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DEVELOPMENT OF ADVANCED REINFORCED CONCRETE BUILDINGS USING HIGH-STRENGTH CONCRETE AND REINFORCEMENT - NEW CONSTRUCTION TECHNOLOGY IN JAPAN -

Shunsuke Otani

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Investigaciones sobre Sismología e Ingeniería Sísmica en el Japón

PRESENTACION

Una de las aportaciones más importantes de la parte japonesa dentro del Convenio de Cooperación Técnica entre la Agencia de Cooperación Internacional del Japón (JICA) y el Centro Nacional de Prevención de Desastres es el envío de expertos de corto plazo. Dentro de las actividades de estos expertos están la asesoría en aspectos específicos de proyectos de investigación, la impartición de seminarios y conferencias, y la participación en eventos técnicos.

En las numerosas conferencias dictadas desde que se inició el Convenio en 1990, se han presentado resultados y experiencias en líneas actuales de investigación y desarrollo tecnológico en materia de prevención de desastres sísmicos en el Japón.

Con objeto de dejar un testimonio permanente del contenido de las conferencias más sobresalientes y de mayor interés para la comunidad ingenieril y científica, el CENAPRED ha emprendido la publicación de esta serie como parte de los Cuadernos de Investigación.

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PROLOGO

En este trabajo, S. Otani presenta las actividades y resultados más sobresalientes de un proyecto coordinado de investigación para desarrollar las metodologías de diseño y la tecnología de construcción de edificios de concreto reforzado de alta resistencia. Como es común en programas de este tipo en el Japón, participaron instituciones de investigación del gobierno y universidades, así como de empresas privadas de construcción. Seguramente resulta interesante para un país como México, con investigación y desarrollo tecnológicos reducidos, observar el nivel de colaboración de instituciones privadas en un proyecto nacional de investigación y desarrollo.

Las especificaciones de materiales y del comportamiento de estructuras desarrolladas en este programa, y descritas sucintamente por Otani, son consistentes con las tendencias presentes en la evolución de reglamentos y normas de construcción. De acuerdo a esta tendencia, estos documentos deberán contener una serie de especificaciones de comportamiento por ser satisfechas en el análisis y diseño; quedará a juicio del ingeniero estructurista la selección de la metodología por emplear. Las características de los agentes reductores de agua de alto rendimiento (superfluidificantes) y los criterios de diseño sísmico de estructuras presentados por Otani son ejemplos de la tendencia mencionada.

Para obtener un comportamiento adecuado de una estructura ante sismos, es indispensable controlar de manera sistemática y rigurosa la calidad de los materiales. Particularmente la sobrerresistencia del acero de refuerzo (cociente de la resistencia al esfuerzo de fluencia) debe ser evaluada; así lo hicieron en el Japón y así debemos hacerlo en México.

Las expresiones para calcular diferentes resistencias presentan avances sobre aquéllas empleadas en concretos reforzados de resistencia normal. Los ingenieros japoneses intentaron incluir, aparentemente con éxito, la mayoría de las variables más significativas que influyen en el comportamiento. Además, desarrollaron metodologías de diseño basadas en teorías plásticas aún para diseñar por corte los elementos que estarán sujetos a grandes deformaciones en el intervalo inelástico.

En diseño sísmico, se adopta la filosofía actual de considerar diferentes intensidades de sismo. En las especificaciones presentadas se reconocen un sismo para distorsiones iguales a 0.005 y otro, de falla (nivel 2), asociado a distorsiones máximas iguales a 0.008. Para ambos niveles se deben emplear análisis no lineales; este requisito seguramente obligará a que los diseños sean casi únicamente hechos por las grandes empresas de consultoría del Japón. Lo anterior se refuerza por el hecho de que en el diseño para el sismo nivel 2 se deban aplicar conceptos de diseño por capacidad para garantizar un comportamiento histerético dúctil y estable de los elementos. La mayoría de los 10,000 diseñadores del Japón sólo conocen métodos basados en esfuerzos permisibles.

Sin duda el lector encontrará útil e interesante el resumen que presenta Otani en este trabajo. Es deseable que la gran cantidad de información obtenida a lo largo de este proyecto sea organizada y traducida a idiomas occidentales. La experiencia japonesa es de gran valor.

DEVELOPMENT OF ADVANCED REINFORCED CONCRETE BUILDINGS USING HIGH-STRENGTH CONCRETE AND REINFORCEMENT - NEW CONSTRUCTION TECHNOLOGY IN JAPAN -

by

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Abstract -- A case history of Japanese New RC project (1988-1993) is outlined. The project was initiated to develop the construction technology to use high-strength concrete and steel in a reinforced concrete construction, including the search for new construction materials, the understanding of fundamental behavior of new materials and members, the development of design methodology and construction technology. Major findings are briefly introduced.

INTRODUCTION

The Building Standard Law of Japan requires that the structural design of a building taller than 60 m in height must be approved by the Minister of Construction after a technical appraisal at the Building Center of Japan. The number of such high-rise reinforced concrete constructions, especially for residential housing, is expected to increase with a rise in the cost of land and the development of construction technology. The use of high-strength concrete became desired in lower-story columns to resist high axial loads without increasing column size.

The use of high-strength concrete has been limited in Japan due to the lack of design and construction guidelines. The Architectural Institute of Japan (AIJ) publishes "Japan Architectural Standard Specification for Reinforced Concrete Work (JASS-5) (Ref. 1)," which provides construction standards for concrete. Specified in JASS-5 are (a) concrete materials, (b) mix proportion, (c) concrete production, (d) concrete transportation and placement, (e) curing, (f) formwork, and (g) placement of reinforcement. However, the use of JASS-5 is limited to the concrete of strength ranging from 15 to 36 MPa. The AIJ Standard for the Calculation of Reinforced Concrete Structures (Ref. 2) specifies the method of design calculation for reinforced concrete buildings using allowable stress procedure. The concrete strength is, however, also limited to 36 MPa.

High strength concrete has been frequently used in prestressed concrete construction and prestressed concrete piles in building construction; concrete strength of more than 30 MPa is commonly used. In the construction of prestressed concrete bridges in Japan, high strength concrete of 40 to 80 MPa has been used; commonly 60 MPa for cast-in-situ concrete members and 80 MPa for precast concrete elements. It should be noted that concrete engineering in Japan has been developed separately for building construction and civil engineering construction.

The use of high strength concrete has been reported in the construction of high-rise buildings; i.e, the concrete of 134 MPa strength was reported in the construction of the Two Union Square Building in Chicago. The use of high strength concrete is desired in the lower stories of a high-rise building to resist high axial loads by a limited column area in order to increase rentable and livable building area. However, the use of such high strength concrete is reported only in the construction in lightly seismic zones.

The research toward the use of high-strength concrete for high-rise reinforced concrete buildings has been conducted separately at various technical research institutes of construction industry in Japan. The concrete of strength exceeding 36 MPa has been used by extrapolating the existing construction technology developed for normal strength concrete. A common and integrated standards are desired for structural design and construction in highly seismic area; the research and development conducted by private companies needed to be surveyed and integrated toward standardization.

A five-year national project (New RC Project, 1988-1993) was organized by the Ministry of Construction, Japanese Government, for the "Development of Advanced Reinforced Concrete Buildings Using High-strength Concrete and Reinforcement (Refs. 3 and 4)" in 1988. The objectives were:

(a) to develop technology for material production, quality control, and construction,

(b) to evaluate the fundamental properties of materials and the behavior of structural members, and

(c) to develop a system of design methodology for a super high-rise reinforced concrete building in highly seismic zones.

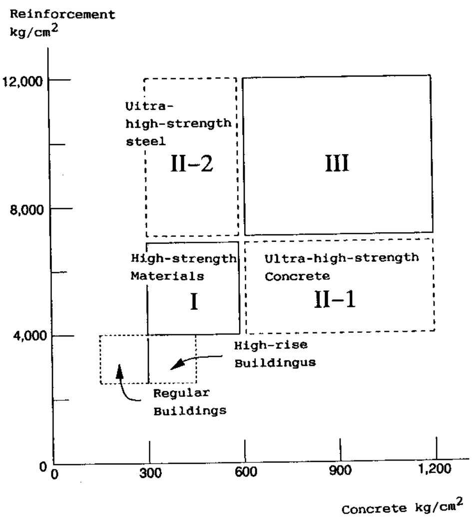


Fig. 1: Target Ranges of Material Strengths in New RC Project

The material strength considered in the project ranged from 30 to 120 MPa for the concrete and from 400 to 1,200 MPa for the longitudinal reinforcement. The high-strength steel of strength ranging from 600 to 1,300 MPa has been commonly used as lateral reinforcement in Japan with experimental support. An emphasis was placed to develop construction technology and design guidelines for buildings using concrete strength up to 60 MPa, and steel strength up to 700 MPa (Fig. 1).

The results of the project will be utilized as technical standards for building administration and will encourage further research and development on advanced reinforced concrete technology by private sectors.

RESEARCH ORGANIZATION

The Building Research Institute of the Ministry of Construction organized and promoted the New RC project. Housing and Urban Development Public Corporation entrusted research funds to the project with an increased expectation toward the construction of high-rise reinforced concrete housings in the near future. Upon solicitation by the Building Research Institute, thirty-four member corporations of the Building Construction Society (BCS) agreed to participate in the project by sharing major research funds and sending technical observers to the project. Japan Cement Association, Japan Concrete Admixture Association, Nippon Slag Association and the Kozai Club (steel manufacturer's organization) provided necessary materials and shared research funds. University researchers were invited to conduct research work.

Research Coordinating Committee (Chairman: Prof. H. Aoyama, then at University of Tokyo) was formed in the Japan Institute of Construction Engineering to coordinate and integrate research works in different fields. Technical Research Committees were organized under the Research Coordinating Committee, including

(a) Concrete Committee (Chairman: Prof. F. Tomosawa, University of Tokyo),
(b) Reinforcing Steel Committee (Chairman: Prof. S. Morita, Kyoto University),
(c) Structures Committee (Chairman: Prof. S. Otani, University of Tokyo),
(d) Structural Design Committee (Chairman: Prof. T. Okada, University of Tokyo), and
(e) Construction and Manufacturing Committee (Chairman: Prof. K. Kamimura, Utsunomiya University).

Several working groups were formed under each committee consisting of university researchers, staff researchers of the Building Research Institute, and representative researchers from participating organizations and construction companies.

Concrete Committee -- The committee was formed to develop high-strength high-quality concrete of strength in excess of 36 MPa and up to 120 MPa, with the following objectives:

(a) The search for materials suitable for high-strength concrete,
(b) The development of specifications for cement, aggregate, admixture and binder,
(c) The evaluation of the properties of high-strength concrete,
(d) The development of guidelines for mix proportioning,
(e) The development of specifications for concrete works, and
(f) The evaluation of durability and fire resistance.

The following working groups were formed:

(a) Material Development WG: Cement, aggregate and admixture suitable for high-strength concrete were developed, and mix to attain high-strength concrete was studied;

(b) Material Performance Evaluation WG: Methods to evaluate workability, mechanical properties, long-term characteristics, durability and fire resistance for high-strength concrete were investigated; and

(c) Construction WG: The methods to estimate concrete strength in structural members and the methods for concrete mixing, concrete pumping and curing were studied.

Reinforcing Steel Committee -- The committee was formed to develop high-strength reinforcing steel to match the high-strength concrete, with the objectives:

(a) The development of high-strength steel,

(b) The evaluation of properties of high-strength steel,

(c) The evaluation of properties of confined concrete,

(d) The development of constitutive equations for reinforced concrete elements for use in the nonlinear finite element analysis, and

(e) The evaluation of bond characteristics between reinforcement and concrete.

The following working groups were formed: (a) Material Development and Mechanical Characteristics WG, (b) Reinforcement Work WG, (c) Confined Concrete WG, (d) Constitutive Equation/Finite Element Method WG, and (e) Bond and Anchorage WG.

Structures Committee -- The committee was formed to study the structural characteristics of high-strength reinforced concrete members, with emphasis on following items:

(a) evaluation of structural characteristics (strength and deformation capacity, hysteresis characteristics) necessary in a structural design and a nonlinear earthquake response analysis,

(b) possible dimensions and reinforcement detailing of members to develop required deformation capacity,

(c) methods of testing specimens and evaluating test results, and

(d) verification of structural design system.

The following working groups were formed:

(a) Lineal Member WG: The investigation of resistances and deformations of beams and columns at flexural cracking, yielding and ultimate stage, shear and bond failure after flexural yielding, and hysteretic characteristics;

(b) Planer Member WG: The investigation of shear strength, flexural strength, and deformation capacity of structural walls under bending and shear,

(c) Shear WG: The investigation of shear resistance and bond splitting failure before flexural yielding of beams and columns, and

(d) Beam-column Connection WG: The investigation of shear strength of beam-column connections, and anchorage of longitudinal reinforcement within beam-column connections.

Structural Design Committee -- The committee was formed to develop a structural design guidelines for a reinforced concrete building especially under earthquake excitation. A new design methodology was necessary in the design to make the best use of high-strength characteristics of the materials. The objectives were:

(a) the development of methods of structural modeling of members,

(b) the search of feasible structural types,

(c) the definition of design loads,

(d) the development of criteria for structural performance during an earthquake, and

(e) the development of design methodology.

The following working groups were formed: (a) Structural Type WG, (b) Design Methodology WG, (c) Earthquake Motion and Loading WG, (d) Foundation Structure WG, (e) Trial Design WG, and (f) Guidelines Drafting WG.

Construction and Manufacturing Committee -- The committee was formed to develop standard specifications for the reinforced concrete work. Two working groups were formed to draft standard specifications for concrete work and reinforcement work.

EXECUTION OF RESEARCH

Most of research work was carried out at the Building Research Institute and invited universities. A significant gap lies in the quality and quantities of research facilities and capability at the universities and at the technical research institutes of construction industry. The research institutes of construction companies have been developed in the last thirty years when Japanese industry rapidly invested funds in research and development fields. However, the cost of executing the experimental work at these technical research institutes became extremely expensive with sophistication of testing facilities.

On the other hand at the universities, very little support has been provided for the acquisition and the maintenance of major research facilities by the Ministry of Education and Science. The number of supporting staff was reduced in the laboratories. These made university researchers difficult to carry out experimental research work. For example, not many universities posses large capacity testing machines necessary for testing structural members using high strength materials. Relatively small specimens had to be tested at universities. However, the cost of experimental research is maintained relatively low at the universities.

The technology to produce high-strength concrete was not available at the universities, and technical support was provided by experts from the technical research institutes, especially for manufacturing high-strength concrete for use in structural specimens. High-strength steel reinforcement was provided by steel manufacturers.

The cost of executing experimental as well as analytical research was kept at very economical levels by the participation of university researchers. Analytical work was carried out at the universities because of the economical cost of computer use.

SCHEDULING OF PROJECT

It was desired that the research was performed in the sequence of
(a) the development of high-strength materials,
(b) the evaluation of the properties of the high-strength materials,
(c) the evaluation of the properties of structural members using the high-strength materials,
(d) the development of structural design guidelines using high-strength structural members, and then
(e) the development of standard specifications for construction.

For example, the method of producing high-strength concrete must be established prior to the fabrication of structural specimens; the properties of structural members must be known before a structural design guidelines is developed. However, the limitation in research period did not allow such ideal development.

On the other hand, some interaction of research was judged necessary through the discussion and exchange of research results at Research Coordinating Committee; e.g., new materials must be developed to meet the requirements of desired structural performance; the dimensions of member specimens and loading for experimental work must reflect the results of trial structural design and expected response. Therefore, all research efforts needed to progress in parallel keeping close coordination.

The first year was devoted to survey past research work on:
(a) the development of high-strength materials,
(b) the investigation of fundamental properties of high-strength materials,
(c) the production of high-strength materials,
(d) the investigation of fundamental structural properties of members and sub-assemblages, and
(e) the development of structural design procedure for super high-rise reinforced concrete buildings.

On the basis of the literature survey, the topics for research needs were identified. A series of pilot tests were conducted to understand the fundamental properties of materials and structural members. A trial design was carried out to determine the expected member sizes of super high-rise buildings.

The second to fourth years were used for research periods to investigate the identified research topics on materials, construction, structural members and structural design.

In the fifth year, Concrete Committee devoted to write guidelines for material production and standard specifications for building construction, including (a) the production and quality control for high-strength materials, (b) the testing methods to evaluate material properties, (c) the requirements for durability and fire resistance, and (d) the construction and quality control for reinforcement placement, concrete work, formwork, and reinforcement joints. Reinforcing Steel Committee summarized (a) the fundamental properties of high-strength steel, (b) the fundamental structural properties of materials, and (c) the development of constitutive models for the nonlinear finite element analysis. Structures Committee evaluated the experimental research findings, and summarized the structural properties of members and sub-assemblages, and suggested the methods to estimate the strength, deformation capacities and hysteretic characteristics. Structural Design Committee developed structural design guidelines for super high-rise reinforced concrete building. Construction Committee proposed the specifications for steel placement, concrete work, quality control, and construction.

Some of major findings of the project reported in the final project year (Ref. 4) are briefly outlined below.

HIGH-STRENGTH HIGH-QUALITY CONCRETE

Cement for High-strength Concrete -- Silica fume has been known to enhance concrete strength; binder consisting of Portland cement, fine powder of blast furnace slag and silica fume was found to be effective to achieve high strength. With a development of water reducing admixture, high concrete strength could be attained by specifying a low water/cement ratio (30 percent) without sacrificing workability (230 mm slump); however excessive amount of water reducing admixture tends to delay setting of cement and attainment of initial strength and to increase shrinkage.

Normal Portland cement, high early strength cement, moderate heat cement and blast furnace slag cement were successfully used to make high-strength mortar. Special types of chemical admixture were developed for use with high strength concrete.

Aggregates for High-strength Concrete -- The quality, shape and size of fine and coarse aggregates must be specified to attain a required concrete strength.

Suitable fine aggregates should be selected by compressive strength test of three trial mortar specimens (ϕ75 x 150 mm), cured in water at 20 deg. C, at 28 days. Coarse aggregates should be selected by compressive strength test of trial concrete specimens (f100 x 200 mm) using suitable fine aggregates. Young's modulus of the trial concrete, observed in the test, should fall within an acceptable range.

If the availability of fine and coarse aggregates is limited in a region, three concrete specimens each at binder-water ratios of 3.0, 3.5, 4.0 and 4.5, at a 250 mm slump, with air content of 3 percent, should be prepared. The combination of aggregates should be selected to meet the required compressive strength and Young's modulus.

High-performance Water Reducing Agent -- High-performance water reducing agent for high-strength concrete must satisfy the following performance criteria;

(a) Target slump of 230 mm +/- 20 mm,

(b) Initial setting time between 5 and 12 hours, and final setting time less than 15 hours,

(c) Compressive strength of concrete using a trial water reducing agent should not fall below that using the standard water reducing agent at 3, 7 and 28 days,

(d) Length change of concrete specimens using a trial water reducing agent should be less than that using the standard water reducing agent,

(e) Relative dynamic modulus of elasticity determined by a freezing and thawing test should be more than 85 percent, and

(f) Change of slump in 60 minutes should be less than 50 mm, and that of air content should be within 1.5 percent.

Mix Proportioning -- Mix proportion is determined for a given mix proportioning strength, air content and slump. Cement substitution ratio of admixture, tested in the New RC project, was 10 percent for silica fume and fly-ash fume, 30 50 50 percent for fine powder blast furnace slug, and 17 percent for admixture of ettringite family.

Water-cement (binder) ratio must be determined for a given mix proportioning strength;

$$F = (A / B^x)(1 - a / 100)^y C \qquad (1)$$

where, F: 28-day compressive strength of a standard cured specimen, x: water-cement (binder) ratio (percent)/100, y: air content in percent, a: strength decay ratio for 1 percent increase in air content, A: a coefficient (=2,260 for good coarse and fine aggregates), B: a coefficient (=17.8 for New RC materials), and C: a coefficient for admixture (= 1.1).

Water content per unit volume of concrete should be determined considering the selected water-cement ratio. Normal range of water content for water-cement ratios is given below;

Water–cement ratio (%)	Water content per unit concrete volume
45	165 - 175 (kg/m^3)
35	160 - 170
25	155 - 165

Volume of coarse aggregate per unit volume of concrete should be determined considering required slump. For maximum coarse aggregate size less than 20 mm, and finess modulus of coarse aggregate of 2.8, volume of coarse aggregate may be 0.60 to 0.64 for 180 mm slump, and 0.58 to 0.62 for 230 mm slump.

Properties of High–strength Concrete -- The properties needed to be clarified are: (a) properties of fresh concrete, (b) short–time properties such as compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, stress–strain relationship including descending branch, and (c) long–time properties such as shrinkage and creep, durability, and fire resistance.

The mechanical properties of hardened concrete should satisfy the specification required to achieve desired performance of structural members. On the other hand, the properties of fresh concrete must meet the requirements for construction.

Some of standard testing methods developed for normal strength concrete were reexamined and modified for high–strength concrete. The compressive strength of concrete higher than 36 MPa is affected by the finishing at the top and bottom of a coupon cylinder; i.e., mechanical polishing of the use of cement paste capping of less than 3 mm is recommended. The compressive strength of higher strength concrete was found to vary from a testing machine to another; low stiffness testing machines yielded a wider scatter in observed compressive strengths; stiffer testing machines yielded larger strains at compressive strength. Higher stiffness testing machines were found more reliable. The testing machine should be used to within the two–thirds of the capacity.

The strength of concrete is influenced by curing process; the development of strength may be estimated by the maturity method; a rapid temperature rise at fresh age may cause ill effect on concrete strength; concrete strength may vary in a section due to the difference in curing process; concrete strength in a structural member evaluated by the test of core concrete was approximately 0.88 to 1.15 times the concrete strength by water cured control cylinders. The difference was observed to decrease with increasing concrete strength.

Young's modulus Ec (MPa) of concrete can be estimated by the following expression (F. Tomosawa, et al.);

$$Ec = k_1 \, k_2 \, 3.35 \times 10^4 \, (\gamma / 2.4)^2 \, (\sigma_B \, 60)^{1/3} \qquad (2)$$

where, γ: mass per unit volume (t/m^3), σ_B: concrete compressive strength (MPa), k_1: coefficient dependent on type of coarse aggregate (k_1 = 0.95 for quartz schist, andesite, basalt and clay–slate, k_1 = 1.2 for lime stone and bauxite, and k_1 = 1.0 for other coarse aggregate), k_2: coefficient dependent on admixture (k_2 = 0.95 for silica fume, fine powder of blast furnace slag and fly ash fume, $k_2 = 1.1$ for fly ash, $k_2 = 1.0$ without admixture).

Concrete cores were taken from a column specimen (water–cement ratio of 35 percent) and tested to study the variation of concrete strength with depth. The strength was lower by approximately 7 percent from the average at the top, and higher by approximately 4 percent near the base.

Durability -- High strength concrete is believed to be dense and durable by the use of low water/cement ratio. However, the use of water reducing agent and high cement content might affect the cracking properties and alkali aggregate reaction. The durability of high strength concrete was studied for freezing resistance, air content, neutralization, sea water resistance, water tightness, and alkali aggregate reaction. The use of air entraining and water reducing agent was recommended to improve freezing resistance.

Fire Resistance -- High density in concrete retards water drying, and resulting high water content was believed to cause bursting of concrete at a high temperature under fire. Concrete coupons and structural members were tested under fire to evaluate the fire resistance and heat insulation property of concrete to protect the reinforcing steel. A column specimen (500 x 500 mm), cured in a dry condition for one year, was subjected to high temperature for three hours. The bursting of concrete was not significant.

Workability -- Workability of fresh concrete is a key issue for the practical use in construction. Setting time, segregation, slump loss, consistency, and heat of hydration were studied extensively. A new index for workability was explored other than a slump value; a standard method to evaluate consistency of concrete and segregation was proposed; and the application of concrete conveying system by pump and pipe was also studied for high-strength concrete.

HIGH–STRENGTH REINFORCING STEEL

The use of high–strength reinforcement can increase member flexural strength without causing the congestion of reinforcement in the formwork and can also increase the deformability of high–strength concrete by proper confinement.

With an increase in the yield stress of longitudinal steel, however, the yield deformation of a reinforced concrete member increases to result in a large story drift at the yielding; the deformation and stiffness must be properly controlled in design. An optimum strength of reinforcing steel with respect to concrete strength was not clear before a systematic experimental and analytical examination of structural members. The desired mechanical properties of reinforcement, such as desired range of yield plateau, yield stress to fracture strength ratio, and strain at fracture, could not be specified by the structural design group at the beginning of the project; the desirability of the yield plateau in the stress–strain relation was pointed out at the initial stage of the project.

For the practical use, the high strength steel must satisfy (1) necessary and stable structural properties, (2) a reasonable cost for production, (3) processing (bending and cutting) by existing equipments, and (4) capability of jointing. The following properties of reinforcement were studied: (1) stress–strain relation under cyclic tension, (2) possibility of gas pressure welding, (3) weldability, (4) property under bending and straightening, (5) properties at high temperature, (6) impact strength, (7) aging, (8) corrosion resistance, and (9) fatigue properties.

Properties of High-strength Reinforcement -- Deformed reinforcement of specified yield strength equal to 685 MPa and 980 MPa has been developed for the longitudinal reinforcement. Grade 685 steel exhibits a clear yield plateau up to a strain equal to 4 times the yield strain. Grade 980 steel does not develop a yield plateau, but the fracture strain reaches more than 7 percent.

A clear yield plateau cannot be developed for a reinforcing steel of strength higher than 800 MPa because such higher strength steel is normally subjected to plastic working or heat-treatment during processing. Yield ratio (a ratio of yield stress to fracture strength) approaches 0.90 for a 800 MPa steel.

Grades 785 and 1275 steel were developed for use as lateral reinforcement. The distribution of yield stresses, yield plateau ranges, fracture strains, and fracture to yield stress ratios of the manufactured steel were studied for quality control.

Splices -- The joint of reinforcing bars was a problem. Gas pressure welding and enclosed arc welding are commonly used for longitudinal reinforcement of nominal yield stress less than 500 MPa, but such methods cannot be used for higher strength steel. The ability for gas pressure welding decreases with the improvement of weldability of reinforcing steel. Grade 685 reinforcing bars jointed by gas pressure welding could develop full material strength in tension, but some damage was observed by bending tests. New mechanical splices using couplers for threaded deformed bars with mortar grout and epoxy grout were developed.

FUNDAMENTAL PROPERTIES OF MATERIALS

Confined Concrete -- A sharp descending branch in the stress-strain relationship of high-strength concrete has created a concern toward the use of high-strength concrete in a member where a large plastic deformation is desired. Experimental studies showed that the use of high-strength lateral reinforcement and sub-ties as confining reinforcement improved the deformation capacity.

The compressive strength f"c of confined concrete in a column can be estimated as follows;

$$f''_c = m\,\sigma_B + k\,p_h\,\sigma_{hy} \qquad (3)$$

where, σ_B: concrete strength obtained from standard cylinder test, m: coefficient dependent on cross section shape (m = 0.8 for a circular section, and 1,0 for a rectangular section), p_h: volume ratio of lateral reinforcement, σ_{hy}: yield stress of lateral reinforcement. The constant k can be evaluated by the following expression;

$$\begin{aligned} k &= 2.09\,(1 - s / 2\,D_c)^2 && \text{for a circular section} \\ &= 11.5\,(d'' / C)(1 - s / 2\,D_c) && \text{for a rectangular section} \end{aligned} \qquad (4)$$

where s: spacing of lateral reinforcement, D_c: center-to-center distance of exterior longitudinal reinforcement, d": nominal diameter of lateral reinforcement, C: center-to-center distance of adjacent longitudinal reinforcing bars supported by the corner of lateral reinforcement (Fig. 2).

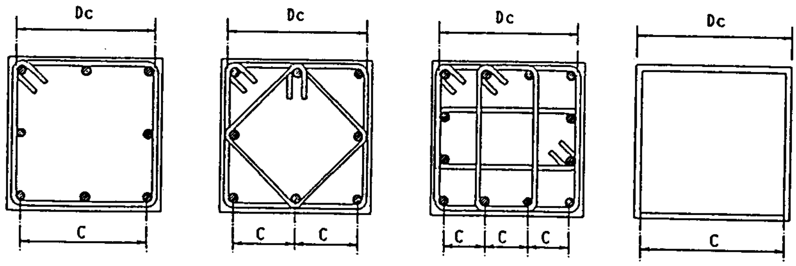


Fig. 2: Notation for Parameters in Eq. (4)

The confining effect was also studied for (1) column specimens under axial loading, (2) characteristics of compression zone in flexure, (3) lateral reinforcement necessary to prevent buckling of longitudinal reinforcement, and (4) development of standard testing method. A series of column specimens with varying spacing of lateral reinforcement were subjected to compression to study the buckling phenomena of longitudinal reinforcement; the buckling was observed after compressive yielding for even a spacing of lateral reinforcement at 8 times bar diameter.

Bond -- With an increase in the yield stress of longitudinal reinforcement, the bond stress between concrete and reinforcing bars at yielding increases. The bond resistance increased proportional to the square root of concrete compressive strength. Therefore, the anchorage of high-strength reinforcement becomes one of critical problems for the use of high strength reinforcement; the slippage of beam reinforcement within an interior beam-column connection is a controlling factor in determining the dimensions of a column in design.

The following research topics were identified: (1) anchorage strength of a reinforcing bar with standard hook, (2) estimation of bond-splitting capacity along the longitudinal reinforcement in a structural member, (3) standard test method for bond resistance, (4) anchorage of a reinforcing bar by mechanical devices, (5) design criteria for a beam-column connection, and (6) mathematical modeling of bond resistance.

The shape of bar deformation could not be changed in order to use the existing roller at the steel manufacturer. The effects of lateral reinforcement and reinforcement depth on bond strength were studied. The bond resistance of high-strength concrete at top and bottom reinforcement did not change as much as that of normal strength concrete. The bond resistance was affected by the method of testing (cantilever beam test, simple beam test, and anti-symmetric moment test).

Lead Length for Anchorage with Standard Hook -- Lead length l_{dh} of a beam reinforcing bar, anchored with a standard 90 deg. hook (with more than 10 d_b extension; d_b: bar diameter) in the beam-column connection, must be longer than 8 d_b, 150 mm, and the value specified in the following equation;

$$l_{dh} = 16\,(1.9\,\sigma_s / f_{do} - 0.9)\,d_b \qquad (5)$$

where, σ_s: design stress of a bar to be anchored, d_b: diameter of the bar, and f_{do}: value determined by the following expression,

$$f_{do} = 85\,k_1\,k_2\,k_3\,k_4\,k_5\,k_6\,\sigma_B^{0.5} \qquad (6)$$

where, k_1: =0.85 for light weight aggregate concrete, and =1.0 for normal weight concrete, k_2: = $(40 / \sigma_B)^{1/6}$, but not less than 1.0, k_3: = 1.0 for the hook bent in the connection and = 0.7 for the hook bent outside the connection, k_4 = 1.0 for a bar with side cover greater than 3 d_b and = 0.8 otherwise, k_5: = 1.15 if the concrete around the hook extension is confined by lateral reinforcement of diameter more than one–third of the anchoring bar at spacing not more than the radius of bend, = 1.0 otherwise, and k_6: a coefficient to express the effect of radius of bend r, given by the following expression;

$$k_6 = 0.7 + 0.1\,r / d_b \qquad (7)$$

but not more than 1.15.

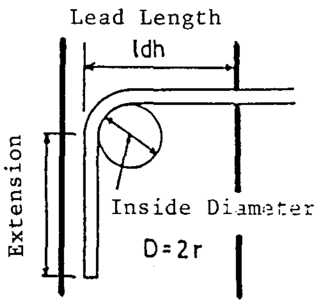


Fig. 3: Definition of Standard Hook

<u>Anchor</u> <u>Strength</u> -- The anchor strength f_d of a bar anchored with a standard hook may be evaluated by the following expression;

$$f_d = 100\,k_1\,k_2\,k_3\,k_6\,k_c\,k_h\,k_s\,\sigma_B^{0.5}\ (\text{MPa}) \qquad (8)$$

where coefficients k_1, k_2, k_3 and k_6 are the same as those defined above. k_c: coefficient to include the effect of side cover C,

$$k_c = 0.43 + 0.1\,C / d_b \qquad (9)$$

but not more than 1.0, k_h: coefficient to include the effect of lead length l_{dh},

$$l_{dh} = 0.544 + 0.038_{\,ldh} / d_b \qquad (10)$$

but not more than 1.15, and k_s: coefficient to include the effect of joint lateral reinforcement of diameter d_s placed within the distance equal to the diameter of the bend from the anchoring bar,

$$k_s = 1 + (2/3)\,(d_s / d_b)^2 \tag{11}$$

The reliability of the equation was examined for 113 specimens, and the average of ratios of the observed to the calculated strength was 1.18 with a standard deviation of 0.18.

Anchorage within Interior Beam–column Connection -- Beam bars of diameter d_b passing through an interior beam–column connection must satisfy the following expression;

$$d_b / h_c < 1.34\,(1.0 + P / A_g\,\sigma_B)\,\sigma_B^{(2/3)} / \sigma_y \tag{12}$$

where, h_c: column width, P: axial force in column under gravity loading, A_g: cross sectional area of column, σ_B: concrete strength (MPa), and σ_y: specified yield stress of beam bars (MPa). The above criterion was proposed to prevent the deterioration of resistance within 3 cycles in a plastic range.

Bond Side–splitting Strength -- The bond stress τ_{bu} at side splitting failure along the beam bottom or column longitudinal reinforcement may be given by the following expression;

$$\tau_{bu} = \{0.053 + 0.12\,b_i + 10\,k_n\,p_w\,b / N\,d_b\}\,\sigma_B^{0.5} \tag{13}$$

where,

$$b_i = (b - N\,d_b) / N\,d_b \tag{14}$$

$$k_n = 1.0 + 0.85\,(n - 2) / N \tag{15}$$

b: member width, N: number of longitudinal reinforcement placed in a layer, d_b: nominal bar diameter, σ_B: concrete strength, n: number of pairs of lateral reinforcement, and pw: lateral reinforcement ratio. The resistance against side splitting along beam top reinforcement should be reduced by the following factor K_o;

$$K_o = o.7143 + 0.002875\,\sigma_B \tag{16}$$

but not less than 0.80. The concrete strength must be not more than 100 MPa in this expression. Higher strength lateral reinforcement must be used for high strength concrete.

Finite Element Method Analysis -- As the material strength increases, it becomes more difficult to test full–scale structural members. Therefore, some structural characteristics must be investigated by analytical tools. The constitutive relations of concrete, reinforcing steel, and bond between concrete and reinforcing steel were studied for use in the nonlinear finite element analysis. Failure criteria of concrete under multi–axial stress conditions were studied extensively. The reliability of the analytical methods must be examined with respect to the results of selected structural member tests. A guidelines became necessary for the use of finite element analysis results in a structural design.

Reinforcement Detailing -- Detailing requirements for lateral reinforcement were studied, including (1) minimum radius of bent for a high strength reinforcing bar, (2) desired shape of lateral reinforcement arrangement to improve confining effect of concrete, and (3) construction of reinforcing cages.

STRUCTURAL MEMBERS AND SUB-ASSEMBLAGES

Theoretical examination of experimental data on high-strength reinforced concrete members was emphasized in order to reduce the number of expensive experimental work. The availability of high-strength reinforcement during the project determined the scale of structural member specimens to be approximately one-half to one-third. Difficulty in testing members made of high-strength materials was also recognized due to the limitation in the capacity of testing machines available at universities. Standard types of structural members were selected for testing. The effect of specimen scale must be clarified to justify the use of small size specimens; however, a full scale test of a structure was not realized in the project.

A series of pilot response analyses on trial design buildings showed that a story drift limitation of approximately 1/50 to 1/100 might govern the structural design. Therefore, a close observation of the behavior in such a deformation range was emphasized although the test was carried out to the failure; an ultimate deformation of a member was defined as a deformation at 85 % of maximum resistance. For a lineal member, flexural yielding was observed at or prior to a member-end rotation of 1/100 rad; in other words, flexural yielding of a member might not take place under a design earthquake. Trial design of a building was felt useful in choosing the dimensions of test specimens, and the amount of reinforcement in section.

The effect of the length of yield plateau and the desired fracture strain of high-strength longitudinal reinforcement could not be studied in the project. An establishment of a standard testing method including loading history was not supported in the project although such standard testing was felt useful for data evaluation.

Behavior of Columns -- The column in lower stories is subjected to high axial load; the following design criteria of columns under high axial load were examined: (1) the ultimate deformation, (2) the behavior after spalling of cover concrete, (3) the limit of axial load, (4) the length of yielding hinge region.

Columns subjected to high axial load and reversals of lateral load failed in shear, developing vertical cracks along the member axis. The use of high-strength lateral reinforcement, especially sub-ties, could improve deformation at failure. Ultimate deformation of beams improved by the use of confining lateral reinforcement.

The bending moment-curvature relation of a section under load reversal was simulated by the fiber model if the axial stress-strain relation of confined concrete was used for a core concrete segment. The use of high-strength longitudinal reinforcement in a column resulted in a slender hysteresis shape, and left a smaller residual deformation although the deformation capacity was comparable with the column using normal-strength longitudinal reinforcement. The axial deformation increased rapidly before the resistance of a column started to deteriorate under lateral load reversals.

The behavior of a column under bi-directional lateral load reversals was studied with and without high axial load. It was noted that the bi-directional loading certainly caused more damage in a column if the column was subjected to the same number of load cycles in the two directions. A constant axial loading during load reversals caused heavier damage in the column than varying axial loading with deformation (compressive loading in one direction and tensile loading in the other direction from a gravity loading level).

In a column subjected to high axial load and lateral load reversals, a rapid increase in the longitudinal strain was observed before the reduction in lateral resistance. The development length within a column was shortened by crushing of concrete by bending when the axial load was high.

Behavior of Beams -- For beams using high strength materials, the following design criteria were reviewed: (1) maximum and minimum longitudinal reinforcement and (2) effective slab width for flexural strength, (3) shape and amount of lateral reinforcement, (4) the length of yield hinge region, (5) measures to prevent shear and bond splitting failure after flexural yielding.

Flexural Strength -- Flexural strength of reinforced concrete members can be evaluated using ACI equivalent rectangular stress block for concrete stress distribution. Coefficient k_1 representing the depth of rectangular stress block may be estimated by the following expression,

$$k_1 = 0.85 \qquad \text{for } \sigma_B < 27 \text{ MPa}$$
$$= 0.85 - 0.05\,(s_B - 27)/7 \qquad \text{for } \sigma_B > 27 \text{ MPa} \tag{17}$$

but k_1 should not be less than 0.65. Strain at the extreme compressive fiber may be taken as 0.003 at flexural strength.

Shear Strength of Members -- Resistance at shear failure and bond splitting failure before flexural yielding was a major research item in the project. The Architectural Institute of Japan published "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (Ref. 5)", in which a new shear design procedure was proposed on the basis of plasticity theorem. The shear design procedure outlined in the AIJ guidelines gave a good estimate of shear strength observed in the tests.

Shear strength V_u of a member is given by the following expression;

$$V_u = b\, j_t\, p_w\, \sigma_{wy} \cot\phi + \alpha\,(1 - \beta)\, b\, D\, v_o\, \sigma_B \tag{18}$$

but if $p_w\, \sigma_{wy} > v_o\, \sigma_B/2$ and

$$\sigma_{wy} < 125\,(v_o\, \sigma_B)^{0.5} \tag{19}$$

where,

$$\alpha = [\{1 + (L/D)^2\}^{0.5} - (L/D)]/2 \tag{20}$$

$$\beta = (1 + \cot^2 f)\, p_w\, s_{wy} / (n_o\, s_B) \tag{21}$$

$$v_o\, \sigma_B = 1.7\,(1 + 2\,n)\, \sigma_B^{0.667} \qquad \text{but} < 1.0 \tag{22}$$

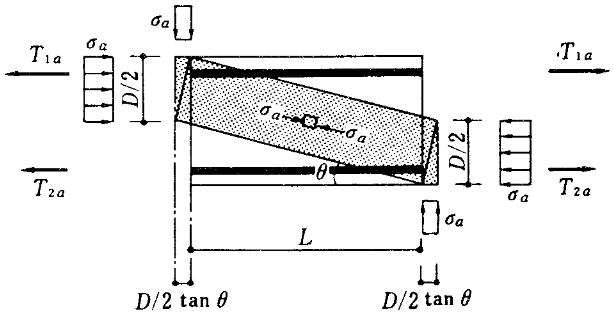
$$\cot\phi = \min\{A, B, C\} \qquad \text{but} > 1.0 \tag{23}$$

$$A = 2.0 - 3\,n \tag{24-1}$$

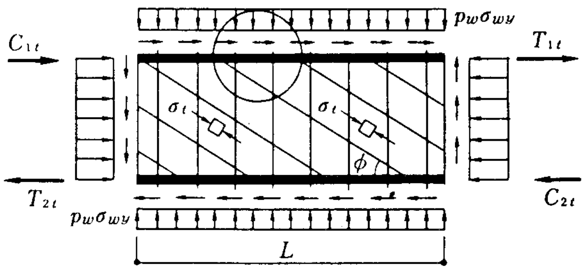
$$B = j_t / (2\,\alpha\,D) \tag{24-2}$$

$$C = \{(\nu_o\,\sigma_B / p_w\,\sigma_{wy}) - 1.0\}^{0.5} \tag{24-3}$$

b: member width, D: member depth, j_t: distance between the centroid of top and bottom reinforcement, L: clear span, n: non-dimensional axial stress (= axial stress / concrete strength), p_w: lateral reinforcement ratio, ν_o: coefficient for effective concrete strength, σ_B: concrete strength, s_{wy}: yield stress of lateral reinforcement, f: angle of strut in truss mechanism.



(a) Arch Mechanism



(b) Truss Mechanism

Fig. : Truss Mechanism and Arch Mechanism for Shear Resistance

In estimating the shear strength at the yield hinge after flexural yielding, the effective concrete strength $\nu\,\sigma_B$ and the angle ϕ of the concrete strut in the truss mechanism are varied with plastic deformation R_p as follows;

$$A = \begin{cases} 2.0 - 3\,n - 50\,R_p & \text{for } 0 < R_p < (1 - 3\,n) / 50 \text{ rad} \\ = 1.0 & \text{for } (1 - 3\,n) / 50 < R_p \text{ rad} \end{cases} \tag{25}$$

and

$$\begin{aligned} v &= (1.0 - 15\, R_p)\, v_o && \text{for } 0 < R_p < 0.05 \text{ rad} \\ &= 0.25\, v_o && \text{for } 0.05 < R_p \end{aligned} \qquad (26)$$

In calculating β, the truss strut angle f should be the one outside the hinge region, and $p_w\, s_{wy}$ should the one in the yield hinge region.

Beam–column Connection -- A beam–column connection is subjected to high shear by the use of high–strength reinforcement in beams. At the same time, the anchorage of beam longitudinal reinforcement within a beam–column connection becomes a critical design issue. A series of tests on beam–column connections indicated that (1) the shear resistance of a connection was found to increase proportional to the square root of compressive strength of concrete, (2) the sub–ties were not found effective resisting shear in the connection until a large story drift, (3) flexural yielding of beams was observed at a story drift angle of more than 1/100 rad.

Shear strength τ_{ju} of a beam–column connection may be expressed as a function of concrete strength σ_B;

$$\tau_{ju} = 0.77\, \sigma_B^{0.667} \qquad (27)$$

If a story drift is limited in a structural design, beams may not yield during a design earthquake and a hysteretic energy dissipation may not be relied upon as a measures to reduce the vibration energy of a structure.

Stiffness Characteristics of Structural Walls -- Resistances and deformations of a structural wall at flexural cracking and yielding, shear cracking were examined. Due to the difficulty in testing large scale structural walls and due to the limitation in research fund, the number of specimens was limited to minimum. Hysteresis energy dissipation of structural walls was small if high–strength materials were used. The importance of confining boundary elements (columns) was pointed out by the experiment. Nonlinear finite element analyses were carried out for parametric study.

STRUCTURAL DESIGN

Design Earthquake Motion -- A set of performance criteria were established in the design of high–rise reinforced concrete buildings. Two levels of earthquake intensity were considered; i.e., (1) Level 1 earthquakes and (2) Level 2 earthquakes. Level 1 earthquakes (maximum ground velocity of 250 mm/sec) may occur once in the lifetime of a building, and Level 2 earthquakes (maximum ground velocity of 500 mm/sec) may be maximum possible earthquake at the construction site. The response of a structure is influenced by the characteristics of an earthquake motion. An artificial earthquake motion was developed for use in design of super–high–rise building.

Performance Criteria in Nonlinear Dynamic Response Analysis -- The performance criteria must be examined by a nonlinear earthquake response analysis of the designed building under two levels of the design earthquake motion.

Under a Level 1 earthquake motion, cracking of concrete may develop, but reinforce–

ment shall not yield. Under a Level 2 earthquake motion, the maximum story drift shall be less than 1/200 rad. Nonstructural elements should not be damaged under a level 1 earthquake.

Under a Level 2 earthquake, yielding may develop at the ends of beams, but no shear and bond failure should take place during a design earthquake. The structural should not collapse. The lateral deformation at 2/3 height of the building divided by the height should be less than a response limit deformation, and the maximum story drift should be less than 1.5 time the response limit deformation. The response limit deformation must be selected by a designer as a value not greater than 1/120 rad.

As the material strength increases, the dimensions of structural members may be reduced, and the stiffness of the structure decreases. Furthermore, with the increase of material strength, the deformation at flexural yielding is significantly increased. If a deformation (drift) limit is specified in the design criteria, the requirement is expected to govern the design. Plastic deformation may not be utilized as a means to resist earthquake motions.

The number of stories in high-rise building depends on the concrete strength used in the lower stories of columns. The descending branch of concrete stress-strain relation is steep; the use of confining lateral reinforcement becomes inevitable to improve the deformability of a member beyond flexural yielding.

Performance Criteria in Nonlinear Static Analysis -- A three-dimensional structure as designed must be analyzed under monotonically increasing static lateral loading. The base shear coefficient at a structural design deformation should be greater than $0.25\ R_t'\ Z'$, where the structural design deformation should be chosen by the designer as a value greater than the deformation at which the energy stored by the structure becomes more than two times that stored at the dynamic response limit deformation. Z': seismic zone factor, and R_t': dynamic characteristic factor,

$$R_t' = 1.6\ Tc / T \tag{28}$$

where Tc: period determined for soil properties at the construction site (= 0.6 sec for intermediate soil), T: period of first-mode vibration of the structure.

No yielding should take place except at beam ends.

Trial Design -- Some 15- to 60-story reinforced concrete buildings with and without structural walls were designed using present design procedure to study the feasibility and to identify expected design problems. It was observed that large plastic deformation could not be utilized before the lateral deformation reached a specified story drift limit of 1/70 to 1/100 rad. Prestressing technique must be applied to realize wide spans. Shear design of beams at lower stories was expected to be critical.

CONSTRUCTION AND QUALITY CONTROL

A more elaborate supervision of construction work and careful quality control are important in the high-strength concrete construction work. Cold joint was found to form at a high temperature and by inadequate compaction during concrete placement, for a low slump concrete and at a long interval between the concrete placement.

Practical methods of compaction was examined by using a large scale specimen and bar–type vibrators. Full–scale experiment was carried out to examine the construction method including placement of reinforcement, fabrication of formwork, transportation of concrete from factory to construction site, placement of concrete.

CONCLUDING REMARKS

A case of New RC Project was outlined for the general and comprehensive development of new construction technology involving the development of the material to the structural design procedure and the construction. In order to develop such a general technology in a limited period, the research and development in individual fields must be closely coordinated.

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NOTA BIOGRAFICA DE SHUNSUKE OTANI

El profesor Otani, graduado de la Universidad de Tokio en 1966, obtuvo sus grados de maestría y doctorado en la Universidad de Illinois en Urbana–Champaign por su trabajo desarrollado sobre el análisis de la respuesta no lineal ante cargas sísmicas de edificios de concreto reforzado.

Después de una corta estancia como profesor de la Universidad de Illinois, fue docente en el Departamento de Ingeniería Civil de la Universidad de Toronto entre 1975 y 1979. En 1979 fue nombrado como profesor asociado en el Departamento de Arquitectura de la Universidad de Tokio, y en 1993 fue ascendido a profesor titular de estructuras.

Participó en las investigaciones de los daños provocados por el sismo de México de 1985, en su calidad de secretario del equipo de investigación enviado por el Instituto de Arquitectura del Japón.

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