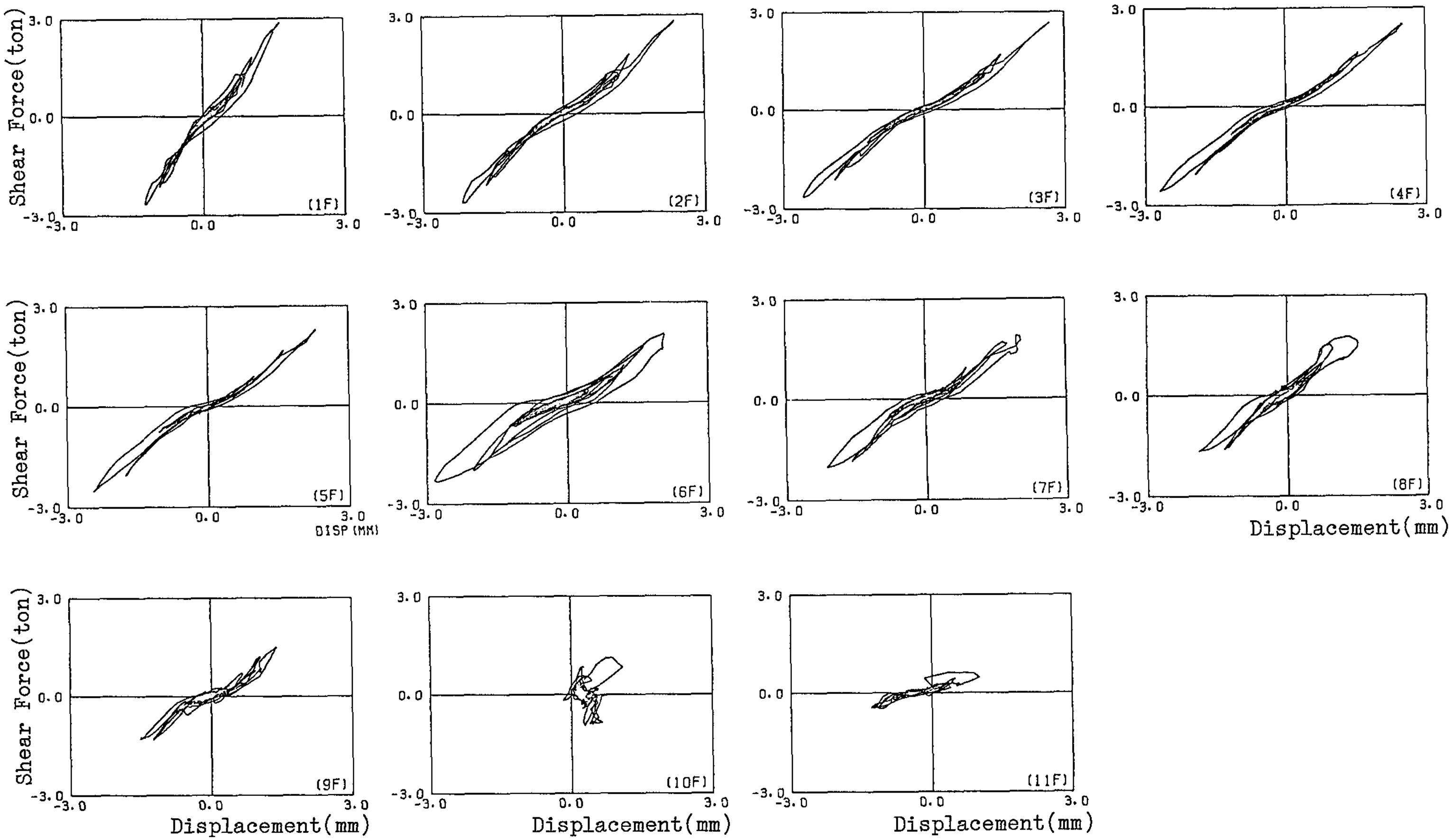


Fig. 9-4 Hysteresis Loops (G600 run)

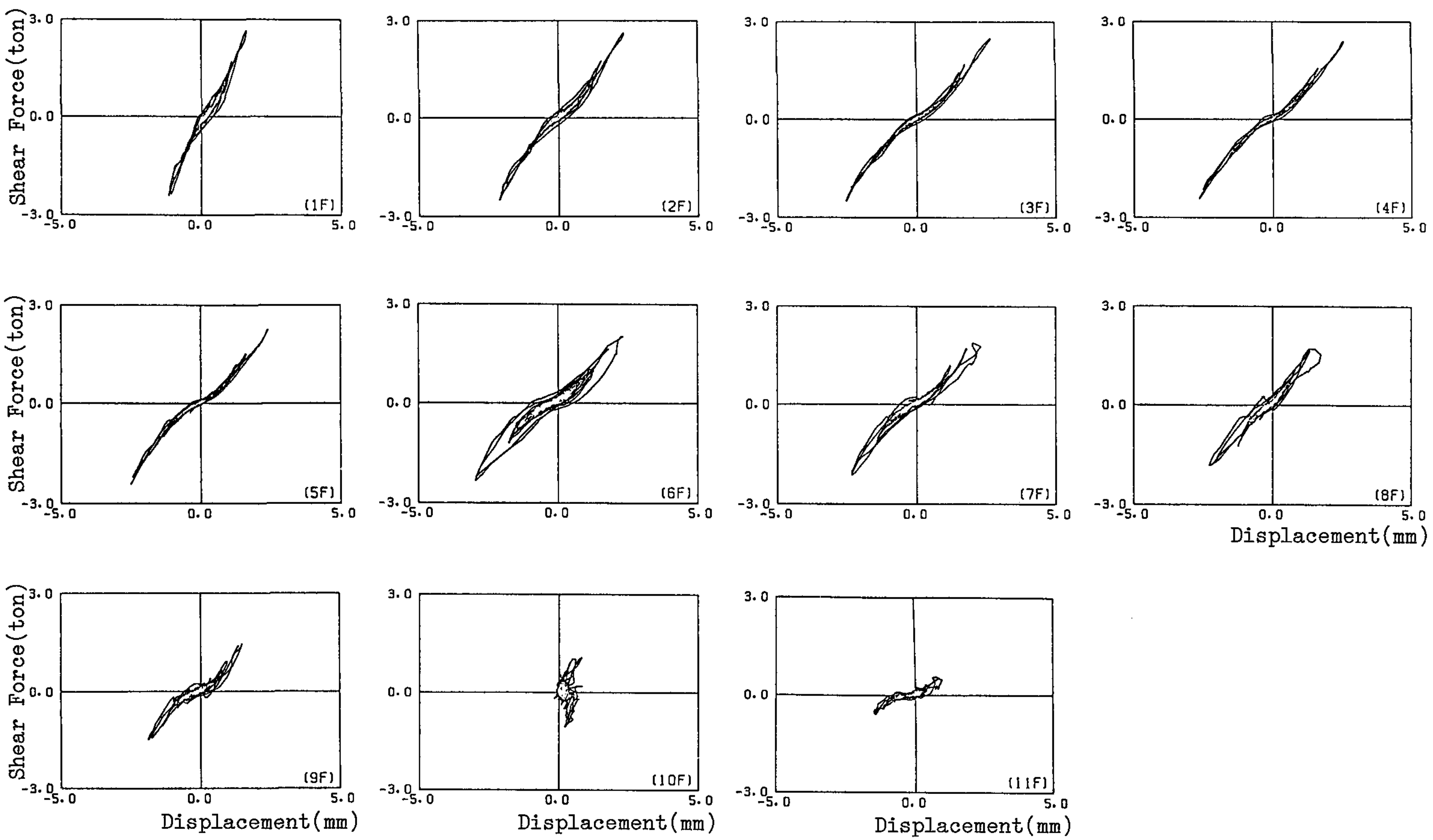


Fig. 9-5 Hysteresis Loops (G800 run)

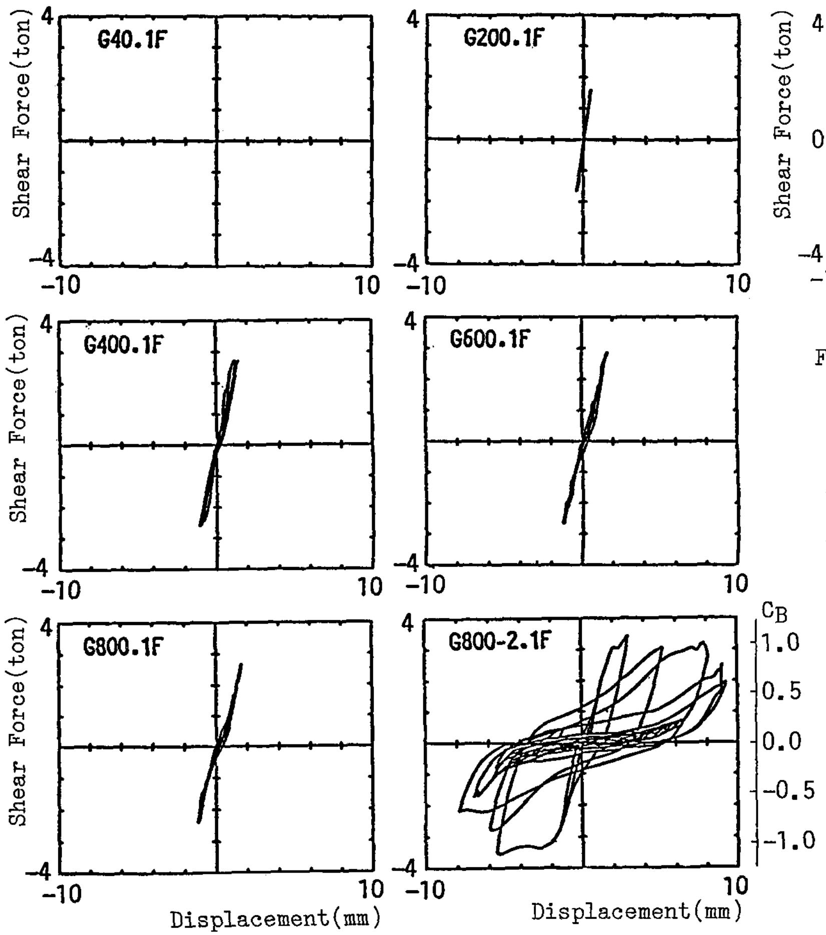


Fig. 9-6 Hysteresis Loops (First Story)

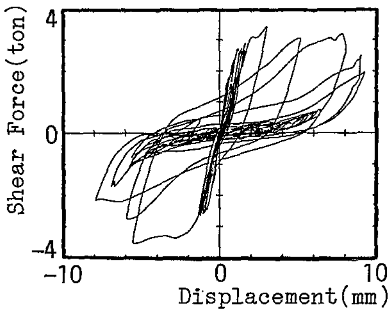


Fig. 9-7 Hysteresis Loop (All runs)

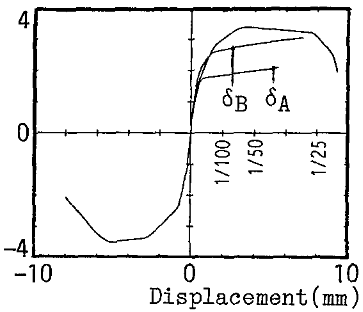


Fig. 10-1 Envelope Curves (Static Analyses)

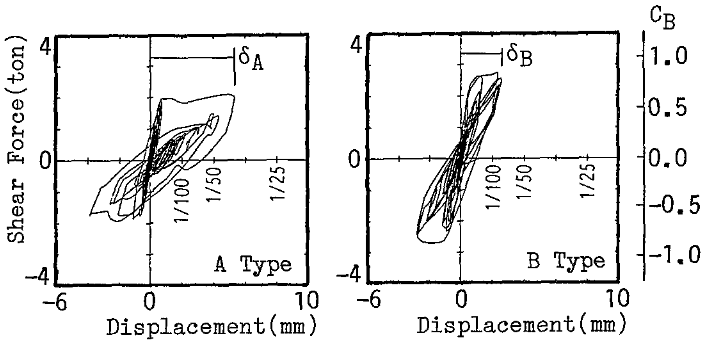


Fig. 10-2 Hysteresis Loops (Dynamic Analyses)

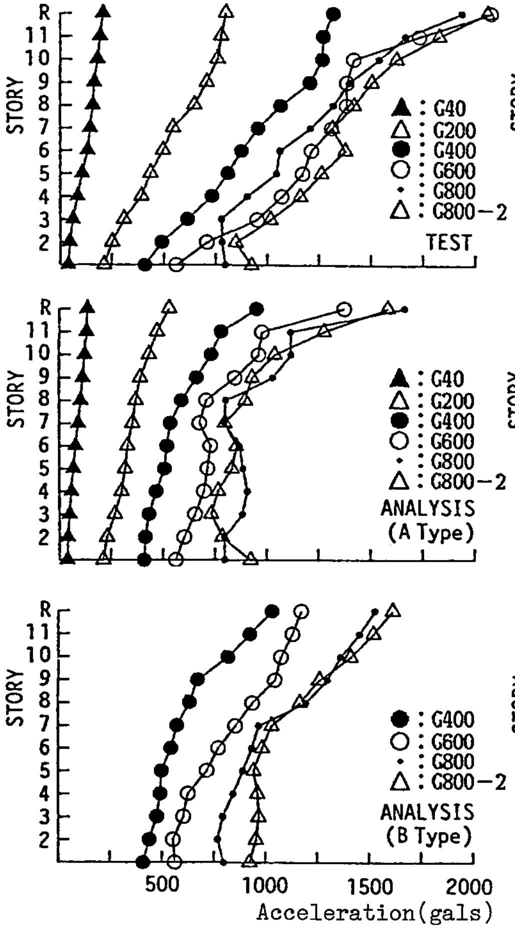


Fig. 11 Maximum Absolute Response Acceleration

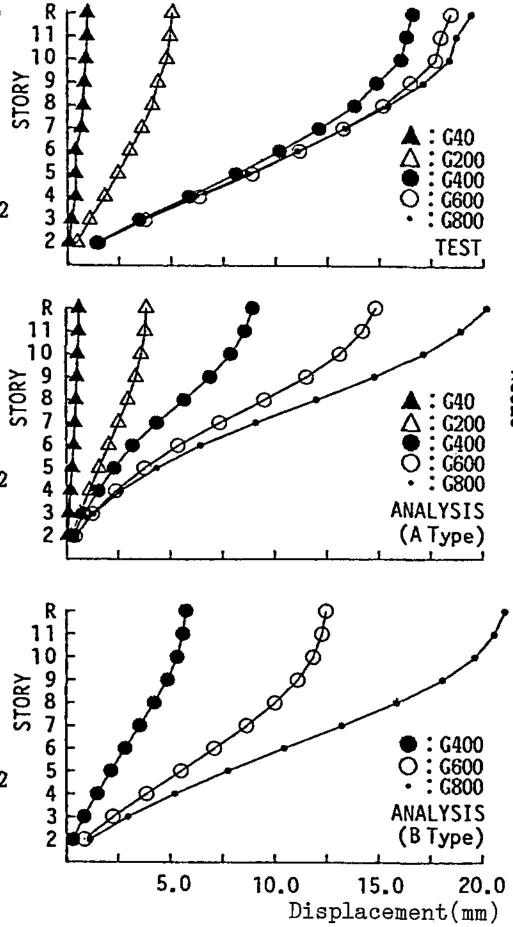


Fig. 12 Maximum Relative Displacement

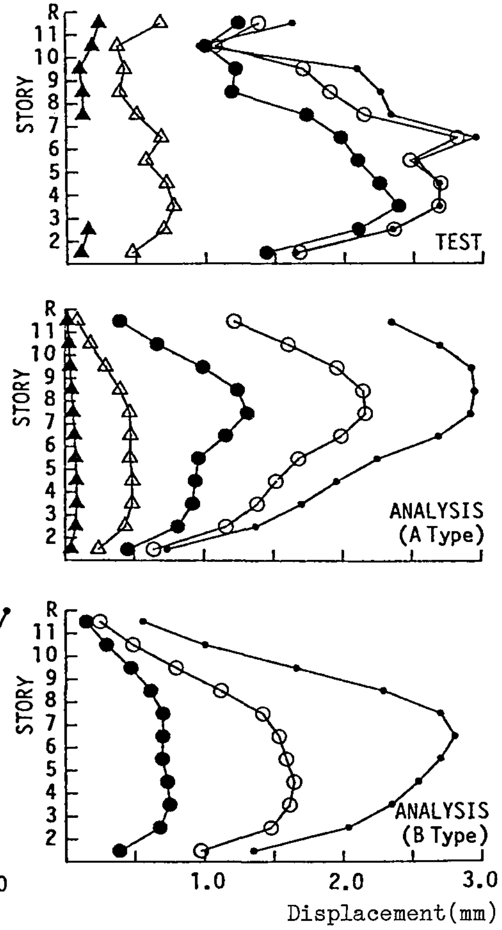


Fig. 13 Maximum Inter-Story Displacement

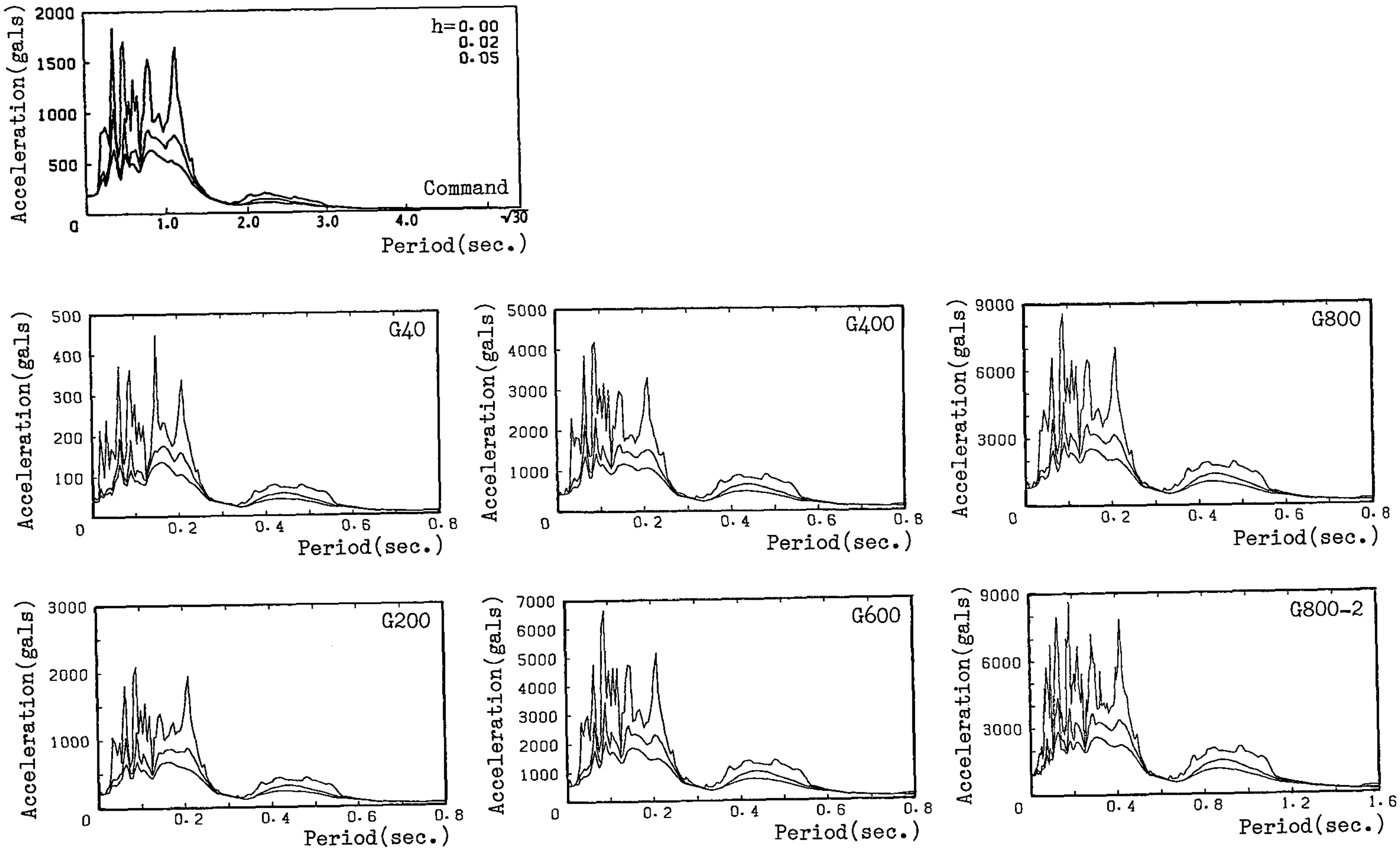


Fig. 14 Acceleration Response Spectra (at the First Floor)

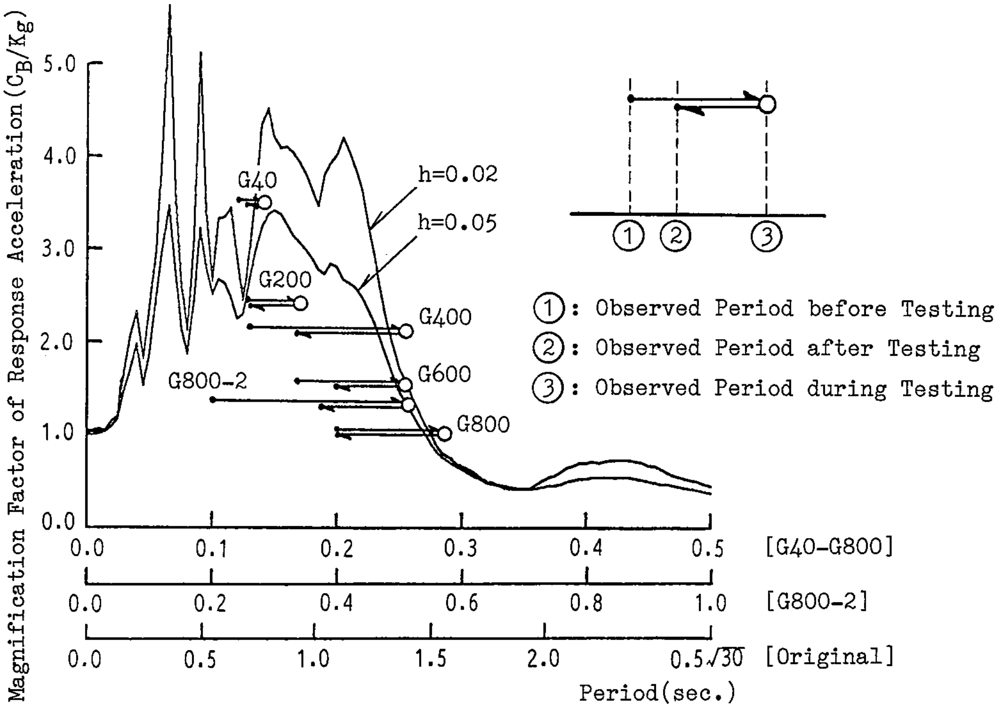


Fig. 15 Magnification Factor of Response Acceleration vs. Fundamental Period

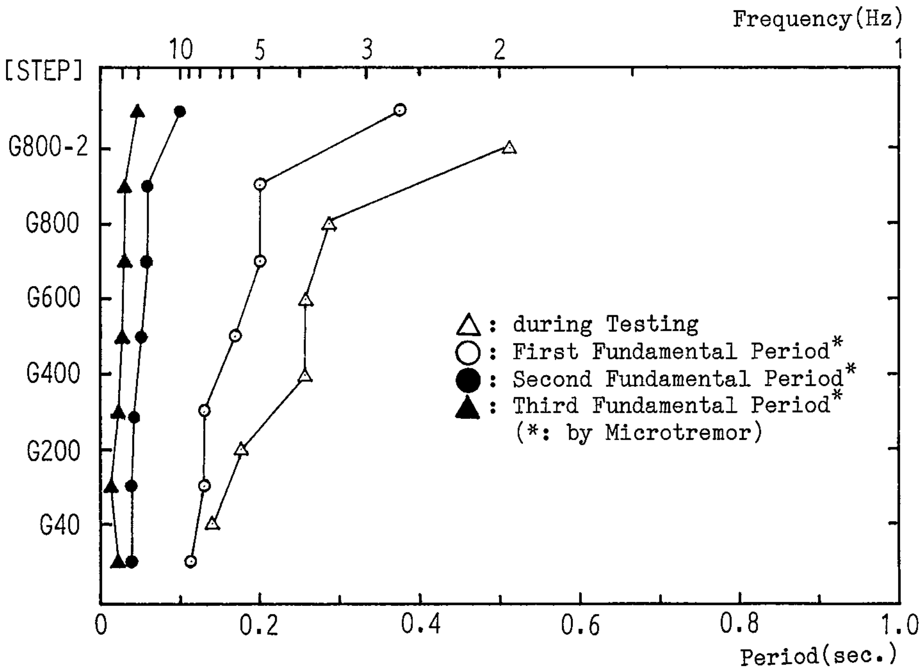


Fig. 16 Changes of Fundamental Periods

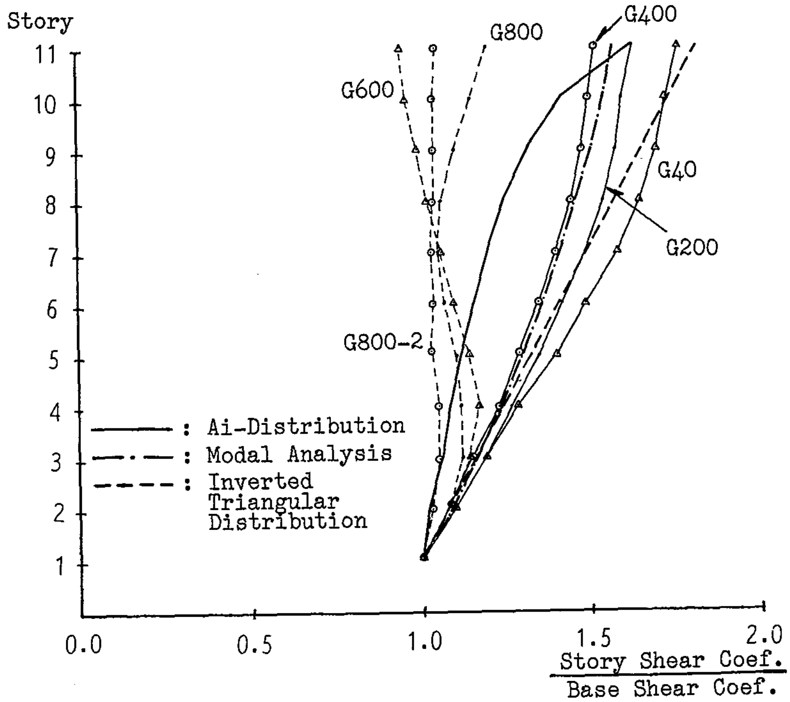


Fig. 17 Distributions of Story Shear Coefficients

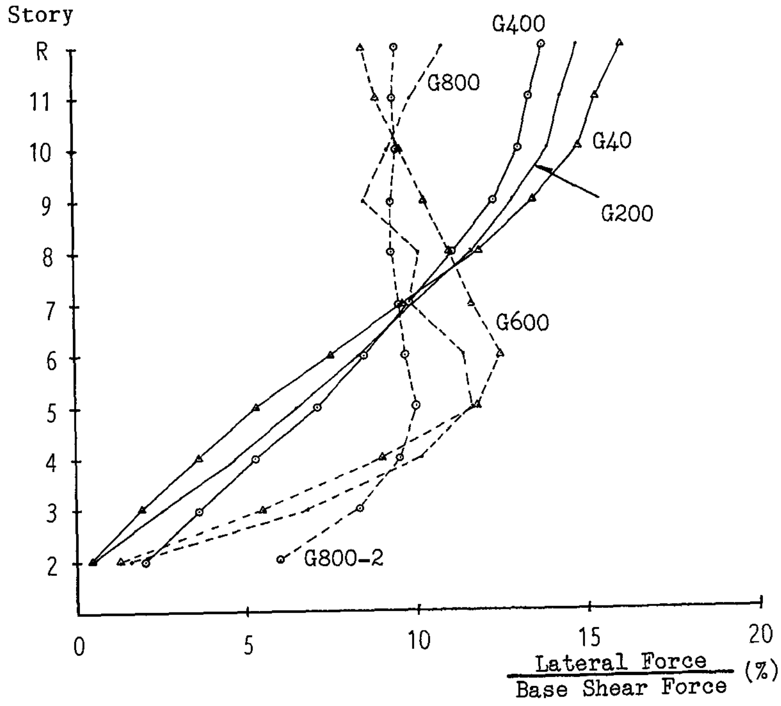


Fig. 18 Distributions of Lateral Force

Table 1 Law of Similarity

	Target	Actual
Length	1/15	1/15
Stress	1	1*1
Strain	1	1
Time	$1/\sqrt{15}$	$1/(\sqrt{15}\times\sqrt{2})$
Weight*2	$1/15^2$	$1/(15^2\times 2)$
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	$1/\sqrt{15}$	$1/(\sqrt{15}\times\sqrt{2})$

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

Table 2 Material Tests
a) Tensile Tests of Reinforcement

	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

b) Compressive Tests of Concrete

Story	Slump (cm)	Strength*1 (kgf/cm^2)	Young's Modulus*1 ($\times 10^5$kgf/cm^2)
Basement	14.5	232.8	2.05
1	25.5	370.4	2.53
2	20.0	348.5	2.37
3	9.0	369.7	2.45
4	13.0	353.3	2.40
5	5.5	417.1	2.67
6	20.0	408.1	2.60
7	19.5	352.7	2.40
8	16.0	377.4	2.46
9	20.5	409.4	2.58
10	20.5	339.8	2.36
11	19.5	351.2	2.34

Note; *1 Average of three cylinders

Table 3 Micro Concrete Mixture

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

Table 4 Test Program

Run Steps	Maximum Accel. (gals)	
	Target	Observed
G40	40	39.3 -36.7
G200	200	202 -213
G400	400	408 -370
G600	600	559 -555
G800	800	782 -795
G800-2	800	922 -809

Table 5 Maximum Responses

	C_B	R_1	R
G40	0.13	1/1960	1/2160
G200	0.50	1/421	1/418
G400	0.84	1/142	1/132
G600	0.89	1/121	1/110
G800	0.83	1/123	1/105
G800-2	1.10	1/17	——

Note; C_B: Base shear Coeff.
R_1: Drift angle at 1st story
R : Overall drift angle

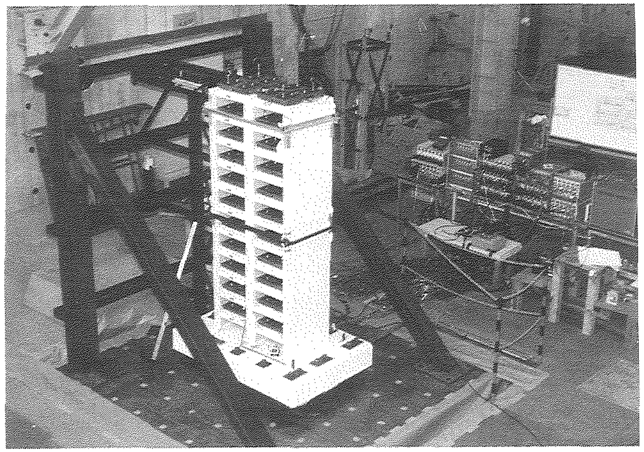


Photo. 1 Sight of Testing

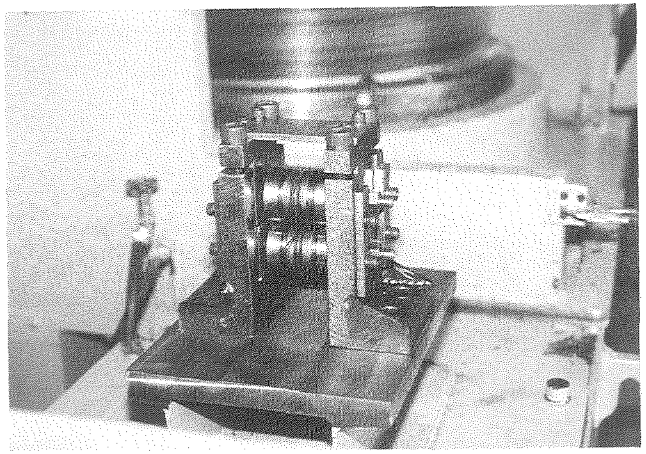


Photo. 2 Deforming Rolls

Photo. 3 Model Structure
(Compare with a person)

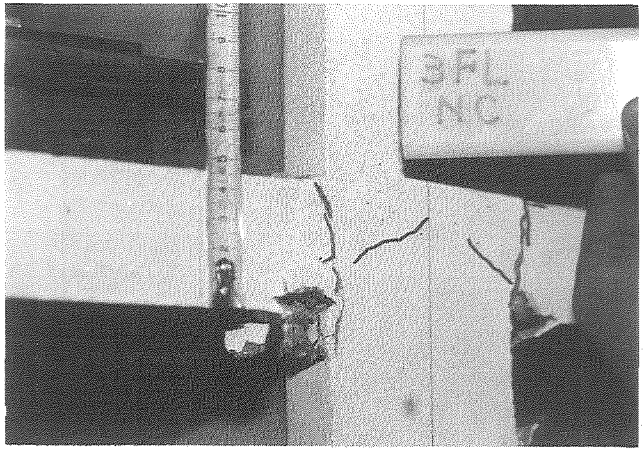


Photo. 4 Cracks at Beam Ends


Photo. 5 Cracks at First Story
(Plastic models are 1/20 scale)

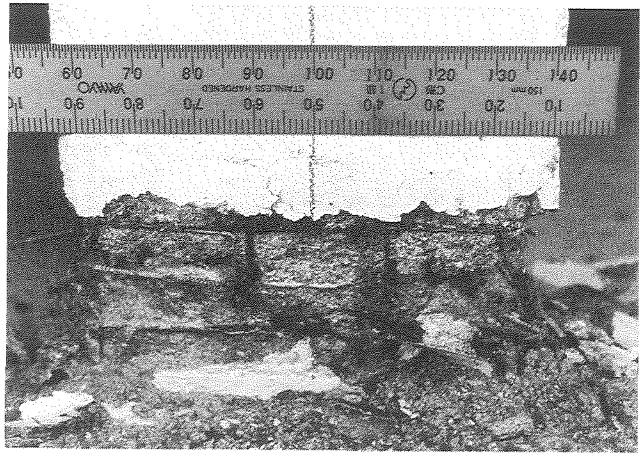


Photo. 6 Cracks of Center Column at First Story

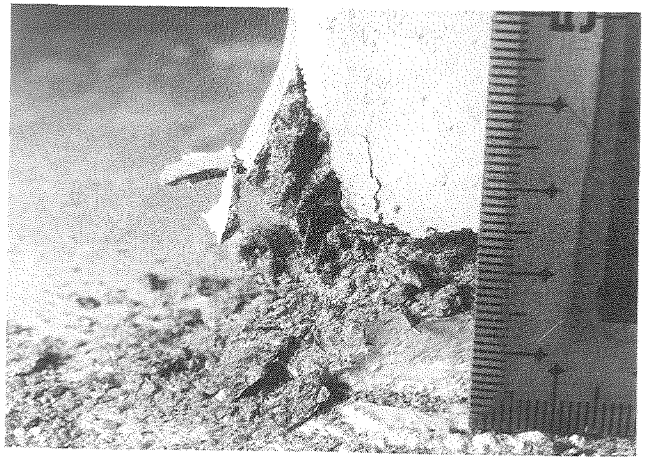


Photo. 7 Cracks of Center Column st First Story
(Reinforcing bars buckled and broke off)