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Development of advanced reinforced concrete buildings with high-strength and high-quality materials

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ABSTRACT: A five-year National Project has been promoted by the Ministry of Construction of Japan since 1988 to develop such structures as super high-rise reinforced concrete buildings in seismic zones. The strength of concrete ranges from 30 to 120 MPa. Yield point of reinforcing bars ranges from 400 to 1,200 MPa.

This paper summarizes research results in three years from 1988 to 1990, mainly related to the structural performance.

1 INTRODUCTION

Reinforced concrete has widely been used for medium scale buildings because of low cost, excellent durability and easy maintenance, and so on.

However, it is impossible to realize super high-rise buildings and buildings with long spans which are currently required from the social point of view, if the material strength remains within ordinary ranges.

Based on this background, the Ministry of Construction of Japan decided to manage a five-year research project entitled "Development of Advanced Reinforced Concrete Buildings Using High-Strength Concrete and Reinforcement"(hereafter referred to as "New RC").

The New RC Project started in 1988 fiscal year, and aims at producing high strength and high quality concrete of the specified strength from 30 to 120 MPa and high strength and high quality reinforcing steel bars of yield strength from 400 to 1,200 MPa, and at developing new field of reinforced concrete buildings by utilizing these materials.

2 OUTLINE OF RESEARCH PLAN

In Fig. 1. major research fields of the project are shown on a plane where the vertical axis is the yield strength of steel bars and the horizontal axis is the compressive strength of concrete.

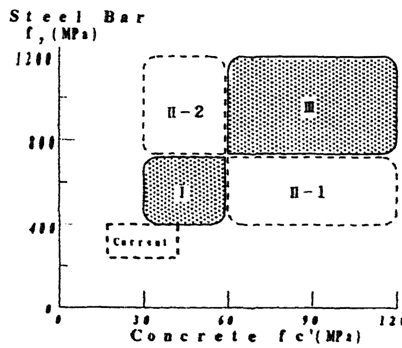

Fig. 1. Strength of materlals and fields (I, II-1, II-2 and III) of reaearch and development.

The small zone named as "Current" in the figure corresponds to the area for current ordinary reinforced concrete buildings and high-rise reinforced concrete buildings (about twenty through thirty stories) developed recently.

Zones I, II-1, II-2 and III are zones treated in the project. Practical results are expected in Zone I and possibly in Zone II-1. Basic subjects have mainly been investigated in Zones II-2 and III.

The objectives of the research and development and the corresponding final results expected in the project are summarized in Table 1. Some of the results will be applicable to refinement of the current reinforced concrete technology.

3 RESEARCH ON CONCRETE

Research items on concrete are : (a) development and quality examination of cement, aggregate, admixture, and binder, (b) establishment of mix proportion, (c) evaluation of workability, mechanical properties, long-term properties, durability and fire resistance, and (d) development of construction techniques.

Photo 1 shows concrete of compressive strength of 100 MPa after slump test. The high range water reducing agent was used in this concrete. The slump was 26 cm and the slump flow was 74 cm although water/cement ratio was 23 %. The adhesiveness of high strength concrete due to usage of large amount of cement is one of the problem for placement, and new cement is now under development in order to improve workability of concrete.

Fire resistance of concrete over 60 MPa is one of the important subject to be further investigated.

Currently, it may be summarized on concrete that sufficient data for practical use of concrete with a specified design strength from 60 to 80 MPa have been accumulated, although some special techniques may be required in order to develop super high strength concrete of a specified design strength over 100 MPa.

Examples of stress-strain relationships of concrete are shown in Fig.2.

4 RESEARCH ON REINFORCING STEEL BARS

Figure 3 shows typical tensile stress-strain relationships of steel bars available on the market. The higher the strength is, the narrower the yield plateau is and the smaller the rupture strain is. The yield point of ultra high strength steel bars is not clear.

High strength reinforcing steel bars with specified yield strength of 700 MPa and improved performance were manufactured and used in the New RC element and member tests. Figure 4 shows an example of typical stress-strain relationships of the improved high strength steel bars. The improved ultra high strength steel bars with a specified yield strength of 1,000 MPa had large rupture strain more than 10 %.

Thread-deformed bar couplers with grouted mortar capable of developing ultimate strength of high strength steel bars were developed. However other splicing method popularly used in Japan such as gas-pressure welding or enclosed inert-gas welding were difficult to develop ultimate strength of high strength steel bars and are under improvement now.

Table 1. Objectives of reserch and development and final results expected.

Objectives	Final Results Expected
1) Development of high-stength and high-quality materials	·Methods for mix proportion method and quality control of concrete (Zone I) ·Methods for production and arrangement of reinforcements (Zone I) ·Guidelines for developing materials for Zone II and III
2) Evaluation of properties of structural members and frames	·Methods for analysis
3) Development of design and construction guidelines	·Structural design guideline (Zone I) ·Construction guideline (Zone I) ·Draft guidelines for structural design and construction (Zone II, III)
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

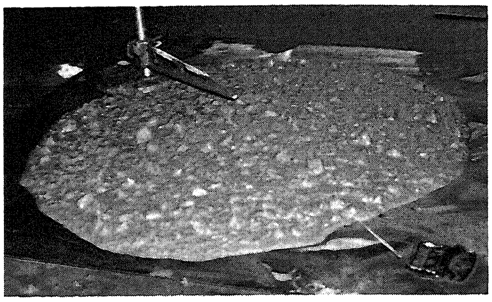

Photo 1. Concrete after slump test.

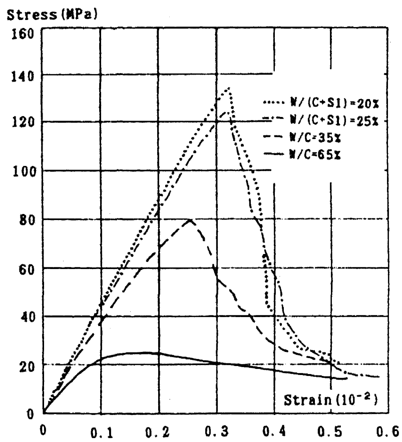

Fig. 2. Examples of stress-strain relationships of concrete.

5. TESTS ON NEW RC ELEMENTS

Many reinforced concrete element tests were conducted to obtain basic mechanical properties. Element tests focused on compressive behavior of confined concrete, bond characteristics, yield criteria of concrete under biaxial stresses, and tension stiffening of reinforced concrete. Some of the highlights of the tests are summarized as follows.

5-1 Confined concrete

Pronounced falling branch of the stress-strain relationship is the distinct feature of high strength concrete.

Many uniaxial compression tests of concrete laterally confined with steel bars were conducted. It is concluded from these tests that ; (i) high strength steel bars are effective in achieving good confinement, (ii) the configuration of hoops is a very important factor for confinement of rectangular columns, and usage of sub-hoops is one of effective confinement configuration, and (iii) the excellent ductility of high strength concrete beyond maximum strength is expected by arranging proper lateral reinforcement.

Figure 5 shows examples of these test results.

5-2 Bond characteristics

The demand on bond between concrete and steel bars increases in proportion to the increase of yield strength of steel bars. On the other hand, the bond capacity does not increase in proportion to the increase of concrete strength. Thus, the bond capacity may become one of the critical problems for the New RC structures. Outlines of two kind of the research on this subject are as follows.

1. Pull-out tests of seventy standard hooks embedded in high strength concrete were carried out. The shape of standard hooks used were in accordance with JASS 5 (AIJ Standard Specification for Reinforced Concrete Construction), which is permitted to apply only to normal strength concrete. From the test results it is revealed that the hooks with yield strength of 800 MPa have enough pull-out strength beyond yield stress of the steel bar, if they are embedded in high strength concrete with com-

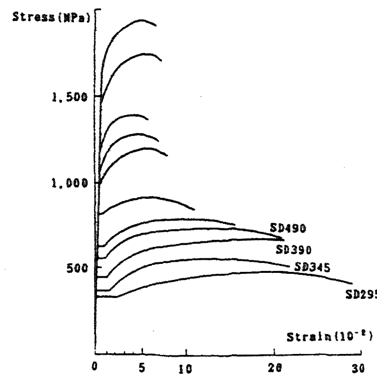

Fig. 3. Examples of stress-strain relationships of steel bars.

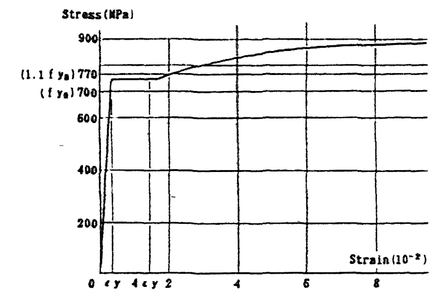

Fig. 4. An example of stress-strain relationships of the improved steel bar of a specified yield strength of 700 MPa.

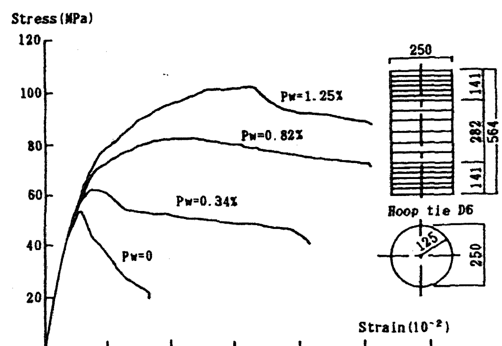

Fig. 5. Examples of stress-strain relationships of confined concrete.

pressive strength more than 80 MPa, using the specification cited in JASS 5.

2. Beams designed to fail in bond splitting failure mode before yielding of tensile longitudinal steel bars were tested. Test results showed that ; (i) the bond strength was proportional to square root of

compressive strength of concrete, and (ii) in case of specimens without lateral reinforcement, bond strengths showed good agreement with those given by the equation proposed by Morita and Fujii[1], and in case of specimens with lateral reinforcement, they were larger than those given by the equation. This results are summarized in Fig. 6[2].

5-3 Failure criterion of ultra high strength concrete under biaxial stresses.

Ultra high strength concrete panels with dimension of 200 x 200 x 50 mm were loaded to failure under biaxial compression. The test condition was similar to the tests of Kupfer et al. [3]. The panels were subjected to monotonously increasing load, maintaining the ratio of principal stresses of 0.0, 0.2, 0.52, 0.75, and 1.0.

Figure 7 shows the obtained schematic failure criterion in terms of principal stresses together with those for normal strength concrete and high strength concrete[4]. The strength of ultra high strength concrete increases more than thirty percent from the strength under uniaxial compression, although the increase of compressive strength decreases to zero in case of the stress ratio of 1.0.

Test results on the failure criterion under tension-compression show that a line connecting uniaxial tensile strength and uniaxial compressive strength represents the failure criterion in this range[4].

6. TESTS ON NEW RC MEMBERS

Shear strength and deformation capacity were the major research items in the test of beams, columns, shear walls and beam-column subassemblages. Bond splitting failure and anchorage strength were also investigated in member tests.

Some of the results derived from these researches are summarized below.

6-1 Flexural behavior of columns

Figure 8 shows two relationships between bending moment at the critical section and top drift angle obtained from shear bending test of columns. Only difference in two specimens is the yield stress of

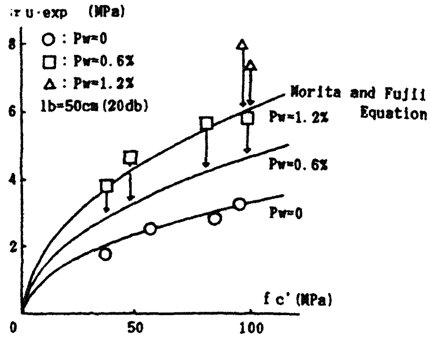

Fig. 6. Test results of the relationship between bond strength and compressive strength of concrete.

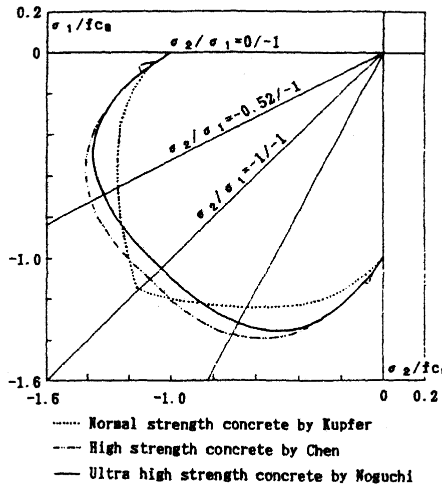

Fig. 7. Schematic failure criterion of the principal stress.

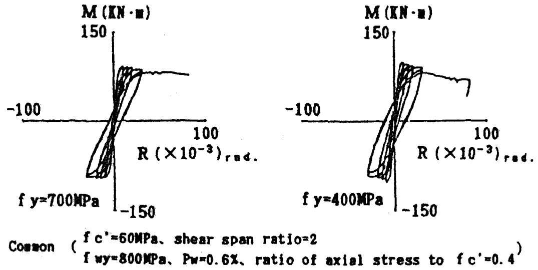

Fig. 8. Relationships between bending moment at the critical section and tip drift angle of columns.

longitudinal steel bars, and one is 700 MPa and the other is 400 MPa, although the product of the total cross sectional area of the longitudinal steel bars by yield stress is the same. By comparing the both results, it is pointed out that residual displacement and energy dissipation of the specimen using high strength longitudinal steel bars are smaller than those using normal strength ones, and good deformability can be expected even if high strength steel is used for longitudinal reinforcement.

The followings are major results from other column tests.

1. If columns have the same amount of lateral confinement, columns with tie reinforcement in core section have larger deformability than those without tie reinforcement. New RC columns with properly arranged lateral reinforcement have sufficient deformation capacity.

2. Usual bending theory is applicable to New RC members if suitable stress-strain relationships of concrete and confined concrete are incorporated.

3. Bond splitting failure remarkably affects the deformation capacity of columns.

4. Splitting failure of concrete along the height of columns, dividing the columns into two or three portions, occurred in some New RC column specimens. This failure was caused mainly by low tensile strength of concrete and may be one of the typical failure pattern of New RC columns with small shear span-depth ratio subjected to high axial stress.

6-2 Flexural behavior of shear walls

Two shear wall Specimens, NW-1 and NW-2, representing the lower part of the shear wall in the trial design of a high-rise(40 stories) New RC building were tested[5].

Compressive strength of concrete was about 90 MPa. Tensile yield strength of steel bars were 800 MPa, 1,000 MPa, and 1,300 MPa for column longitudinal bars, wall reinforcement and column hoops, respectively. Horizontal force was applied to the top of the specimen with the axial force equivalent to that of the assumed 40-story New RC building. Shear span ratios were 2.0 for NW-1 and 1.33 for NW-2, respectively.

Following conclusions were obtained (see Fig.9).

1. Both specimens did not show remarkable strength deterioration until final failure, but their restoring force characteristics were "S" shaped hysteretic loops with poor energy absorption.

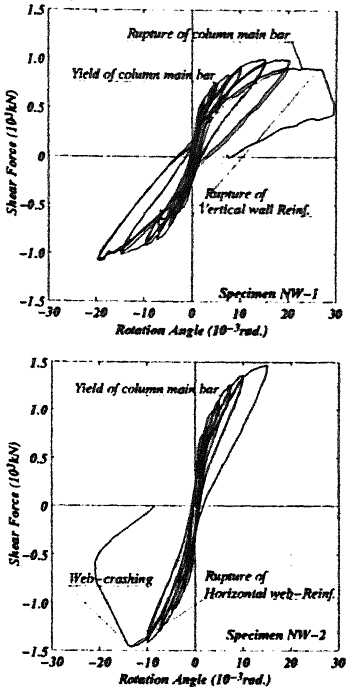

Fig. 9. Relationships between lateral shear and tip drift angle of shear walls.

2. Longitudinal steel bars of a boundary column of NW-1 ruptured at the drift angle of 0.025 rad. Compressive failure in wall panel occurred at 0.015 rad. in NW-2. But columns of the specimens could sustain the axial force.

3. Flexural strength of New RC shear walls could be estimated by the same equation for normal strength shear walls.

6-3 Shear strength of beams

As for this subject, we have already reached the final conclusions as follows through shear tests of New RC beams[6].

1. Empirical equation proposed by Arakawa[7] underestimates the shear strength of New RC beams.

2. Shear strength of New RC beams could be estimated accurately by the AIJ method[8] using the effective compressive strength of concrete proposed by CEB[9].

6-4 Shear behavior of exterior beam column joint panel

The following conclusions are listed

by Joh[10] although the values may be changed somehow according to further research.

1. At least 17 % of compressive strength of concrete can be expected for shear strength of exterior beam column joint panels using concrete less than 80 MPa in compressive strength.

2. Axial force has little effect on the shear strength of New RC exterior beam column joint panels if the axial stress is less than 30% of compressive strength of concrete.

3. Shear crack strength can be estimated by the principal stress method.

7. RESEARCH ON STRUCTURAL DESIGN

Trial designs of a sixty-story moment resisting frame structure, a sixty-story wall-frame structure, a forty-story double tube structure, a forty-story tube-core structure, and a fifty-story structure with long span were carried out and seismic behaviors of the buildings were examined. The construction site was assumed to be in Tokyo area, and current Japanese seismic requirements were adopted to these buildings. Findings from these trial designs are that; (i) in the structural design of the buildings using New RC materials, allowable permanent axial stress for column, allowable interstory drift of 0.5% at the design base shear, shear stress of beam column joint panel, will be important factors to dectate the building design. However, shear stresses of beams and columns at the design base shear are very small, (ii) nonlinear earthquake response analysis showed relatively small values of drift, and (iii) super high-rise moment resisting frame structures will be easily designed if New RC materials are used.

8.CONCLUSION

New RC has great merits in structural performance, although some demerits compared to its high strength are found. It is expected that super or ultra high-rise buildings will be easily realized by New RC and new types of reinforced concrete buildings will be developed by New RC in near future.

ACKNOWLEDGMENT

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