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# Recent development in design and construction of high-rise reinforced concrete buildings in Japan

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## ABSTRACT

Japan experienced a quick development of highrise reinforced concrete frame-type apartment building construction, about 30 stories high, in the last decade. Outline of this development is first introduced in terms of planning of buildings, materials, construction methods, earthquake resistant design and dynamic response analysis. This quick development was made possible by, among others, the available high strength concrete and steel. In an attempt to further promote development of new and advanced reinforced concrete building structures, a five-year national project was started in 1988 in Japan, promoted by the Building Research Institute, Ministry of Construction. Outline of this project is introduced in the second part of this paper. It aims at the development and use of concrete up to 120 MPa, and steel up to 1,200 MPa.

## INTRODUCTION

The Building Standard Law in Japan provides design seismic loadings and principal design procedures for buildings up to 60 m in height. Structural design of any building with the height in excess of 60 m is subjected to the review of the Structural Review Committee for Highrise Buildings of the Building Center of Japan, and subsequently a special permit by the Minister of Construction is issued.

As far as reinforced concrete (RC) buildings are concerned, the height had been limited to about 20 m in practice by means of administrative guidance. Any building taller than, say, seven stories had to be constructed by steel structure or composite steel and reinforced concrete (SRC) structure. This administrative guidance was a traditional one, stemming out from public distrust on the seismic resistance of concrete structures ever since 1923 Kanto Earthquake.

In the recent ten years or so, this trend has changed rapidly. There are currently various movements towards the higher RC construction. Among them,

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the most remarkable is the increase of highrise RC frame construction. Kajima Construction Co. broke out the movement. They completed the first highrise RC construction, an 18-story apartment building, in 1974, followed by another 25-story apartment building in 1980. These highrise buildings were realized after a long and extensive effort in research and development of the company. Other construction companies followed, and the number of concrete buildings increased together with the increase of total highrise building construction.

Figure 1 shows the amount of annual highrise construction in Japan, which is the number of annual reception by the Building Center for the review of the Committee for Highrise Buildings. The figure also shows number of SRC and RC buildings in each year. Total number in each year varies from less than 10 to more than 100, reflecting economic fall and rise. Concrete construction takes about 23 percent on the average, however more than half of it is taken up by RC construction in recent years.

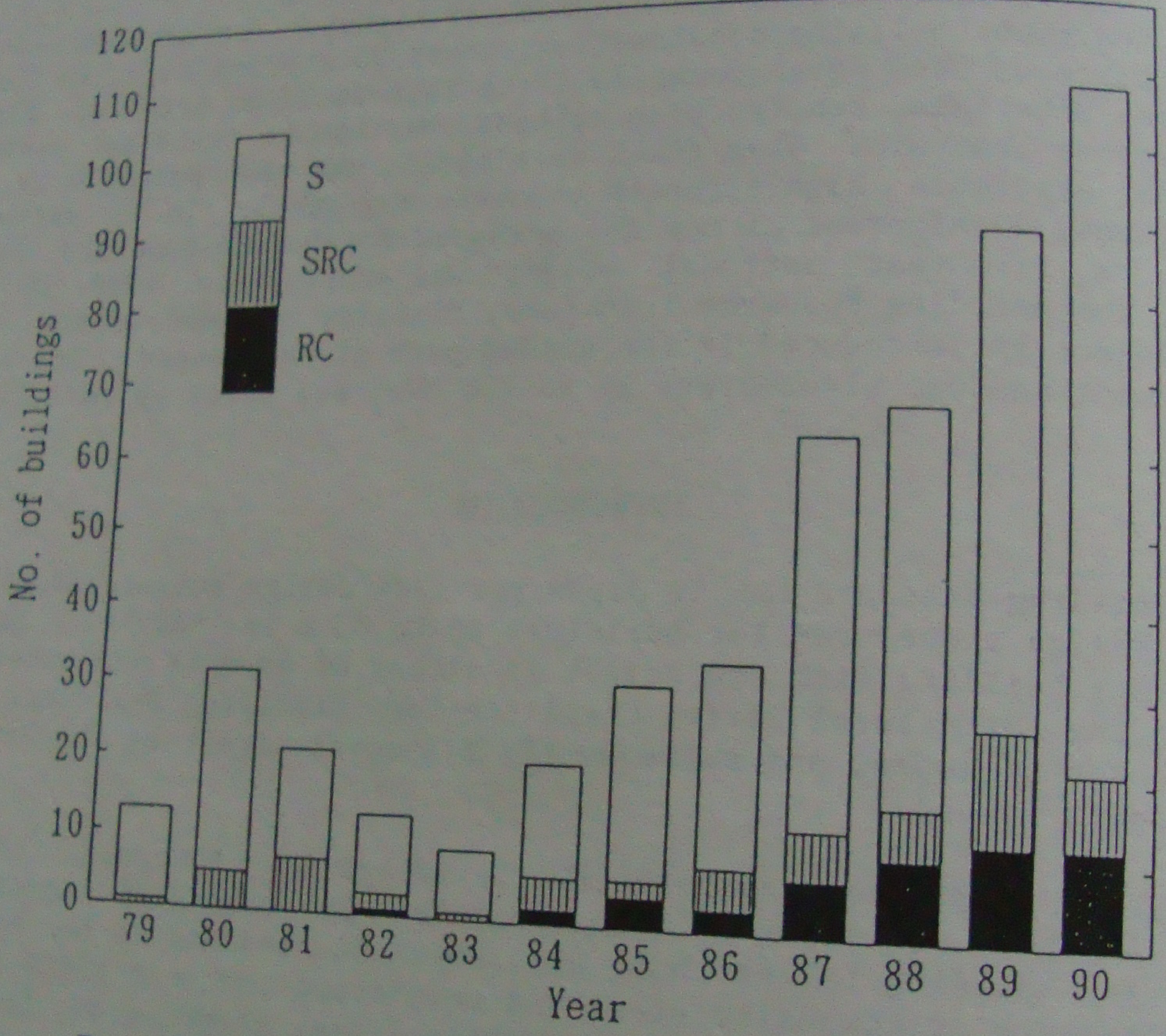


Figure 1. Annual highrise Construction in Japan

The quick development of highrise RC construction owes to many things, but availability of high strength materials was evidently the most fundamental factor. In an attempt to further promote development of new and advanced type of RC construction, the Ministry of Construction started in 1988 a national five year research project entitled "Development of Advanced Reinforced Concrete Buildings using High-strength Concrete and Reinforcement" (usually referred to as "New RC"). This is a very ambitious project, which will probably lead to the realization of highrise RC buildings up to 60 stories, and buildings with wider spans, allowing for use in greater variety.

This paper introduces, in the first half, the current state-of-the-art of structural design and construction of highrise RC buildings, and in the second half, the outline of the New RC national project of the Ministry of Construction.

## PLANNING, MATERIALS, AND CONSTRUCTION OF HIGHRISE RC

### Floor Plan and Elevation

Highrise RC construction, currently, is used exclusively for apartment houses, because of better habitability provided by concrete. Floor plan of these buildings is generally regular, and symmetric with respect to one or two axes. In almost all cases, all frames in both directions are designed as moment resisting frames. Span length is around 5 m, which is shorter than SRC or steel buildings. The small span is adopted in order to limit the axial load on a column, and thereby reduce the seismic force acting on a column.

The number of stories of highrise RC buildings ranges from 20 to 40 stories. The story height is about 3 m, which is also very small, permissible only for residential buildings. The story height is gradually reduced in upper stories corresponding to the reduction of beam depth, with the minimum clear structural height to the beam soffit of about 2.1 m. The frame elevation is generally quite regular, avoiding sudden change or discontinuity of stiffness in the vertical direction. Most buildings have one-story basement, and the foundation is supported, in most cases, by bearing piles of cast-in-place concrete.

### Framing Members

Column section is usually square, with the maximum dimension of about 90 cm at the base of buildings. Axial reinforcement ratio is about 2 to 3 %. To provide effective confinement to the core concrete, columns are provided with one or two of the following types of lateral reinforcement: rectangular or circular spirals, flush butt (FB) rings, closed sub-hoops, high strength deformed PC steel with 1,275 MPa yield stress (Urbon), or welded wire fabric.

To overcome large seismic overturning moment which produces dominating axial forces in exterior columns in lower stories, additional axial bars (core bars) are frequently located in the central portion of these column sections.

Beams are of rectangular sections with relatively large width. Four-leg stirrups are generally used. Urbon stirrups are often used to increase shear resistance.

### Materials

All highrise RC buildings use concrete with specified strength much higher than ordinary buildings. In the lowest portion either 36 or 42 MPa concrete is used. Strength is gradually reduced in upper stories. Lightweight concrete is not used.

The use of high strength and large size reinforcing bars is indispensable for highrise RC construction. Longitudinal bars up to 41 mm diameter (D41) with 390 MPa yield stress are used. Lateral reinforcement consists of either D16 bars of 295 MPa steel or high strength deformed PC bars with 1,275 MPa yield stress (Urbon).

### Use of Precast Concrete

There are divided opinions as to the advantage of applying precast concrete to highrise RC construction. On one hand, it decreases the amount of on-site labor, thereby decreasing construction time. On the other hand, it increases the number of job types. Since at least a part of concrete must be cast on the site, both labors associated with precast and cast-in-situ concrete must be combined. In fact a wide spectrum in the degree of use of precast concrete is seen in practice, as follows.

(1) All concrete cast on the site. It is an extreme case, but it is probably the most popular method at present for highrise RC construction.

(2) Partial application of precast concrete to floor slabs. When the building has exterior cantilever balconies, they may be most easily constructed as precast elements. For interior floor slabs, composite slabs are often used, consisting of precast panel used also as formwork and cast-in-situ upper course utilized as monolithic diaphragm for earthquake resistance.

(3) Partial application of precast concrete to beams. When adopting precast beams, bar arrangement at the intersection of beams must be organized completely with utmost care in the design stage. Splices of precast beams are located at the beam-column joints, or at the center of spans. Beams are precast only to mid-depth, leaving upper portion for cast-in-situ concrete. This enables the insertion of upper bars after precast members are placed in position, thereby easing the bar arrangement at the beam-column connections. Composite slabs are almost always adopted with precast beams.

(4) Precasting columns. Columns are usually the last member to apply precasting technique, but there are a few applications of precast columns in combination with the cast-in-situ floor system. NMB splice-sleeves or similar splices are used for longitudinal bars. A unique method was also developed to precast columns without longitudinal bars but with sheaths instead. Bare longitudinal bars are installed, concrete unit is lowered, and finally sheaths are grouted for integrity.

### Reinforcement Cage Fabrication

For all cast-in-situ columns and beams, reinforcement cages are prefabricated on the ground, for higher construction efficiency and accuracy. Columns are usually prefabricated for each story, and beams in two directions are prefabricated together, in the single or double cross-type shape, with splices at midspans. The anchorage at exterior beam ends are frequently provided by the so-called U-type anchorage, to avoid bar congestion in the beam-column joints.

## Re-bar Splices

Lap splices are not used at all in highrise RC construction. Currently following splices are used in practice:

(1) Gas butt welding with automated welders.
(2) Enclosed gas-shield arc welding with a parallel root gap.
(3) Mechanical splice with squeezed steel collars.
(4) Mechanical splice with infilled steel sleeves.
(5) Use of screw-type deformed bars and threaded couplers. Either lock nuts or grouting (resin or mortar) is used to tighten couplers. Combination of (4) and (5) is also available.

## Formwork and Concrete Casting

For the cast-in-situ concrete, a variety of system formworks are used. Particularly for a floor system, large system formworks are often adopted which combine formworks for two-way beams, floor slabs, and shoring.

Almost all highrise constructions adopt separate concrete casting for columns and floor systems, often called vertical-horizontal (VH) separate casting. Superplasticizer or high performance AE water reducer is used in the concrete mix, to get slump of about 18 cm. Column concrete is usually cast by buckets, while concrete pump is used to cast floor system.

# EARTHQUAKE RESISTANT DESIGN AND RESPONSE ANALYSIS

## Design Principles and Procedures

As the basic principle of earthquake resistant design, beam hinge mechanism, or strong column-weak beam mechanism, is always assumed. Column hinges are allowed at the bottom of the first story and the top of the uppermost story, and at the exterior columns in the tension side of the lower stories. The beam hinge mechanism is assumed in order to provide large energy dissipating capacity distributed all around the structure.

Earthquake resistant design criteria are summarized in Table 1. These criteria are similar to those for steel or SRC highrise buildings with the height in excess of 60 m. They are not explicitly stipulated in the Building Code. They have been traditionally used in the review by the Building Center of Japan, as a kind of current consensus among structural engineers.

The design procedure consists of two phases, which essentially correspond to the two levels in Table 1. The first phase design is to protect weak links of the structure, that is, yield hinge locations assumed in the mechanism, from forming yield hinges under the action of level 1 earthquake. For this purpose, design seismic loads are determined, usually referring to Building Code and preliminary earthquake response analysis, and members are proportioned to carry forces resulting from the design seismic loads.

The second phase design is to ensure the assumed mechanism to form under

Table 1. Earthquake resistant design criteria

| Seismic hazard level | Level 1 | Level 2 |
|---|---|---|
| Probability of recurrence | Once in lifetime | Possible maximum |
| Maximum ground velocity (in Tokyo) | 25 cm/s | 50 cm/s |
| Member forces | Concrete cracks but no steel yields | Steel yields but no building collapses |
| Story ductility factor | less than 1 | less than 2 |
| Member ductility factor | less than 1 | less than 4 |
| Story drift angle | less than 1/200 | less than 1/100 |

the action of level 2 earthquake. Collapse load associated with the mechanism formation is calculated, which is similar in definition as the ultimate load carrying capacity in the Building Standard Law. It is generally expected that this load level exceeds at least one and half times the design seismic loads. Structural members outside yield hinges are proportioned to forces associated with the mechanism formation enhanced by appropriate magnification factors.

A series of nonlinear time history earthquake response analysis are performed to confirm the design criteria in Table 1.

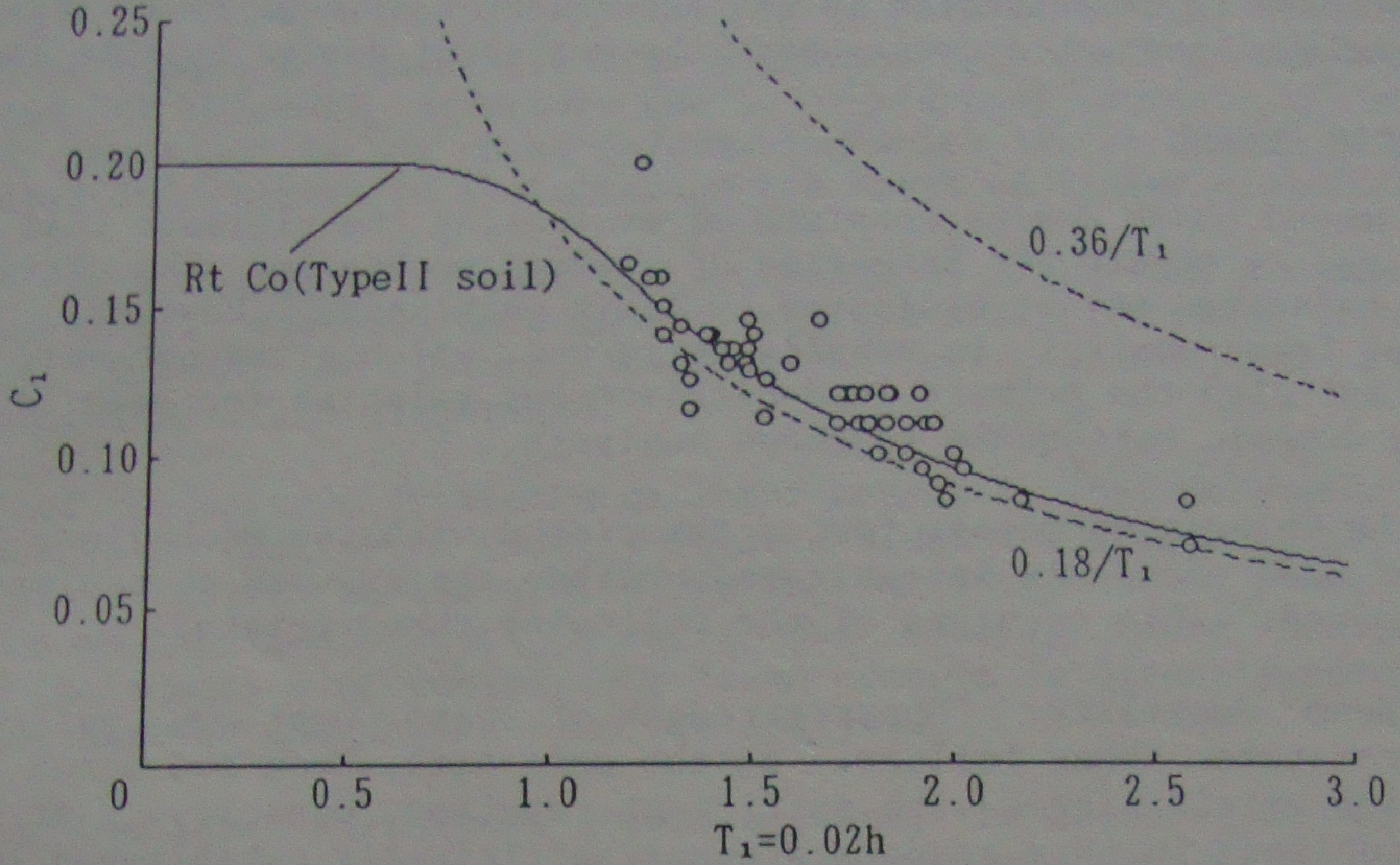
## Design Seismic Loading

Current Japanese Building Code provides design seismic forces for buildings up to 60 m in height only. However, considering that the range of height for recent highrise RC buildings exceeds the limit of 60 m only with a relatively small margin, it is a common practice for structural engineers to just extrapolate the provision of Building Code, and modify slightly, as needed, by a preliminary earthquake response analysis.

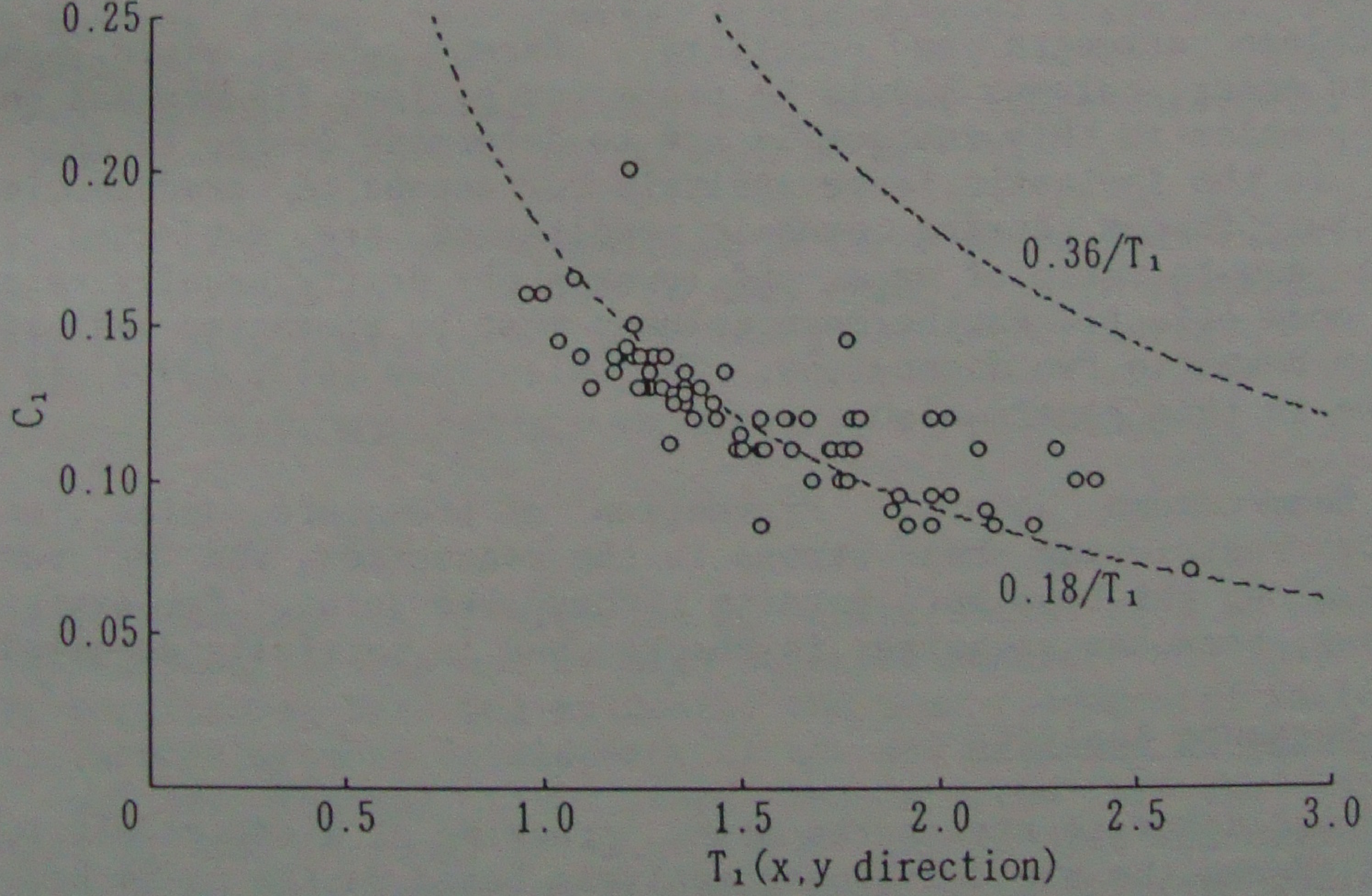
Figure 2(a) shows the design base shear coefficient of highrise RC buildings against the fundamental natural period from an equation stipulated in the code, i.e. $T_1 = 0.02\ h$, where h is building height in m. Most design falls around the code curve for second class (intermediate) soil. Figure 2(b) shows the design base shear coefficient against calculated elastic fundamental natural period. The range shown by dotted curves corresponds to most highrise construction in Japan, either steel or SRC construction. It seems highrise RC buildings have slightly lower base shear, as long as they are compared on the basis of elastic natural period. Probably it would be a more fair comparison to take natural period based on cracked sections, although it is not a common practice to do so in Japan.

## First Phase Design

The first phase design consists of structural analysis for design loads and proportioning of members. Structural analysis is carried out for permanent loading as well as design earthquake loading. Computer analysis is normally performed using displacement method, based on the uncracked section, considering flexural, shear and axial deformation of members, and rigid zones at member ends. When the structure is susceptible to torsional deformation,



(a) Fundamental period from Code equation



(b) Fundamental period from analysis

Figure 2. Relationship between base shear Coefficient and fundamental natural Period

three-dimensional frame analysis is carried out.

Moment redistribution is applied in some cases, although it is not widely used. The amount of moment redistribution is usually modest, and its appropriateness is demonstrated in the subsequent nonlinear frame analysis, so that no yield hinges would occur under the action of design seismic loads.

### Second Phase Design

The second phase design consists of evaluating the ultimate load carrying capacity, and to ensure the formation of assumed mechanism. The ultimate load carrying capacity may be evaluated by limit analysis. However, nonlinear incremental frame analysis is usually performed, which gives not only ultimate capacity but also the primary load-displacement relation for each story for use in the dynamic earthquake response analysis.

For the calculated member forces associated with the mechanism, ultimate strength of each member is investigated whether the assumed mechanism would be actually formed. This consists of the following three points:

(1) Beam ductility. Shear strength of beams must be sufficient to prevent premature shear failure. At the same time, beam end zones must be designed for yield hinges with sufficient rotation capacity. At present, design guidelines in this respect are not sufficiently established in Japan, but the recent publication of Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (AIJ, 1990) is gradually getting popularity among practical design.

(2) Column strength and ductility. Except where yield hinges are expected to occur, columns should be protected against flexure and shear. A practical problem in this respect is how to determine design forces. Forces determined in the inelastic frame analysis correspond to predetermined load profile, but forces during dynamic excitation are subjected to much fluctuation due to ratio of upper and lower story drift, usually referred to as higher mode effect. Furthermore columns must be protected against forces coming from beams in two dimensions. The Guidelines (AIJ, 1990) is serving for practice in this regard also.

(3) Beam-column joints. Prevention of premature joint failure is achieved by restricting shear stress in the connection, and by restricting bond stress along the beam bars passing through the joint. For exterior beam-column joints, beam bar anchorage is checked and is carefully detailed.

### Earthquake Response Analysis

Reinforced concrete structures start cracking at a relatively low level of loading. Hence the elastic linear analysis based on the uncracked section serves little in predicting actual behavior. As a simplified analytical model for nonlinear analysis, a lumped mass shear model is almost exclusively used in the time history dynamic response analysis for both level 1 and level 2 earthquake ground motions.

The restoring force characteristics of stories are defined by simplifying the load-displacement relation from incremental frame analysis into an equivalent trilinear relation. Degrading trilinear model or Takeda model is used for hysteresis rules under reversal.

In some cases, so-called flexural shear model is used, in which flexural deformation of overall structure due to overturning moment is separately evaluated and added to the shear deformation which is the frame deformation. The flexural deformation is evaluated on the basis of linear elasticity.

When the building is susceptible to torsional vibration, a dynamic quasi-three-dimensional model is used in the response analysis, which consists of many shear models, or flexural shear models, corresponding to each frame interconnected by rigid diaphragms.

One of the serious drawbacks of shear models is that it cannot predict member ductility factor. Usually it is evaluated indirectly by equating dynamic story drift to the static one in the incremental frame analysis. However, some engineers opt to carry out dynamic frame analysis where inelastic deformation of constituent frame members is directly accounted for in the time history earthquake response analysis.

As for the input earthquake ground motions, the Building Center of Japan recommends the use of waveforms in the following three categories (BCJ, 1986) for any highrise buildings:

(1) Well known "standard" motions, e.g. El Centro 1940 NS and Taft 1952 EW.
(2) Records taken at nearby stations, e.g. Tokyo 101 1956 NS for buildings in Tokyo.
(3) Records containing relatively long period components, e.g. Hachinohe 1968 NS and EW, Sendai TH030 1978 NS and EW.

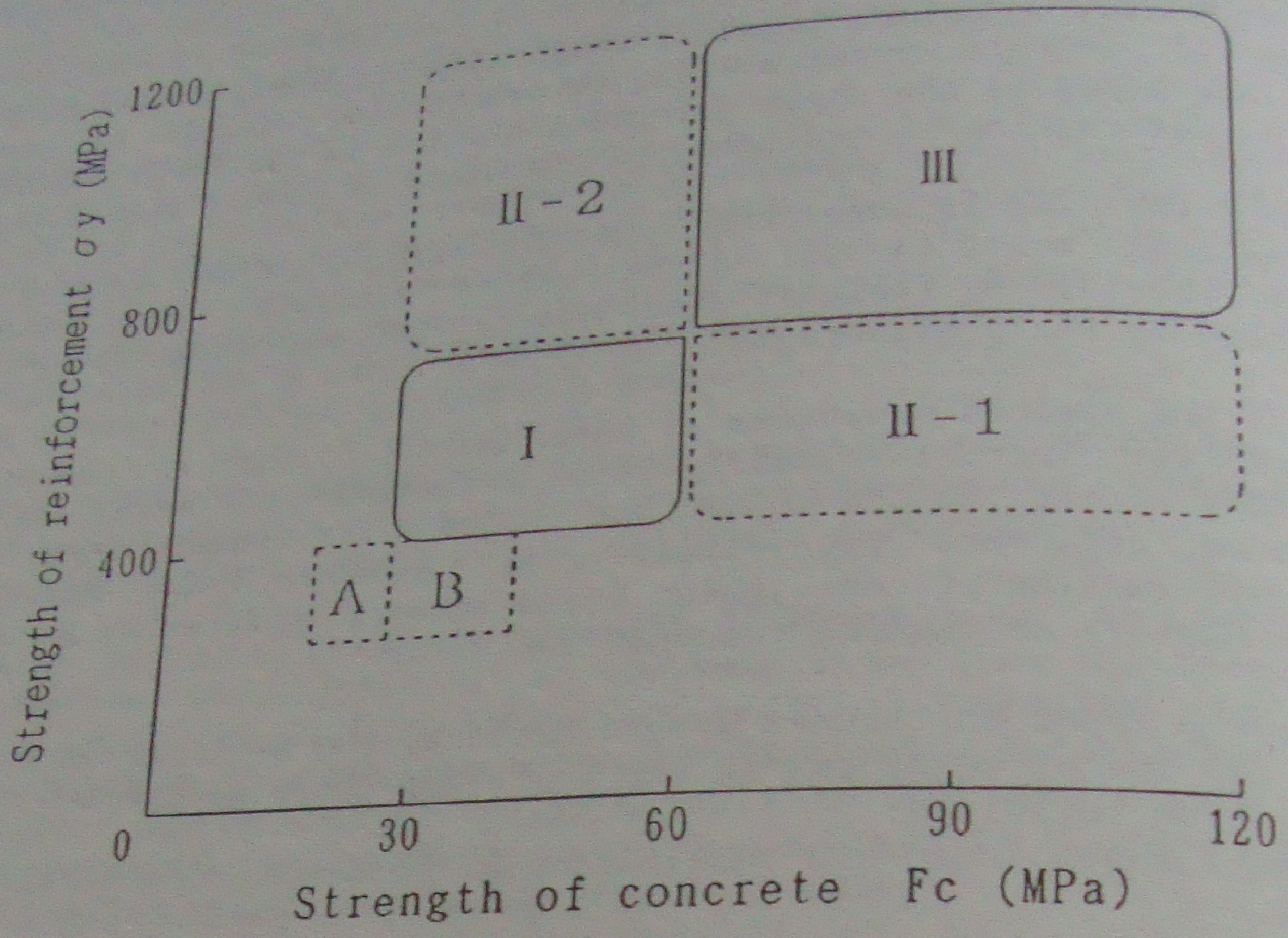
Earthquake motions are normalized in terms of maximum velocity to the levels as prescribed in Table 1. In many cases, design criteria for story drift angle in Table 1 are found to be the governing criteria.

## NATIONAL PROJECT ON ADVANCED RC BUILDINGS

### Range of Material Strength

The quick development of highrise RC construction owes to many things, but the development of the use of high strength concrete and high strength, large size reinforcing bars was evidently the most fundamental factor. In an attempt to further promote development of new and advanced RC construction, a national project lasting five years was started by the Ministry of Construction in 1988 (Aoyama, et al., 1990). The project was officially named as "The Project on Development of Advanced Reinforced Concrete Buildings using High-strength Concrete and Reinforcement", but it is usually referred to as "New RC Project".

The range of material strength set out as the target of this project is shown in Fig. 3. The vertical axis shows the yield strength of steel bars,



Zone:Type of RC buildings & materials
A:Low-rise buildings
B:High-rise buildings
I:High-strength concrete & reinforcement
II-1:Ultra high-strength concrete & high-strength reinforcement
II-2:High-strength concrete & ultra high-strength reinforcement
III:Ultra high-strength concrete & reinforcement

Figure 3. Strength of Materials and Fields of Research and Development

and the horizontal axis shows the compressive strength of concrete. Small zones A and B in the figure correspond to the ranges for ordinary RC buildings and highrise RC buildings, respectively. As seen in the figure the currently used materials for highrise RC buildings occupy only small zones.

In contrast, the ranges of strength for concrete and steel for this project are much larger. Concrete from 30 to 120 MPa and steel from 400 to 1,200 MPa are included. Comparing the zones for these ranges of materials to zones A and B, it is obviously unrealistic to assume that structural behavior of New RC structures can be understood simply by extrapolating the knowledge of ordinary RC structures. The area in Fig. 3 for the New RC is further divided into four zones, namely zones I, II-1, II-2, and III. Structures in these zones will be studied and developed by somewhat different tactics.

Experimental approach is indispensable, but in general, theoretical examination of experimental data will be emphasized in this project. Current technical knowledge on RC structures will also be re-examined.

In some zones in Fig. 3, particularly in zone III, basic problems will have to be re-examined, and hence the project may not yield much practical results. Most practical results are expected in zones I and II-1, because these zones are relatively close to the boundary of the current technology, and simple extrapolation will be effective at least partially.

## Objectives of Research and Development and Final Expected Results

The objectives of research and development and the corresponding final results expected in the project are summarized in Table 2. Results will be partly available to refine the current RC technology. In the table under the third objective, the word "guidelines" for structural design and construction do not mean a type of guidelines that will give full details of technology, but it will give only basic principles for design and construction practice. Such a soft type of guidelines is preferred at this stage of the game, as definite and detailed specification-type guidelines often tend to impede development of relevant technology.

## Research Organization

The Building Research Institute of the Ministry of Construction is in charge of conducting the project. Research committees were set up in an organization called Japan Institute for Construction Engineering, to organize people from universities, Housing and Urban Development Corporation, makers of cement, admixtures, and steel, and construction companies.

Technical Coordinating Committee (TCC) is the central body for coordinating the entire project. Research Promoting Committee acts as a mediator between the TCC and participating construction companies which are sponsors of the project; i.e., the entire New RC project is financed by the combination of national fund from the Ministry of Construction and contributions from these participating companies. Technical Advisory Board consists of technical authorities of all related engineering fields and acts just as the name implies. The above-mentioned three committees are chaired by the writer.

Under the Technical Coordination Committee, five technical committees were installed. They are in charge of making research programs in detail, implementing research works, and integrating research results in five particular fields. The names and chairmen of these committees are: Concrete Committee, chaired by Prof. F. Tomosawa, University of Tokyo; Reinforcement Committee, chaired by Prof. S. Morita, Kyoto University; Structural Element Committee, chaired by Prof. S. Otani, University of Tokyo; Structural Design Committee, chaired by Prof. T. Okada, University of Tokyo; and Construction and Manufacturing Committee, to start in 1991 and chaired by Prof. K. Kamimura, Utsunomiya University. Technical committees organize working groups as needed.

Table 2. Objectives of research and development and final expected results

| Objectives | Final expected results<br>For New RC | <br>For current RC |
|---|---|---|
| 1) Development of high-strength and high-quality materials | Methods for mix proportion method and quality control of concrete (Zone I)<br>Methods for production and arrangement of reinforcements (Zone I)<br>Guidelines for developing materials for Zones II and III | Revision of design method for mix proportion and quality control method for concrete<br>Revision of reinforcement quality standards<br>Revision of upper limits of reinforcement strength |
| 2) Evaluation of properties of members and frames | Methods of analysis | Revision of current methods of analysis |
| 3) Development of design and construction guidelines | Structural design guidelines (Zone I)<br>Construction guidelines (Zone I)<br>Draft guidelines for structural design and construction (Zones II, III) | Revision of structural design methods<br>Revision of construction standards |
| 4) Feasibility study on RC buildings in Zone II-1 | New type high-rise buildings | |
| 5) Feasibility study on RC buildings in Zone III | New images of RC buildings | |

## Items for Research and Development

Following research items were assigned to each technical committees at the onset of the project.

For the Concrete Committee:
(1) Development of materials necessary for making high-strength and super high-strength concrete. Quality standards of the materials.
(2) Physical properties of high-strength and super high-strength concrete.
(3) Mix proportion design, casting and curing works and quality control.

For the Reinforcement Committee:
(1) Development of high-strength and super high-strength steel bars. Mechanical properties of steel bars.
(2) Mechanical properties of confined concrete.
(3) Constitutive equations for RC elements and application of finite element method.

(4) Bond between concrete and steel bars. Anchorage and arrangement of steel bars.

For the Structural Element Committee:
(1) Mechanical properties of beams 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.

For the Structural Design Committee:
(1) Methods for modeling and analysis of structural frames in each zone.
(2) Practically feasible types of structures.
(3) Design seismic loads and requirements for structural performance.
(4) Design methodology.

For the Construction and Manufacturing Committee, research items are to be established.

## Major Research Topics in the Project

One of the most fundamental and important topics is the ductility of high-strength reinforced concrete. High-strength concrete has been used mainly as countermeasure to high axial stress in the lower story columns of highrise buildings. Maximum number of stories of highrise RC buildings is almost completely determined in practice by the concrete strength, such as 25 stories for 36 MPa, or 30 stories for 42 MPa. From the viewpoint of axial column stress, higher concrete strength is the most vital element in order to realize higher buildings.

However, it has been pointed out that the falling branch of a stress-strain curve of high-strength concrete is more pronounced, and further it is more difficult to improve the falling branch by lateral confinement. It is necessary to develop the most effective method of lateral confinement, and at the same time, to recognize the limitation of improved ductility by means of lateral confinement.

Another problem related to the ductility of high-strength reinforced concrete is the property of high-strength steel. At present super high-strength steel bars of 1,300 MPa specified yield strength are used very frequently in practice for lateral shear reinforcement, but they have never been used as longitudinal reinforcement. In order for high-strength steel bars to be used as longitudinal reinforcement, their quality in terms of stress-strain relationship should be improved. The most important practical problem is how much improvement can be specified and realized by steel manufacturers. In the long run, the ductility of New RC members will have to be lower than ordinary RC members, and hence it will be necessary to develop design philosophy which depends more on strength, but less on ductility, of constituent materials.

Bond between concrete and reinforcing bars is another basic issue in New RC. Demand on bond increases in proportion to the increase of yield strength of steel bars, but the bond capacity does not increase in proportion to the increase of concrete strength. Thus the bond becomes one of the critical problems of New RC structures. In particular, resistance against bond splitting failure is an important subject for bar development.

The use of high strength materials usually results in a reduction of cross section of members, thus reduction of stiffness of members and structures. Among structural design criteria listed in Table 1, that for the drift angle governs in most highrise RC buildings even at present, and it is expected to be more so for New RC buildings if the same design criteria as in Table 1 are maintained. Since the design criterion for drift was established not on any rational basis, it is not easy to challenge for its revision by a rational discussion. But the author believes that we will have to start discussing on it seriously, sooner or later.

## CONCLUSION

In this paper the author first reviewed the present state-of-the-art of the design and construction of highrise RC buildings in Japan, a highly seismic country. The quick development of highrise RC construction owes to many factors, but the availability of high strength materials was the most fundamental factor that enabled the development. In the second part of the paper, the author outlined a Japanese national research project entitled "Development of Advanced RC Buildings using High-strength Concrete and Reinforcement (New RC)". It is a project to try to develop high-strength and super high-strength materials for RC structures, and to provide necessary design aids for highrise and other new RC structures. It is expected that by 1993 our knowledge on the reinforced concrete will be substantially enlarged as illustrated in Fig. 3.

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