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DEVELOPMENT OF NEW REINFORCED CONCRETE STRUCTURES

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ABSTRACT

Five-year Japanese national research project on the development of advanced reinforced concrete building structures with high-strength and high-quality materials, commonly called as "New RC Project", was completed in 1993. The material strength for concrete ranges from 30 to120 MPa and that for steel bars does from 400 to 1200 MPa. A method to evaluate structural performance of New RC elements and structures was developed, primarily through theoretical studies, which was subsequently investigated experimentally. New RC Structural Design Guidelines was developed mainly for earthquake resistance. It is based on the dynamic response analysis with a clear definition of required safety. A major achievement in the construction engineering was the development of New RC Standard Specification. Concrete strength in the New RC Standard Specification is based on the strength development of concrete in the structure and cylinders under corresponding curing condition, in order to produce the specified strength in the structure with the maximum reliability. Application feasibility studies were made for buildings utilizing ultra high-strength materials. They include studies on a high-rise flat plate building, megastructures, etc.

KEYWORDS

High-strength concrete; high-strength steel bars; seismic design; construction standard; high-rise building.

OUTLINE OF THE PROJECT

Outputs of the Project

The material strength for concrete ranges from 30 to120 MPa and that for steel bars does from 400 to 1200 MPa. The major fruits of the project were: 1) development of high-strength and high-quality materials, 2) evaluation of structural properties of elements, members and frames, 3) design and construction guidelines, and 4) feasibility studies on RC buildings utilizing ultra high-strength materials.

Organization for the Project

The Building Research Institute of the Ministry of Construction of Japanese Government was in charge of conducting the entire 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.

STRUCTURAL DESIGN OF NEW RC

Features of Structural Design

New RC Structural Design presents a structural design method for high-rise buildings, but not in a specification style on detailed procedures of structural member proportioning. Rather it aims at basic principles to establish required performance of a building and method to evaluate behavior of a building to be designed. The design of a structure involves various kinds of external loading. However Japanese RC buildings are usually governed by seismic design considerations. For this reason the proposed guidelines deal mainly with the seismic design. Some specific feature of the guidelines are introduced below.

(1) Earthquake Resistant Design in Two Stages
The guidelines introduce seismic safety investigation in two stages, namely, one for Level I earthquake motion and another for level II earthquake motion. For level I earthquake motion which would happen once in the lifetime of the building, serviceability should be maintained. For level II earthquake motion which may be the possible maximum motion to the structure, safety must be maintained, by maintaining suitable collapse mechanism and lateral load-carrying capacity.

(2) Proposal of Design Earthquake Motion
The guidelines include proposal of earthquake motion that should be used in the design of New RC structures. Proposal for level II motion was made in the form of response spectrum as shown in Figure 1. This motion was assumed at the exposed engineering bedrock on which the building is to be supported. This proposal was developed from studies of earthquake motion prediction assuming an earthquake of 7. 9 magnitude, similar to the Great Kanto Earthquake of 1923. The design earthquake motion for level I earthquake is assumed to be 40 percent of the above level II motion . This was derived from the study concerning the return periods of two levels of earthquake motion.

(3) Bidirectional and Vertical Earthquake Motions
The guidelines require that three dimensional earthquake motions are to be considered. Practical application of this consideration is also given.

(4) Clarification of Required Safety
The safety of a structure under level I and II earthquake motions is specified in the levels of material or members. In the static analysis for level II motions, the overall structural safety is to be investigated.

(5)Structural Design Equations
In the New RC project, force-displacement relationship was supposed to be idealized into a tri linear relationship. The terminal points for three lines are craking of concrete, yielding of steel bars, and deformation capacity. The equations to estimate forces and displacements at these points were presented and their accuracy was examined in the project.

(6) Variation of Material Strength and Error in Strength Evaluation

Concept of dependable strength and upper bound strength was introduced considering variation of material strength and accuracy of strength evaluation equations. This may simplify the probability estimation of assumed performance.

(7) Structural Design of Foundation and Soil-Structure Interaction

Soil-structure interaction and superstructure-substructure interaction are to be considered in the design of foundation and evaluation of earthquake input to the superstructure. These features are quite general in nature, thus the basic concept of the guidelines is believed to be applicable not only to New RC structures but also to other concrete or steel structures. It is quite natural, of course, to assume that much works would have to be done before such application becomes practical.

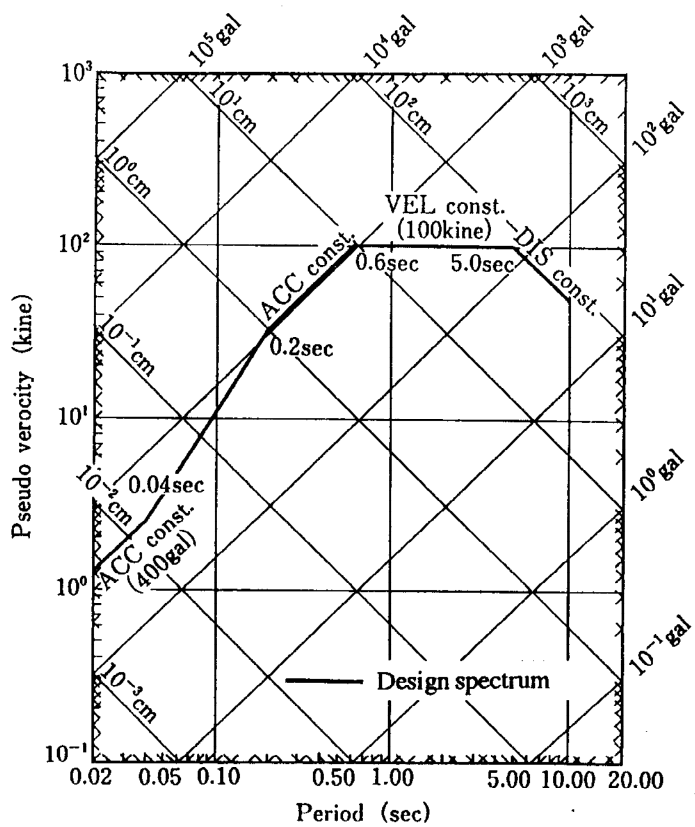

Fig. 1. Design response spectrum on exposed engineering foundation.

Design Criteria

The design criteria are expressed as the combination of design earthquake intensity and design drift limitations, as shown in Table 1. A structure must satisfy serviceability performance criteria for level I earthquake motion. The serviceability is examined by nonlinear earthquake response analysis. The serviceability criteria are : (a) story drift should be less than the serviceability drift limit, (b) no structural members should, in principle, develop yielding, and (c) nonstructural elements should not be damaged. A structure must satisfy safety performance criteria for level II earthquake motions. Safety criteria were prepared for the nonlinear earthquake response analysis and for the nonlinear static analysis separately. The static analysis is required to compensate the uncertainty in the characteristics of earthquake motions, the reliability of analytical methods, and limited number of earthquake motions used in the response analysis. The response analysis is required to take into account the dynamic effect, that is, the effect of force distribution under earthquake excitation different from the assumed static force distribution.

Table 1. Design criteria for earthquake motion.

Intensity of motion	Drift	Member
Level I	Story drift is not larger than serviceability drift limit.	No structural member should, in principle, develop yielding.
Level II	Building drift is not larger than response drift limit. Story drift is less than 1.5 time of response drift limit.	Locations where yielding is permitted must maintain its full resistance. Locations where yielding is not permitted should not develop yielding. Brittle failure should not take place in any member.

note:

(1) Serviceability and response limit drifts may be selected by a structural designer, but should not exceed 1/200 and 1/120, respectively.

(2) Building drift is defined a s the lateral deflection at the two-third height of a building divided by the height at the level.

CONSTRUCTION OF NEW RC

General Provisions

Various series of laboratory tests and full size construction test were carried out. A new construction standard specification for the construction using New RC materials were developed.

Reinforcement

The reinforcement shall conform to quality standard related to yielding plateau, fracture strain, yield ratio, etc., defined in the project (Morita and Shiohara, 1996). In the fabrication of reinforcement, shape of standard hook and bend radius shall be determined by the designer. Steel bars shall be bent, in principle, in the air temperature. The allowance of fabrication is determined from the accuracy of splices and accuracy required in the cage fabrication which is recommended throughout the standard. As to the quality control, necessary items for inspection, time and frequency of inspection, and acceptance criteria are shown in the standard.

Formwork

Some particular features of the New RC standard are the requirement for formwork as a part of permanent structure, such as precast composite slab elements, higher lateral pressure on formwork from fresh concrete of low yield stress, and longer period before form removal.

Concrete

(1) General

Concrete with specified strength between 36 and 60 MPa is dealt with in full detail. Concrete exceeding 60 MPa should be treated after preliminary testing.

(2) Concrete Quality

Slump of concrete between 36 and 50 MPa shall be not more than 21 cm, and for concrete between 50 and 60 MPa slump not more than 23 cm or slump flow not more than 50 cm. If segregation resistance has been confirmed a larger slump flow, but not more than 65 cm, may be specified. Compressive strength of structural concrete shall be defined by the 91-day strength of concrete core bored from the structure, and the strength control shall be made by testing concrete cylinders under conditions that would reasonably represent the condition of structural concrete. Strength control criteria shall be based on 5 percent failure threshold. Figure 2 illustrates the concept of strength build-up of concrete under various curing conditions. Young's modulus of concrete is an important parameter to describe the seismic performance of New RC structures. The durability requirement for high-strength concrete is shown in several items such as total chloride content, neutralization, drying shrinkage or freeze-thaw resistance. Fire resistance of high-strength concrete is similar to that of normal strength concrete provided that concrete is sufficiently dry. The cover to reinforcement is taken same as for normal strength concrete.

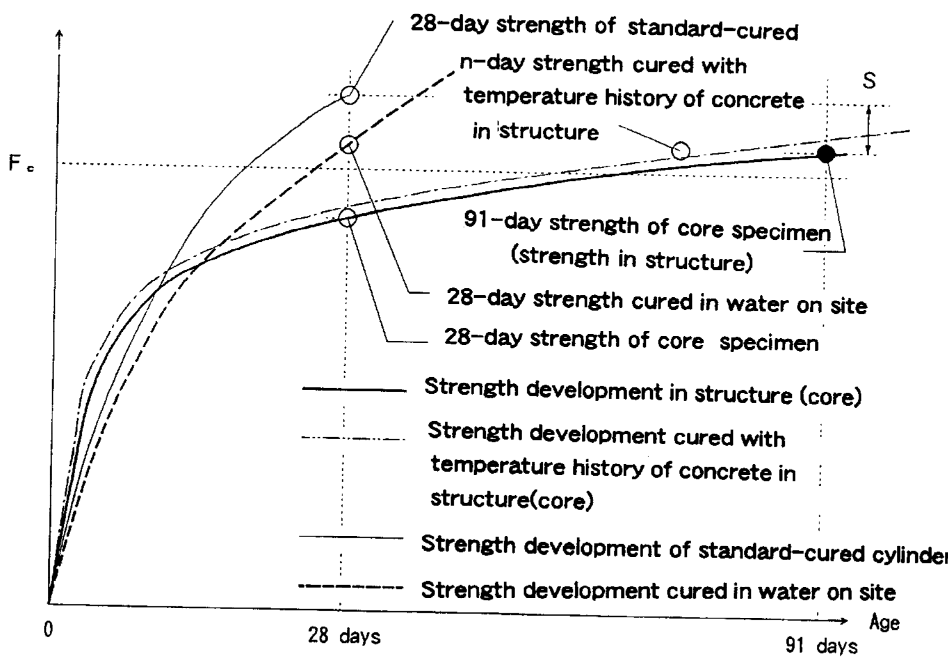

Fig. 2. Concept of concrete strength in structure.

(3) Material

Cement quality is to be tested by compression test of mortar specimen at 30 percent water cement ratio and age of 28 days. For coarse and fine aggregate, it is necessary to produce not only required strength but also required Young's modulus. As to alkali-aggregate reaction, material judged as harmless by test shall be used. Chemical admixture to be used in high-strength concrete is the high-performance AE water reducer, and its quality is specified in the standard. Mineral admixture such as silica fume or blast furnace slag fine powder need not be used for high-strength concrete up to 60 MPa. When these and other mineral admixtures are used for high-strength concrete in excess of 60 MPa, quality standards for each material included in the construction standard may be referred to.

(4) Mix

The target strength for proportioning high-strength concrete is represented by the standard-cured cylinder tests at control age between 28 and 91 days, and is expressed by the following equations.

$$F_n \geqq F_c + S_o + K\sigma_o \qquad (1)$$

$$F_n \geqq 0.9(F_c + S_o) + 3\sigma_o \qquad (2)$$

where, F_n= target strength at control age of n days,

F_c= specified design strength,

S_o= strength difference at age of n days between standard-cured cylinders and structural concrete cylinders,

σ_o= standard deviation of strength of structural concrete control cylinders, to be taken as one tenth of (F_c+S_o) if tests are not performed, and

K= a coefficient corresponding to the permissible failure threshold of structural concrete control cylinders.

The unit binder content of more than 350 kg/m^3 is recommended. The unit water content of less than 175 kg/m^3 is recommended. The entrained air may be between 2 and 4.5 percent and the largest value of 4.5 percent is taken when freezing is expected.

(5) Manufacture of Concrete

High-strength concrete requires longer mixing time due to its high viscosity. Proper mixing time may be determined from the electric current measurement of the concrete mixer. Inspection at the plant must be made by the general contractor as needed. Inspection at the site must follow the details shown in the standard.

(6) Placement and Surface Finishing

Concrete transportation is made by bucket or concrete pump. Construction joint are placed near the midspan of girders and slabs, and girder bottom and slab top of columns and walls. Metal wraths, wood sticks, or air fences may be used for horizontal construction joints. Surface finishing of high-strength concrete is more difficult than normal strength concrete due to its high viscosity. Spraying water after surface finishing is effective to prevent excessive drying and cracking.

(7) Curing

Moist curing by spraying, curing mats or membrane curant should last for at least 2 days (until 3 days of age) for 50 to 60 MPa concrete, 3 days (until 4 days of age) for 40 to 50 MPa, 4 days (until 5 days of age) for 27 to 40 MPa, and 7 days for up to 27 MPa concrete. If form panels are removed before these days, concrete surface must be kept moist until above days by appropriate methods.

FEASIBILITY OF NEW RC AND CONSTRUCTION EXAMPLES

Feasibility of Ultra high-Strength RC

In the New RC project, feasibility of new structures using high-strength concrete and high-strength steel bars was studied in several stages. Two examples are introduced below.

(1) High-rise Flat Slab
Flat slab construction is an advantageous construction in providing large architectural openings or intensive underfloor piping, and can be acceptable in seismic zones by providing lateral stiffness and resistance by walls. Photograph 1 shows a high-rise flat slab resort hotel or condominium, designed by using high-strength materials.

(2) Megastructure
A megastructure refers to a building consisting of giant columns and girders to resist lateral load, with small substructures to hold each story between the mega-floors. The advantage of megastructure is that the substructure to accommodate for architectural detail is free of lateral load and is hence quite free in structural configuration, and furthermore it is free to modify or reconstruct as the occupancy requires. Photograph 1 illustrates a example of megastructures, shown to be constructable by using New RC material.

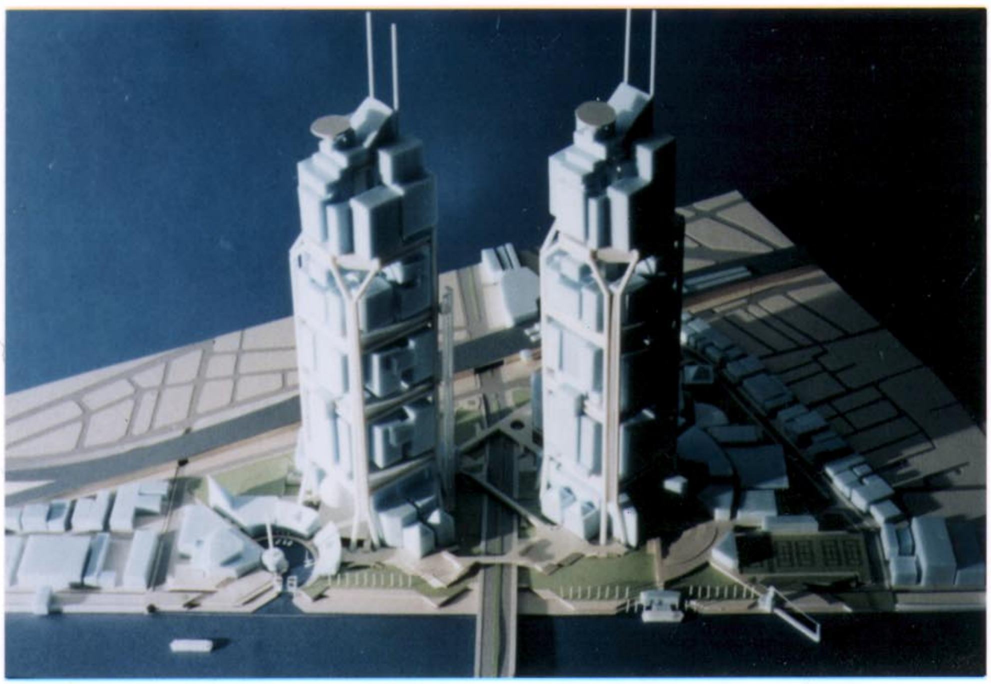

Photo. 1. Megastructure of 300m high utilizing high-strength materials.

Construction Examples

Several buildings of high-strength materials were designed during the time of the New RC project, and are being constructed at present. Table 2 shows seven examples that use high-strength concrete of 60 MPa and high-strength steel bars. They have all passed the review of the Technical Appraisal Committee of the Building Center of Japan. Followings may be pointed out as common features of these New RC buildings : (1) increased height, (2) increased span length, (3) use of high-strength steel bars of 490 MPa for girders, and 685 MPa for columns, and (4) use of precast units and hybrid structures.

Table 2. New RC buildings.

NO.	Name	Floor	Eaves Height (m)	Strength of concrete	materials (MPa) Reinforcement
1	VIRATON-SHIMA HOTEL PROJECT	38	133.85	60	390
2	EBINA DAI-ICHI SEIMEI BUILDING 490	25	107.80	60	490
3	OHJIMA 1-CHOME PROJECT 490	39	125.3	60	490
4	THE SCENE JYOHOKU	45	160	60	685
5	SEISHIN-MINAMI GARDEN TOWN PROJECT	22	68.22	60	490
6	HANKYU HILLS COURT TAKATSUKI 7th	20	63.90	60	490
7	SHIP PROJECT	28	88.35	42	685

CONCLUSIONS

1. High-strength and high-quality concrete and steel bars were developed for practical use.
2. Structural design equations evaluating mechanical performance of high-strength reinforced concrete structural elements are presented in the project. They were developed theoretically or empirically, backed up by experimental data.
3. Structural design and construction guidelines were proposed.
4. Future possibilities of New RC structures were discussed based on feasibility studies and New RC buildings under construction.

REFERENCE

Morita, S. and H. Shiohara (1996). Development of high-strength mild steel deformed bars for high performance reinforced concrete structural members. *11WCEE Acapulco, México.*