Experimental Studies on Reinforced Concrete Structures

in

Building Research Institute

from 1989 to 1992

by

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ABSTRACT

Three research projects on the fields of reinforced concrete have launched at 1989 for four years. One is national research project on the development of high strength concrete and steel for super light weighted and super high rise buildings, the second one is also national research project on the utilizing new materials for r/c buildings instead of steel, and the third one is U.S.-JAPAN Coordinated Research program on precast concrete buildings. These research programs have the common(same) objectives, that are to propose (or draft) design guidelines. In order to propose design guidelines, fundamental and applied experimental studies are planned and conducted. This paper introduces the outlines of theses research programs and main experimental works, and their experimental methods.

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1. INTRODUCTION

Three projects related to reinforced concrete structures are now ongoing in B.R.I.. Two of these are National Research Projects on the high strength reinforced concrete and on the utilization new materials. One of these is the U.S.-JAPAN Cooperative Research Project on precast concrete structures Many experimental works are planned and conducted under these projects. This paper introduces the outline of these research programs and main experimental works, and their experimental methods.

2. OUTLINE OF EACH PROJECT

2.1 NEW RC [Ref.1]

2.1.1 Target

Target zone of materials in this project is shown in Fig. 2.1.1. The objectives of this project are followings;
(1) Development of high-strength and high-quality materials
(2) Evaluation of properties of structural members and frames
(3) Development of design and construction guidelines
(4) Feasibility study on RC buildings in Zone II-1
(5) Feasibility study on RC buildings in Zone III

2.1.2 Organization

B.R.I is in charge of conducting the project. Research committees are set up in Japan Institute for Construction Engineering(JICE) to organize universities, private companies. etc.. Three committees are conducting research items and to integrate research results. Figure 2.1.2 shows a organization of this project.

2.1.3 Research items

Research items in Structural Committee and Structural Design Committee are as follows:

Structural Committee
(1) Mechanical properties of beam and columns.
(2) Mechanical properties of shear walls.
(3) Effect of shear force on beams, columns, and shear walls.
(4) Mechanical properties of beam-column joints and frames.
(5) Mechanical properties of foundations

Structural design Committee
(1) Method for modeling and analysis of behavior of structural frames in each zone.
(2) Practicable types of structural frames.
(3) Design loads and requirements for structural performance.
(4) Design methodology.

2.2 PRESSS [Ref.2]

2.2.1 Target

The target of this PRESSS project in Japan is to develop design guidelines for precast concrete moment resisting frame buildings.
This guidelines is drafted based on the ultimate strength design concept.
And also design manual for precast member connections is to be provided.

2.2.2 Organization - - - Fig. 2.2.1

Technical coordinate committee is organized in Building Center of Japan(B.C.J). Under this committee, design and joint committees are organized. Many WG are working to assist these committees.

2.2.3 Research items [Ref.3] Fig. 2.2.2

(1) Tests of sub-element consisting precast concrete
(2) Test of precast member subassemblies

2.3 New Materials (Continuous fiber rod concrete)

This project consists of mainly two parts; building part and civil engineer part. And building part is divided to two parts; metal and non-metal. Then non-metal part is built from three working groups; fiber tip WG, continuous fiber rod WG, and new function WG. This paper mention about only the research on continuous fiber rod concrete. COntinuous fiber rod is made by continuous fiber filaments gathered and stuck by resin.
2.3.1 Target

It is investigated if the same estimation method for structural performance, durability, and fire resistance of existing r/c and prestressed r/c members can be adopted to reinforced concrete members reinforced by continuous fiber rod instead of steel bar. Finally draft of design guidelines of utilizing continuous fiber rod concrete will be proposed based on a limit state design concept.

2.3.2 Organization

Between BRI and related association and private companies make an agreement of coordinate research program. BRI commits this research projects to Kokudo Kaihatsu Gijyutsu Center(KKGC or JICE). In KKGC, several committees are organized to perform this research. On the other hand related associations and private companies entrust the research on new materials to Kenchiku Kenkyuu Shinkou Kyohkai(KKSK). In KKSK several research committees are organized to assist the activities of committee in KKGC. Figure 2.3.1 shows the organization of this project.

2.3.3 Research items Table. 2.3.1

Fundamental test
(1)Test method on tensile strength
(2)Bond strength by simple pull out test
(3)Tensile creep
(4)Anti chemical
(5)High temperature Tensile strength

Structural test
(1)Bond split test

(2)Tention stiffening test
(3)Bond characteristics in beam
(4)Strength of bent corner
(5)Simple beam test
(6)Shear bending test of beam
(7)Confinement
(8)Flexural performance of PC beams

3. OUTLINE OF MAIN EXPERIMENTS

3.1 New RC

Due to minimization of the section of structural member, column-beam joints, and corner column become critical parts in seismic design.

3.1.1 Column-Beam Joints

(1) Objectives
To investigate the appliance of evaluation method of shear strength for existing r/c joints to that for New RC joints

(2) Methods
Inner joint (inner column and beam joint; cross shaped joint), and exterior joint(exterior column and beam joint; T or L shaped joint) are tested. Main parameters are concrete strength and reinforcement in joint.

(3) Results
Joint strength will be estimated by the function of concrete strength. The effect of reinforcement is very small.

3.1.2 Column's Behavior Suffered from Multi Direction Forces

(1) Objectives
In high rise r/c building, corner or exterior columns are suffered from multi directional forces. Especially, a capacity of column to sustain axial load during a strong earthquake will be determine a design. Deformation and axial strength capacity are investigated.

(2) Methods
Uni-axial compression test, pure bending test, and shear bending test were conducted [Ref.1]. After that multi directional force test is done.

(3) Results
Under high axial load, vertical crack will be expected.
Deformation capacity, and load carrying capacity decrease compared with that of specimen tested under one directional loading.

3.1.3 Others

Many tests are going in universities and B.R.I..
(1) bond
(2) shear
etc.

3.2 Presss Project

3.2.1 Strut-and-tie model

(1) Objectives

New design concepts are necessary for design of site-cast concrete connections. Recently, generalizations of the truss analogy have been proposed in the form of strut-and-tie-models, which treat transfer of stress in a member graphically. The strut-and-tie-model is examined whether or not it can be used as a new design tool for site cast connections.

(2) Methods and Results

Test on strength of concrete interface subjected to compression and shear is conducted [Ref.4].

3.3 New materials

3.3.1 Bond Split test

(1) Objectives
It is the objectives to investigate the bond characteristics of CFR and justification of test method.

(2) Method
Specimen and loading method is illustrated in Fig.3.3.1. Measurement is shown in Fig.3.3.2. Twelve kind of CFR and one deformed steel bar are tested.

(3) Results
Relationship between normalized bond strength and ratio of knot height to diameter is shown in Fig.3.3.3.
$\tau_{max}/\sqrt{\sigma_B} = 2.14 * (100*h/d)^{0.22}$
where h: height of knot, d: diameter
$\tau_{max}/\sqrt{\sigma_B}$: normalized bond strength

Comparison of bond strength between test results and calculated results propose in Ref.5.is plotted in Fig.3.3.4.
Bond split strength can be estimated by the method used for r/c member, considering the effect of knot height and failure mode.
This bond splitting test method is seemed to be good for CFR.

4. Trend of experimental work in BRI in a future
In order to use high strength and new materials development of standard test method is necessary. Experiments for verifing structural performance are also necessary. But we should try to establish standards of fundamental test to evaluate various members and materials.
A good example is a strut-and-tie model to be justified a assumed mechanism in presss project. Small and fundamental test to define unknown factors are conducted.

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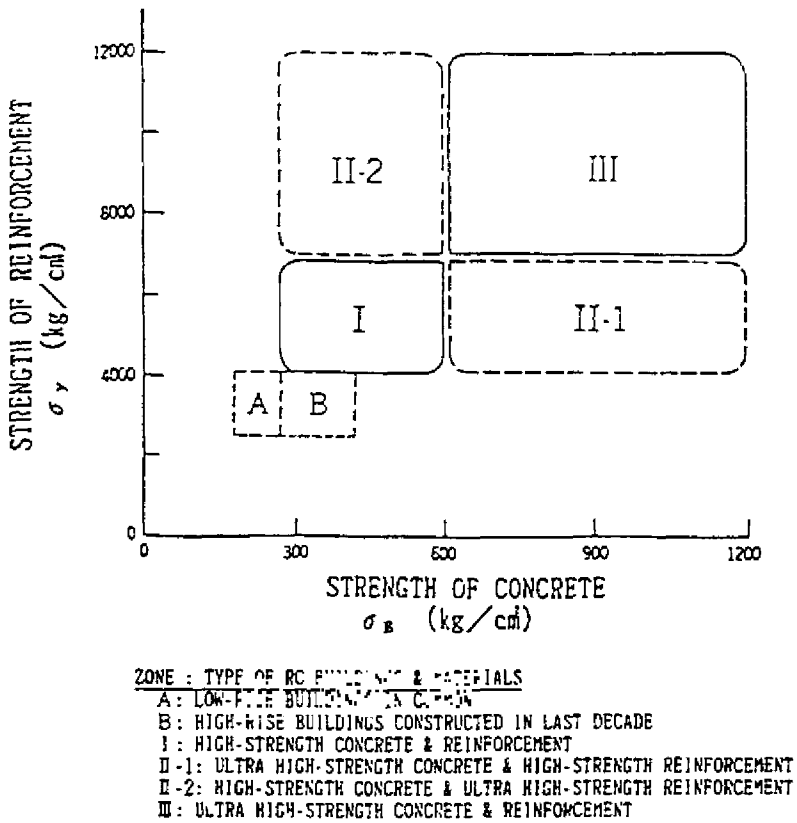


Fig. 2.1.1 **Strength of Materials and Field of Research and Development**

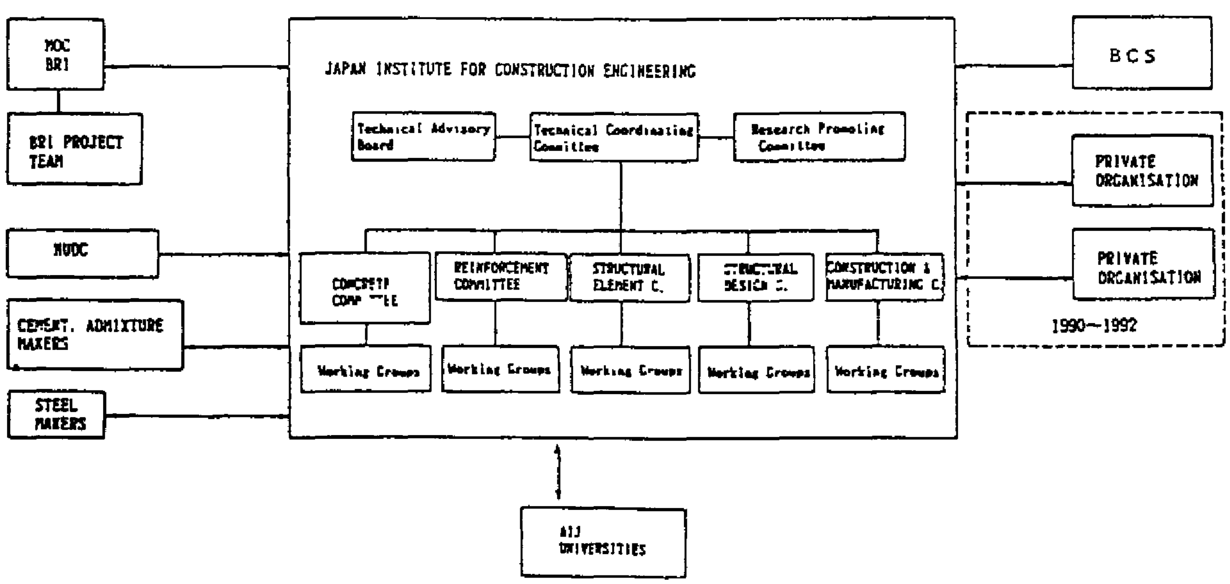


Fig. 2:1.2 **Organization for Research and Development**

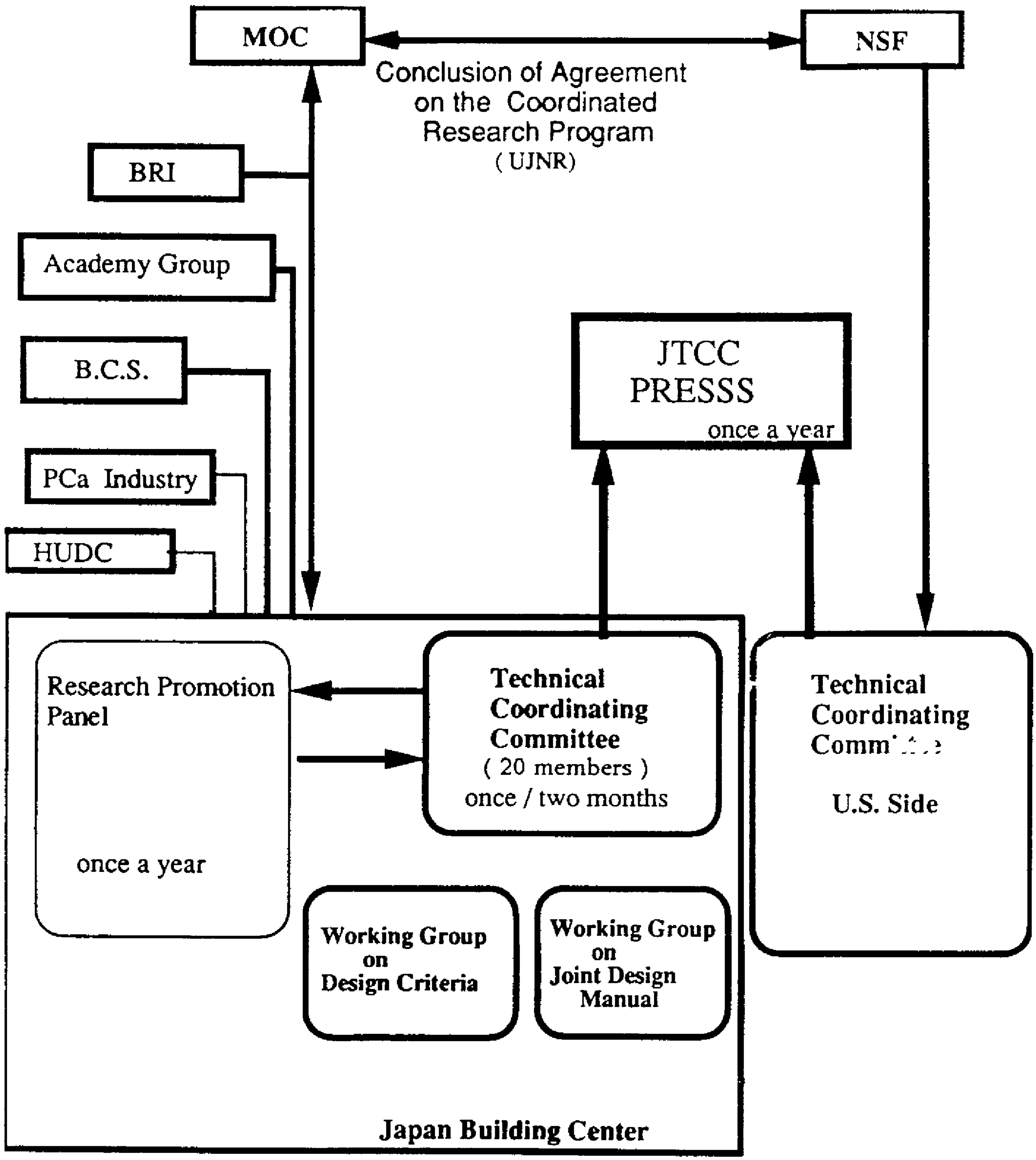
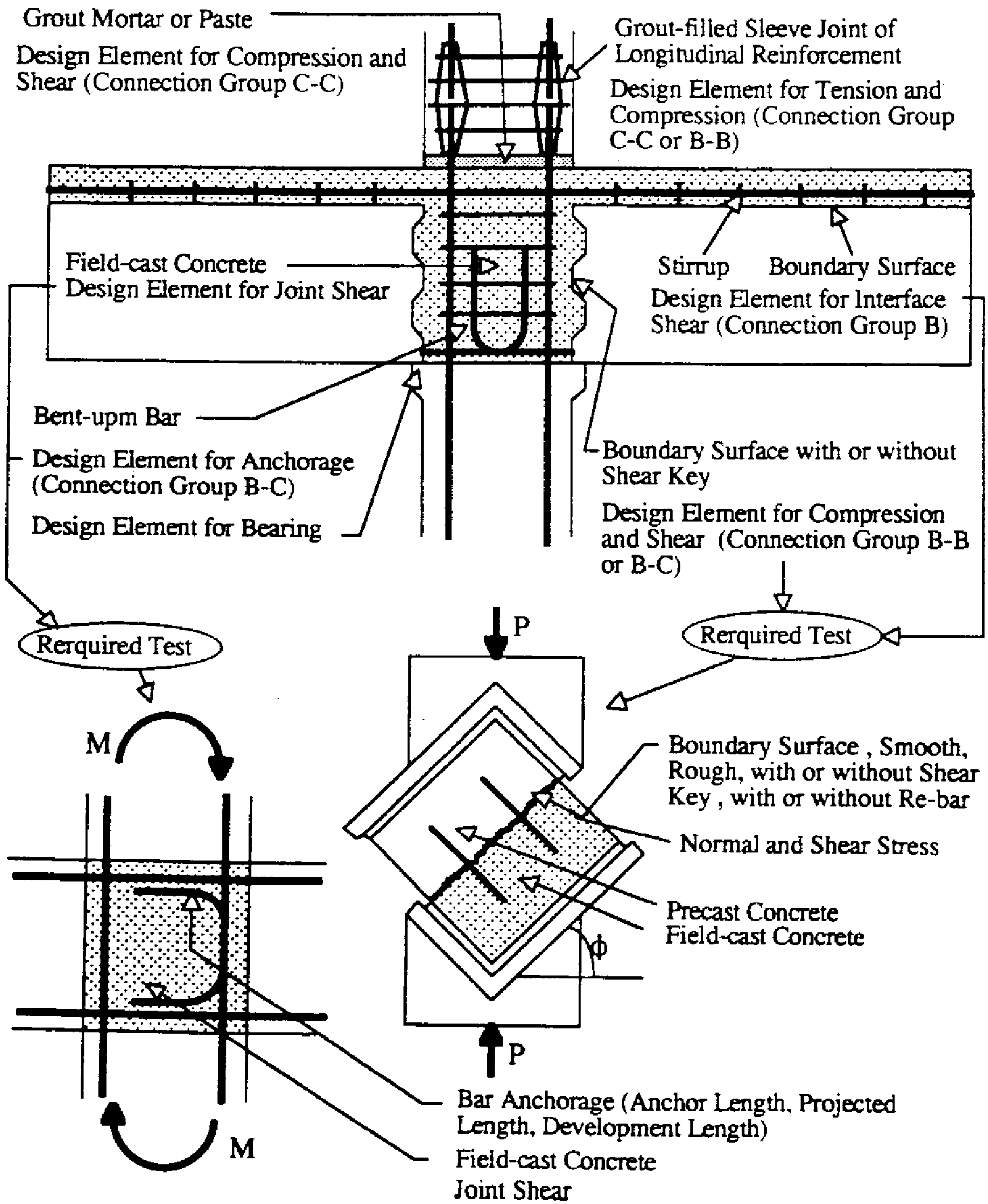


Fig. 2.2.1 **PRESSS Executive Structure**

Fig. 2.2.2 An Example of typical Framing System (Design Elements and Related Experiments)



Organization for New materials

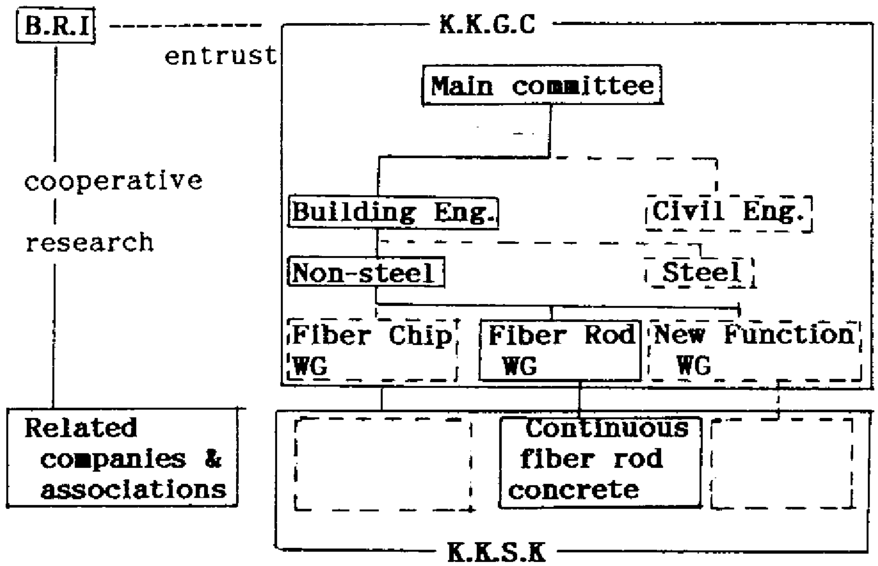


Fig. 2.3.1 Organization for the research project of New Materials

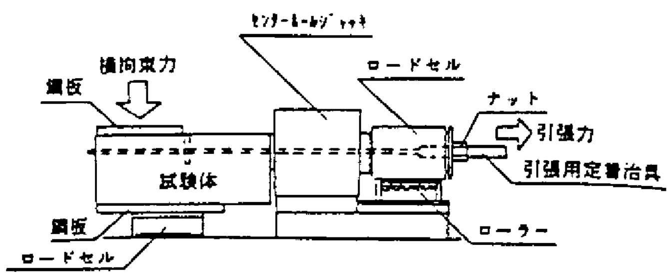


Fig. 3.3.1 Specimen and loading method

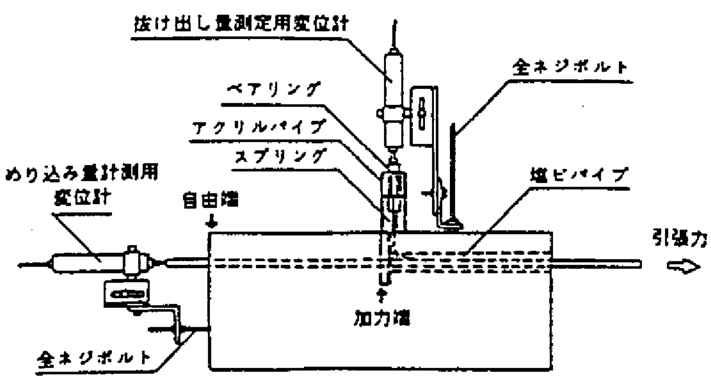


Fig. 3.3.2 Measurment

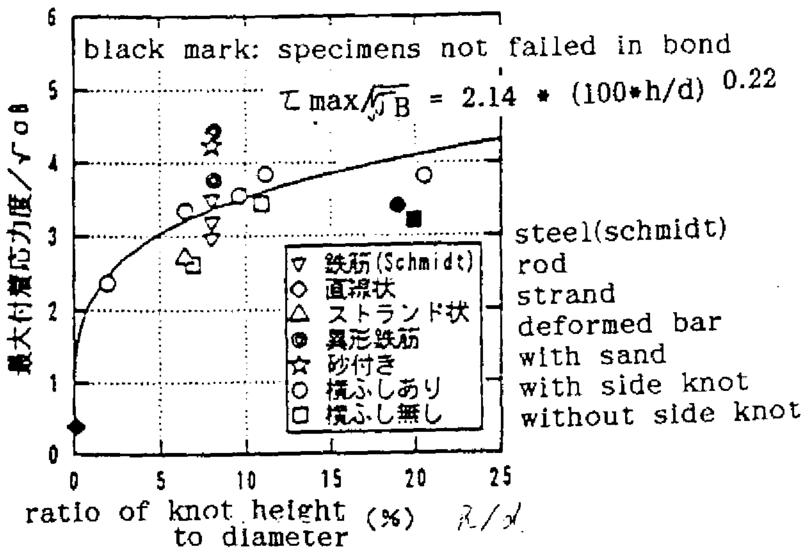


Fig. 3.3.3 Bond strength vs. ratio of knot height to diameter

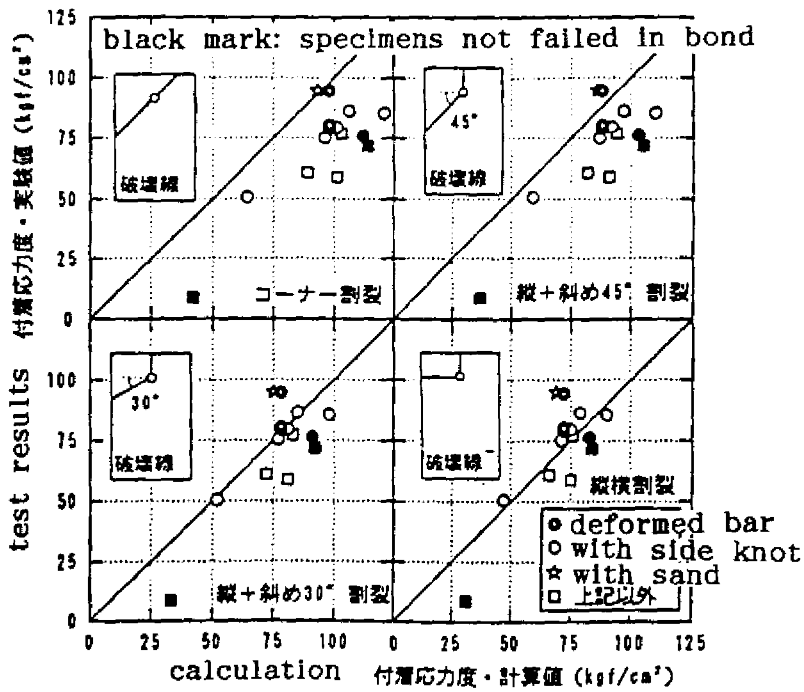


Fig. 3.3.4 Comparison of test results and calculation

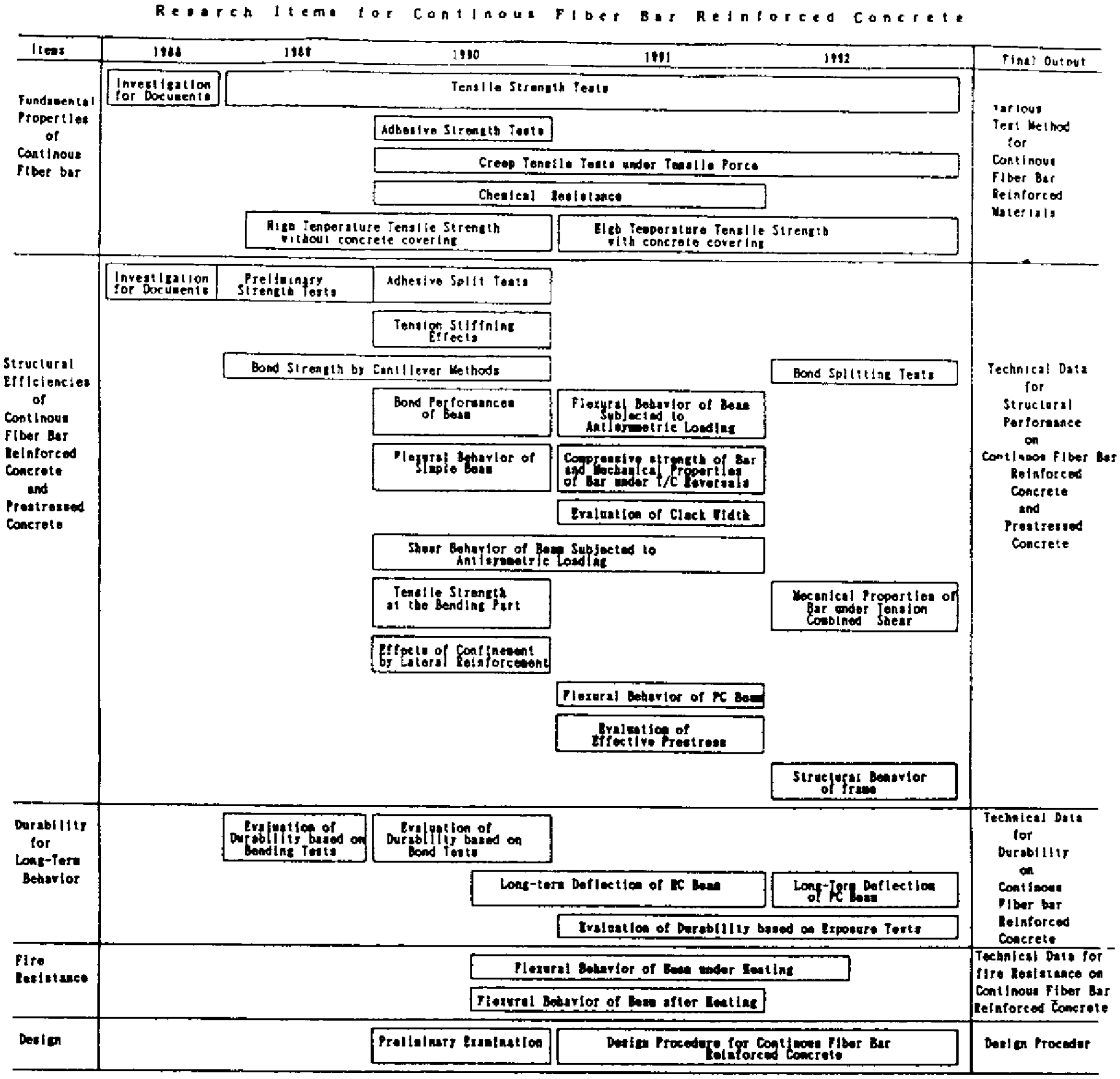


Table 2.3.1: Research items for CFB-RC

SHAKING TABLE TESTS
OF REINFORCED CONCRETE 1/15 SCALED MODEL STRUCTURES

Fumitoshi KUMAZAWA[1] and Tsuneo OKADA[2]

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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2) Director General and Professor, ditto.

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 $9.08kgf/cm^2$ 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 $150kgf/cm^2$ 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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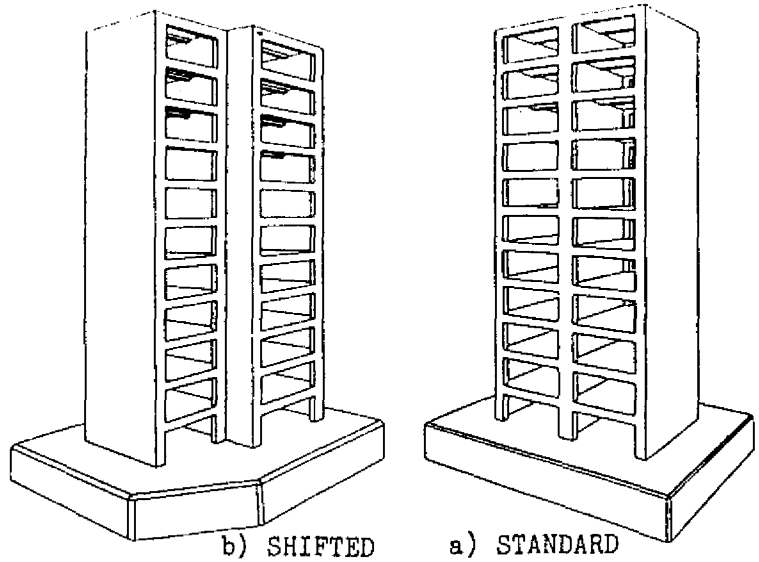


Fig. 1 General Views of Model Structures

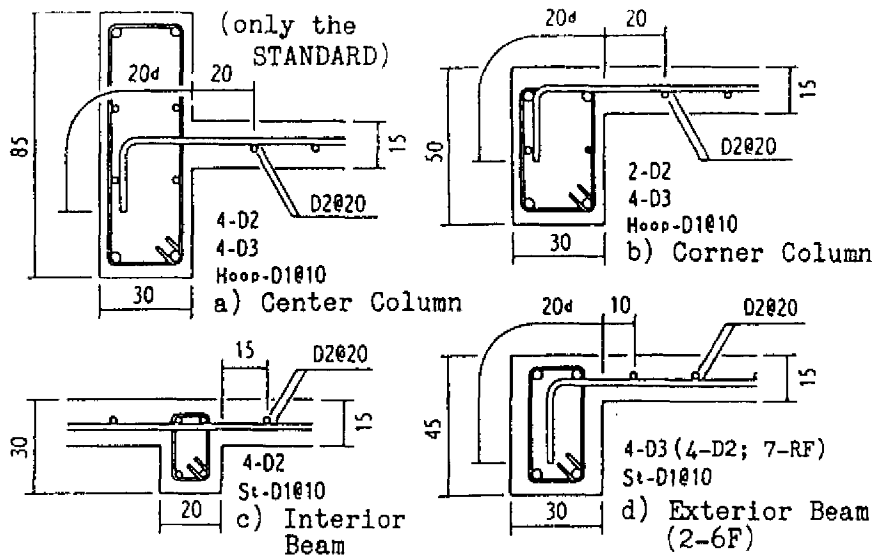


Fig. 3 Dimensions of Columns and Beams

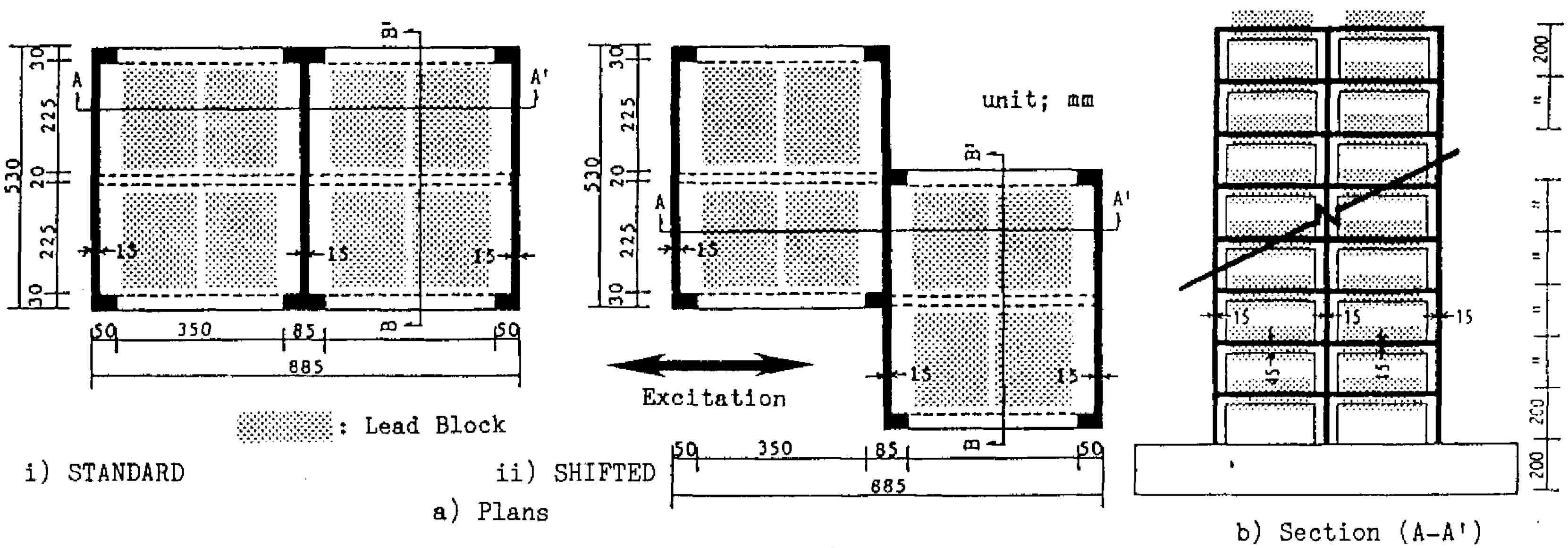
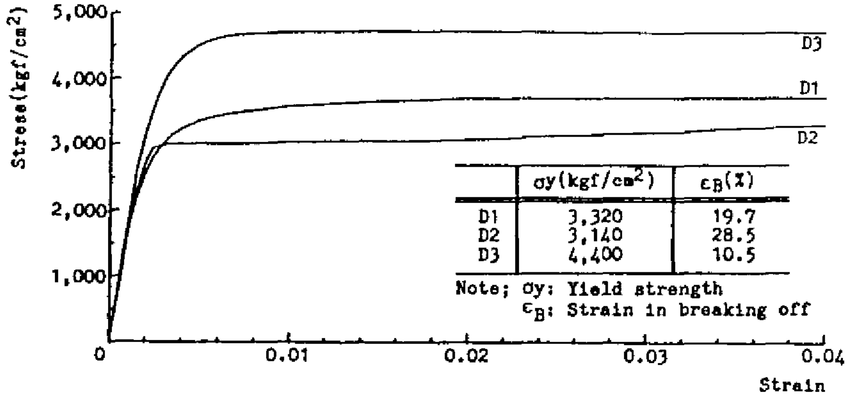


Fig. 2 Plans and Section of Model Structures



	σy(kgf/cm²)	εB(%)
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)

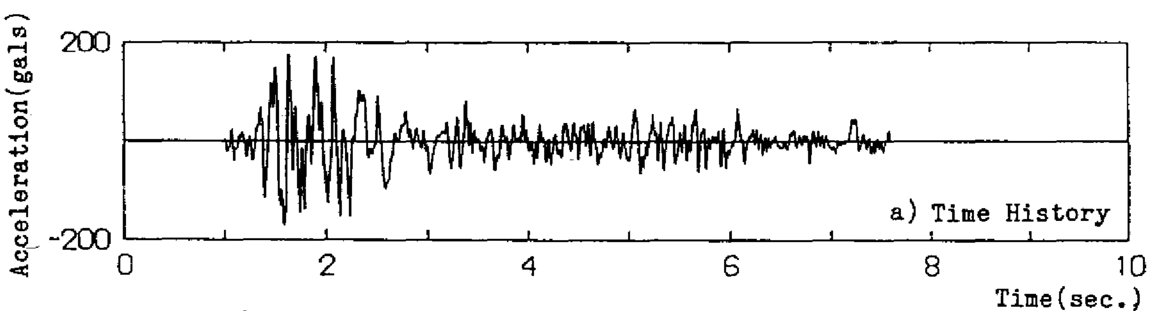
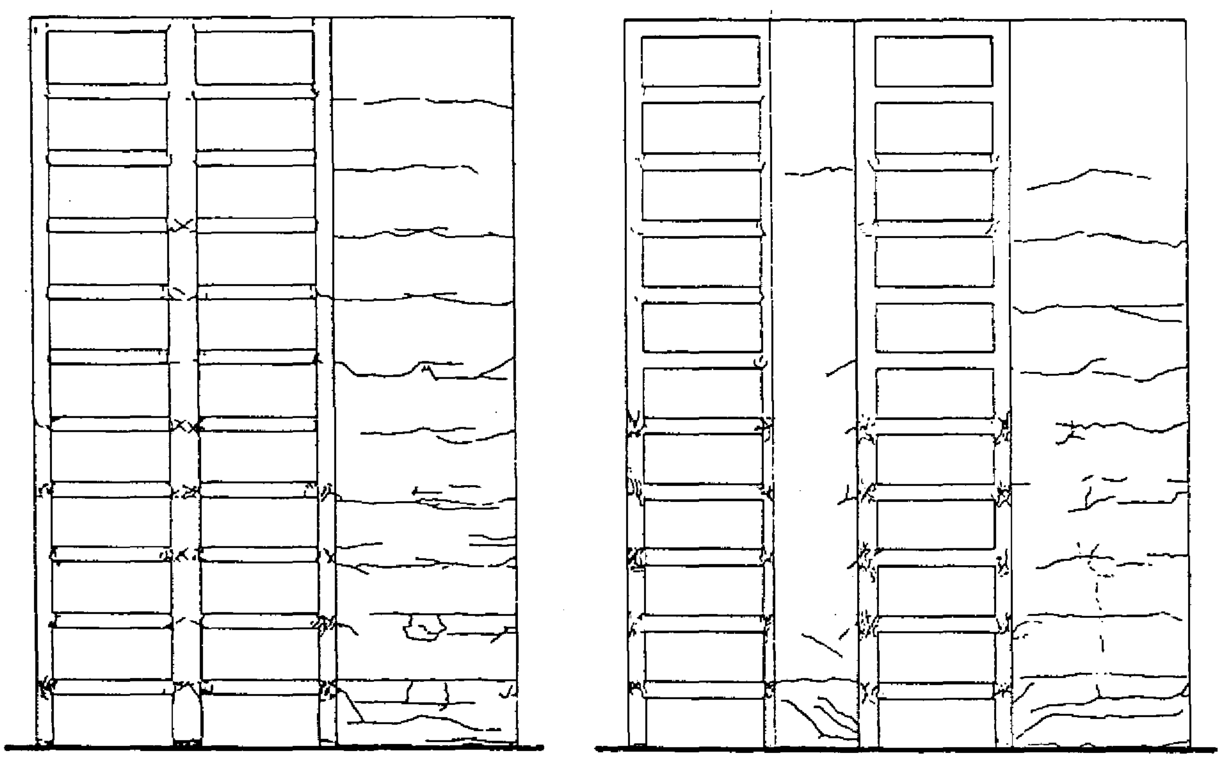
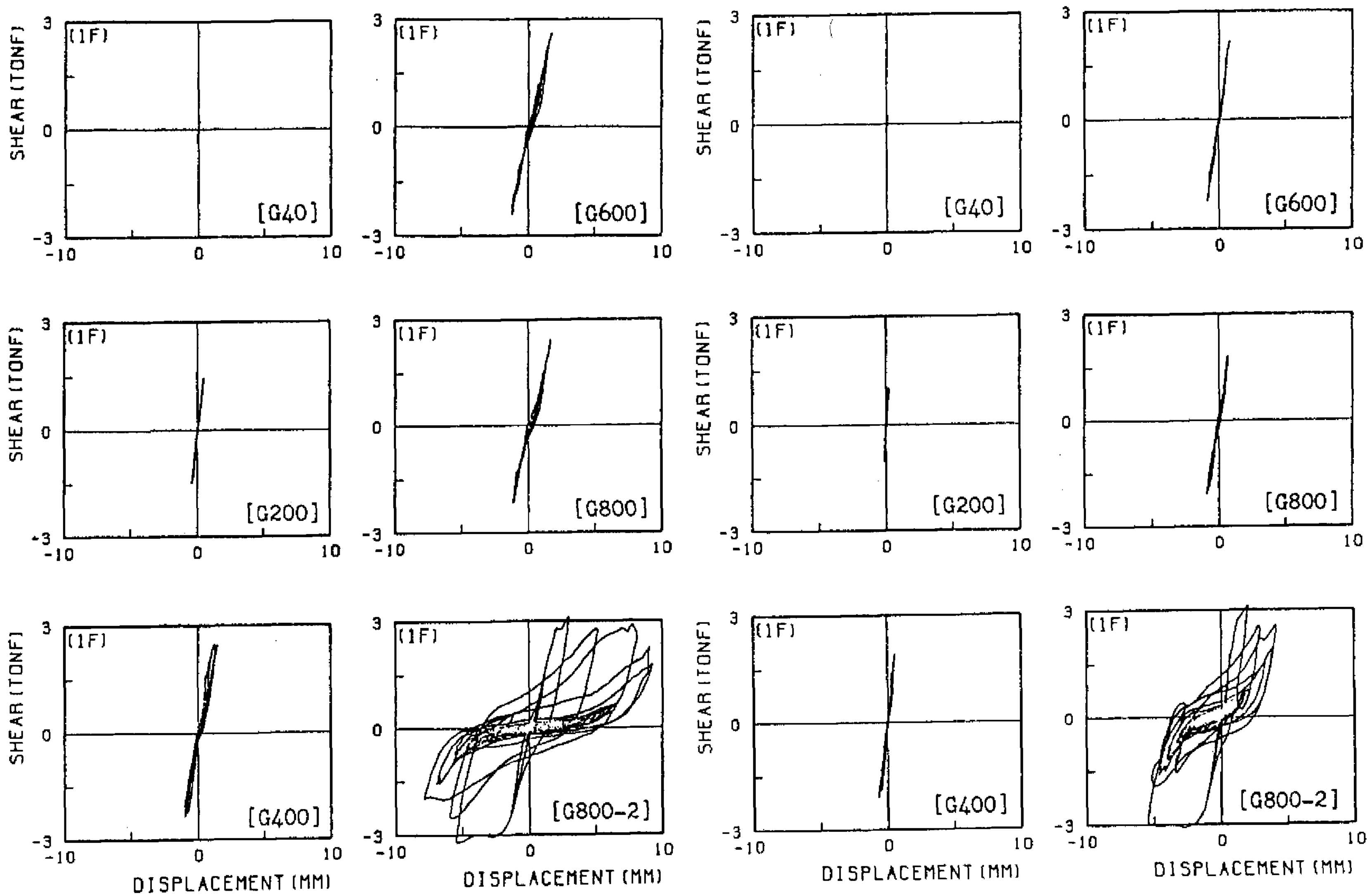


Fig. 5 Time History of Input Acceleration



a) STANDARD b) SHIFTED

Fig. 6 Final Crack Patterns



a) STANDARD

b) SHIFTED

Fig. 7 Hysteresis Loop (First Story)

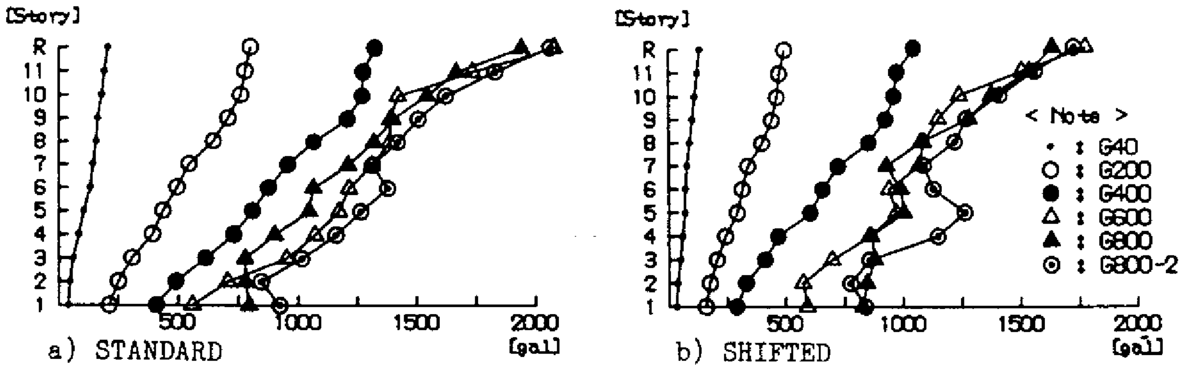


Fig. 8 Maximum Absolute Acceleration

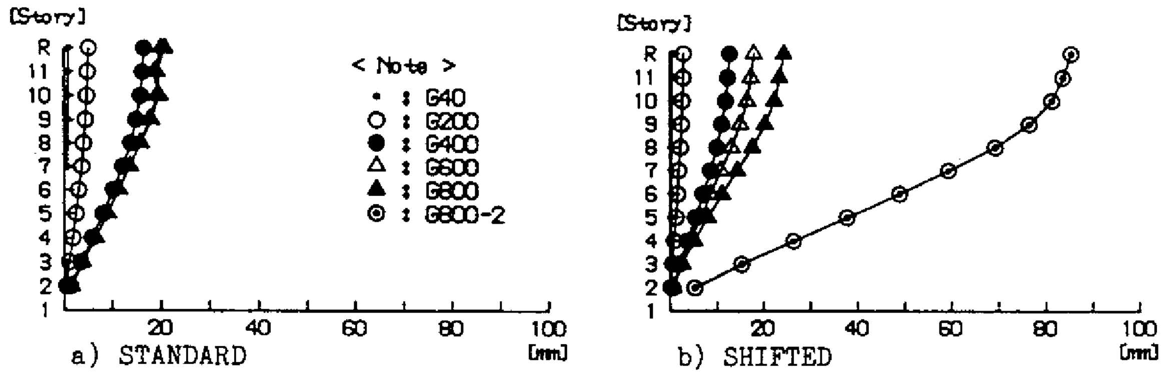


Fig. 9 Maximum Relative Displacement

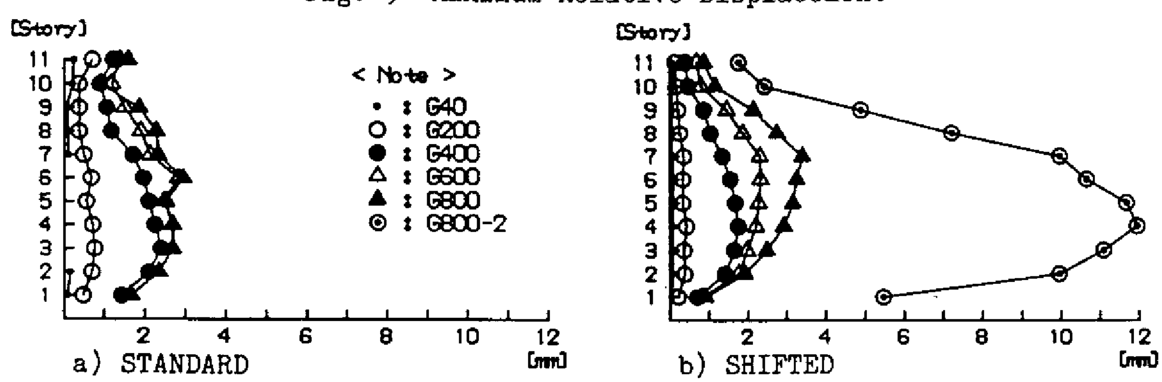


Fig. 10 Maximum Inter-Story Displacement

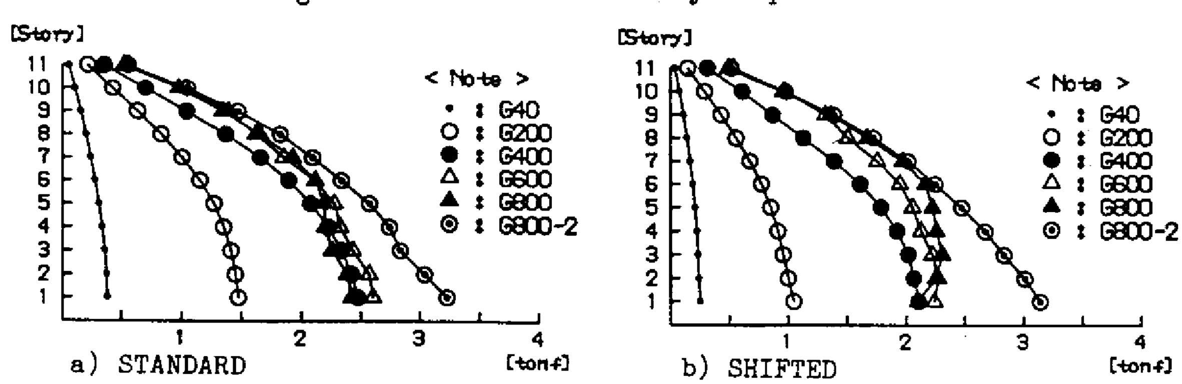
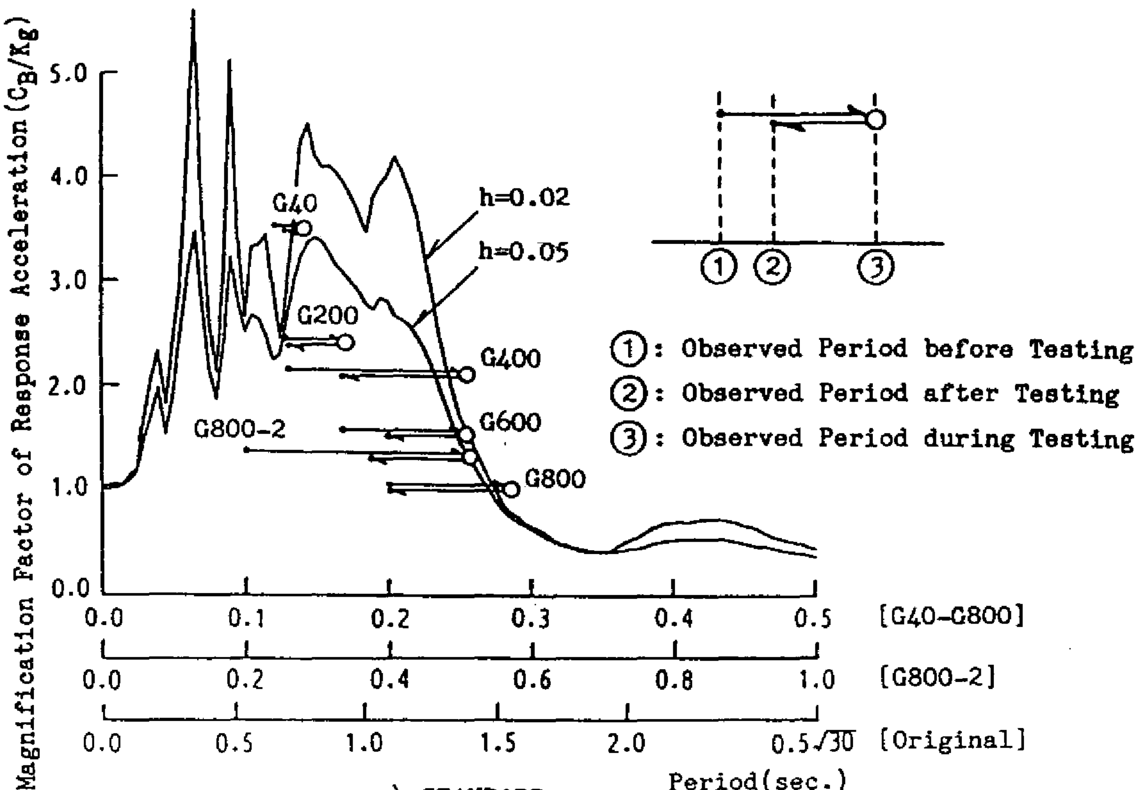
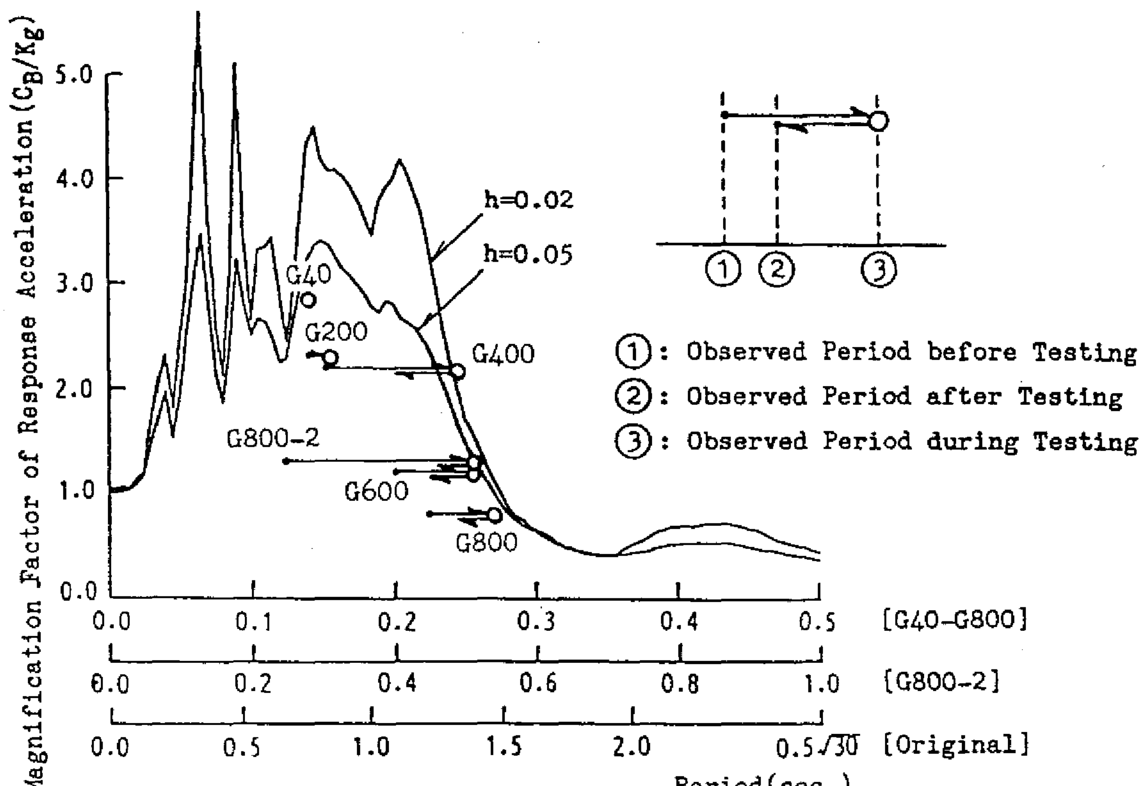


Fig. 11 Maximum Story Shear Force



a) STANDARD



b) SHIFTED

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

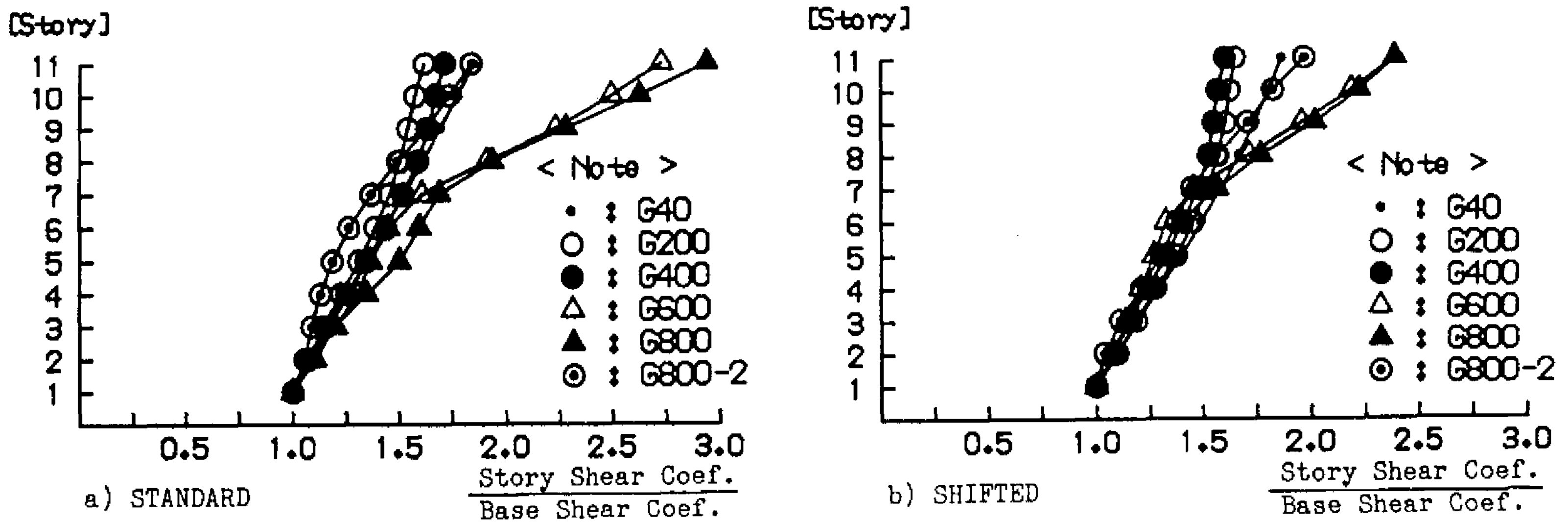


Fig. 13 Distribution of Story Shear Coefficients in Positive Direction
(each story shear is the maximum)

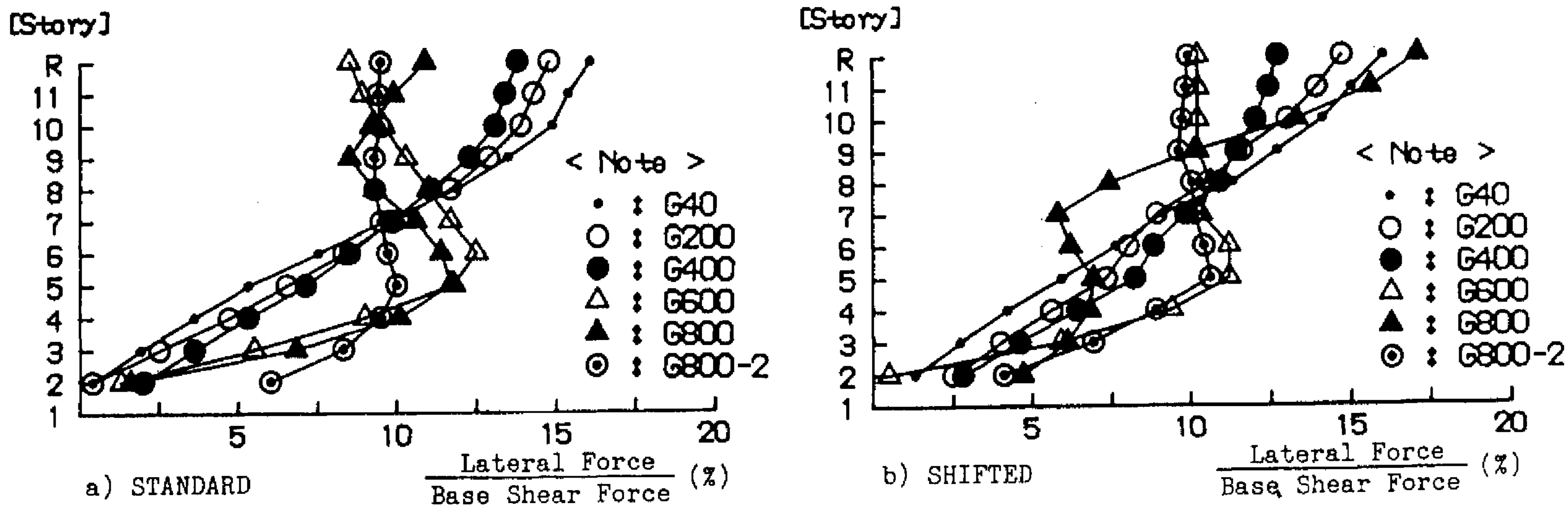


Fig. 14 Distribution of Lateral Force
(at the time when base shear is the maximum in positive direction)

Table 1 Law of Similarity

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