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STRESS-STRAIN RELATIONSHIP OF REINFORCING BARS IN CONCRETE AND MECHANICAL BEHAVIOR OF RC BEAMS IN FLEXURE

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SYNOPSIS

Mechanical behavior of a deformed bar covered by concrete is different from the one without concrete. The behavior of re-bars in concrete was examined by two types of tests; i.e. tensile test and beam test. In the tensile test, spreading process of yield zone and load deformation curve of re-bar covered by normal concrete or by steel fiber reinforced concrete was compared with those without cover concrete. In case of deformed re-bar with cover concrete, deformation after yielding was restricted by the cover remarkably and yield plateau was not observed, whereas, in case of round re-bar, bond was lost after yielding and deformation process was all the same as that of re-bars without cover. In flexural test of RC beams, deformed, round and partially unbonded re-bars were used so as to change the bond property. Calculated load deflection curves of RC beam, based on the stress-strain curve model from the tensile test of re-bar covered by concrete coincided well with the tested one, while those based on commonly used bi-linear model did not coincide well and showed fairly low load level.

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1. INTRODUCTION

Since limit state design for reinforced concrete (RC) structures has been adopted, it has become more and more important to calculate precisely not only the strength but also the deformation of RC structural members, because the ultimate limit state of section failure as well as that of mechanism must be precisely estimated.

For strength design of RC members, the design strength is calculated so that it will always be smaller than the true strength to have a certain allowance in the modelling of material property as well as in calculation method. This design method has long been considered to promise safety and has been adopted. The method sometimes invites excess margin in the strength, and in some cases, this causes change in the failure pattern from the expected one to another (e.g. from flexure to shear failure) and reduce the safety as a result.

Flexural design strength of RC beams is always calculated, world wide[1-4], under the conditions of strain compatibility and stress equilibrium, assuming the stress vs. strain curves of concrete and re-bar and neglecting concrete tension. The shape of the stress strain curve of concrete is, in general, modeled as the combination of a parabola and a straight line, or as a rectangular; on the other hand, that of re-bar is modeled as bi-linear (elasto-plastic). It has been recognized that the calculated ultimate strength of RC beams changes only slightly while the shape of the curve of concrete changes largely[5]. It is also recognized that measured flexural strength coincide well with calculated one which is based on the above assumptions when round re-bars are used[5]. The measured strengths of small RC beams with deformed re-bars are, however, about 10 to 20 percent larger than the calculated ones[6,7]. Measured strength became more than 30 percent higher for RC beams made with steel fiber reinforced concrete [8]. The use of deformed re-bars and steel fiber improves bond property between re-bars and concrete and probably this affects the tensile behavior of re-bars in concrete. In calculating the relation of bending moment vs. curvature as well as flexural strength of RC beams, only the property of cracked section is taken into account in general. In actual beams, non-cracked portion also exists. The deformation of re-bars is restricted by the sorrounding concrete in these areas. It must be somewhat different from that in cracked section. The section properties of a cracked section alone are not enough to evaluate the poperty of RC beams precisely.

In order to calculate the load-deformation curve and flexural strength of RC beams, the effect of non-cracked section is taken into account in this study. From the view point of structural analysis and design, RC beam section is always assumed to be composed of re-bars and concrete, where tensile force in the section is taken by only re-bars. Actually, the tensile force is thought to be taken by the re-bars covered with concrete. Two types of test were performed; (a) tensile test and (b) beam test. Tensile tests of re-bars covered with concrete were carried out to see a spreading process of yield zone of re-bars within concrete. Stress-strain relations were also examined. They were compared with the one without concrete (naked re-bars). Loading tests of RC beams with deformed re-bars, round bars (low bond strength) and those treated as partially bondless (to be called "unbond" re-bars, hereafter) were also conducted. The effect of bond on the deformation and strength characteristics of the beams were investigated. In addition, using stress-strain curve model derived from the tensile tests, simulation analysis of the load deflection relation of RC beams was carried out.

2. OUTLINE OF EXPERIMENTS

2.1 Tensile Test

The shape of a tensile test specimen was, as shown in Fig. 1, 10 cm square concrete section with 60 cm long, and a re-bar of 100 cm long was placed at the center of the section.

Two kinds of deformed bar (D13 and D16) and one kind of round bar (R13) were used. Kinds of the tensile test specimens are shown in Table 1. The re-bars of D16 were grooved by a special milling process to 4x8 mm channel, as shown in Fig. 2(a). At first, two bars were scraped off to the center of the section along the bar axis and the channel was grooved. Then, the two halves were glued with epoxy resin into a single bar having about the same cross section as the original bar. Calculated cross section of the processed bar was 1.959 cm^2 (original cross section was 1.986 cm^2), where specific gravity was assumed to be 7.85. Water proof type electric resistance wire strain gages (2 mm gage length) were attached at the channel. There were two types of gage location according to their pitchs; 25 mm or 40 mm, as illustrated in Fig. 2(b).

Normal concrete (NC) and steel fiber reinforced concrete (SFRC) were adopted as concrete. Cement used was high early strength portland cement. River sand (Spec. gravity = 2.58, F.M. = 2.70) and crushed river gravel (Max. size = 15 mm, Spec. gravity = 2.60) were used. The diameter and the length of the steel fibers (cut wire type) were 0.5x30 mm. The amount of the fiber

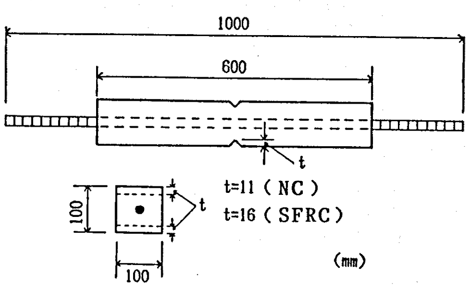

Fig. 1 Specimen for tensile test

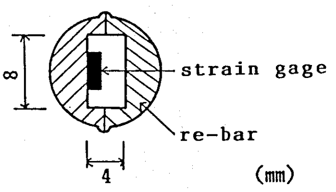

Fig. 2(a) Section of processed re-bar

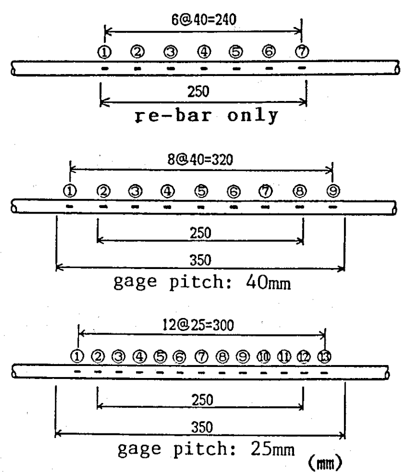

Fig. 2(b) Positions of wire strain gages

Table 1 Kind of tension test specimens

specimen	re-bar	bar area	concrete	gage pitch	no.
MN40 MN25	D16 milling pros.	1.959cm²	NC	40mm 25mm	1 1
MF40 MF25			SFRC	40mm 25mm	1 1
MS40			———	40mm	1
D16	orig. bar	1.986cm²	———	———	3
P13 F13	D13	1.267cm²	NC SFRC	———	3 3
M13 R13	φ13	1.327cm²	NC SFRC	———	3 2
D13 φ13	D13 φ13	1.267cm² 1.327cm²	———	———	3 3

addition in concrete was 2 % by volume. Mix proportions of the concrete are shown in Table 2. These mixes were also used for RC beams described later.

In order to make sure that the first crack would occur within deformation measuring gage length, a set of notch was mounted on the opposite face at the middle of the specimen. The notch depth was 11 mm for NC and 16 mm for SFRC, and the reduction ratio of the section area was 22 and 32 %, respectively. For specimens with D13, both ends of the re-bar were welded to D19 bars and were strengthened so that it would not fail outside the concrete portion. To avoid the concrete cracking due to the sudden change of bar section, spiral reinforcement was also provided in these end zones. For specimens with D16 and R13, only the spiral reinforcement was provided.

Each specimens were cast laterally in a mold with two layers. Specimens for compression, tensile and flexural strength tests (∅10x20cm, ∅15x15cm and 10x10x40cm, respectively) were made at the same time. The specimens were removed from the mold one day after casting and then wet curing was made for two weeks. Concrete strength at the age of 28 days was shown in Table 3, including those for RC beam test.

Tensile test was conducted at one month after casting of the specimens. Tensile test of re-bar without concrete was also made at the same time. Riele

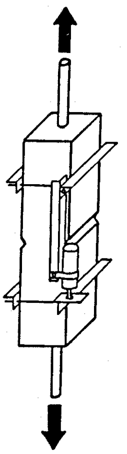

Fig. 3 Tensile test and measuring method

Table 2 Mix proportions of concrete

concrete	W/C (%)	s/a (%)	W kg/m³	C kg/m³	S kg/m³	G kg/m³	S.F. kg/m³	WRA
NC	60	47	183	304	850	954	———	———
SFRC+	54	69	195	363	1111	497	157	C x0.25%
SFRC*	54	69	207	384	1060	478	157	C x0.25%

+ for tensile and beam test
* for only tensile test of mill. processed bar

Table 3 Strengths of concrete

kind	bar	concrete	comp. MPa	flex. MPa	tens. MPa
tensile test	mill.	NC SFRC	40.8 46.7	6.34 10.47	3.19 4.04
	def.	NC SFRC	44.0 53.7	6.24 11.87	4.06 6.41
beam test	def.	NC SFRC	35.1 49.5	5.23 11.27	3.06 5.98
	round	NC SFRC	39.1 50.1	6.18 10.61	3.50 6.30
	unbond	NC SFRC	42.7 47.3	6.11 10.47	2.83 6.52

Table 4 Kinds of beam specimens

name	kind of re-bar	kind of concrete	comp. reinf.
CP0 CP10	deform. σ_{sy}=364MPa As=2.53cm²	NC σ_c=35.1MPa	none with
CF0 CF10		SFRC σ_c=49.5MPa	none with
PP0	round σ_{sy}=324MPa	NC σ_c=39.1MPa	none
PF0	As=2.65cm²	SFRC 蚕 σ_c=50.1MPa	none
UP0 UP10	"unbond" σ_{sy}=364MPa As=2.53cm²	NC σ_c=42.7MPa	none with
UF0 UF10		SFRC σ_c=47.3MPa	none with

type universal loading machine (100 tonf capacity) was used. Measuring gage length of deformation (strictly speaking, elongation) was 250 mm including the notched portion, which corresponded to the moment span length of RC beam test. Two displacement transducers (stroke:50 mm, accuracy:5/1000 mm) were attached to the specimen at symmetrical positions in a section by an appropriate jig, as shown in Fig. 3. At the loading test, electrical signals from the displacement transducers and that from strain gages in a re-bar were put together with load signals into a data logger which was under control of a personal computor. All the data was recorded in a floppy disc. Displacement of the cross head of the loading machine was also measured and recorded mechanically.

In case of tesile test of re-bar without cover concrete, gage length was also kept to 250 mm. Gage points got closer to holder as could as possible so as to break re-bar inside the gage length. The same length naked re-bars as pull test specimens were also tested and the relation of load-displacement of the testing mechine was recorded.

2.2 Beam Test

Shape of a beam specimen was 10x18x170 cm, as shown in Fig. 4. For tension reinforcement two kinds of re-bar, 2D13 or 2R13, were used, which were also provided in the tensile test (tensile steel ratio was 1.64 or 1.72 %, respectively). For doubly reinforced beams, 2D10 re-bar (σ_{sy}: 368 MPa) were used (compression steel ratio was 0.93 %). Two types of concrete, i.e. NC and SFRC, were adopted. There were ten kinds of beam specimens with different combinations of re-bar and concrete, as shown in Table 4. Two specimens were made for each kind. An unbond re-bar (partially bondless deformed re-bar) was made by coating the original re-bar with synthetic rubber and grease and by wrapping it with plasic film to lose bond between re-bar and concrete for a mid part of 45 cm in a beam, as shown in Fig. 5. A water proof type wire strain gage (gage length: 2 mm) was attached to a tensile re-bar in each specimen. For the specimens with deformed re-bar and SFRC, a 3 cm deep notch was made at the bottom of the center that the first crack occur within the moment span region. Stirrups were provided by 10 cm pitch in shear span so as not to cause shear failure. Placing and curing methods were the same as that for the tensile tests.

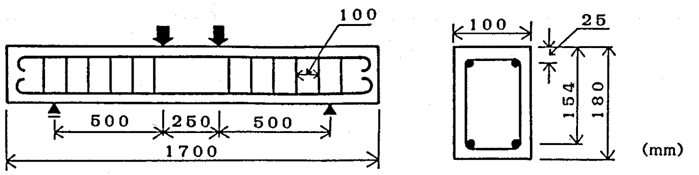

Fig. 4 Specimen for beam test

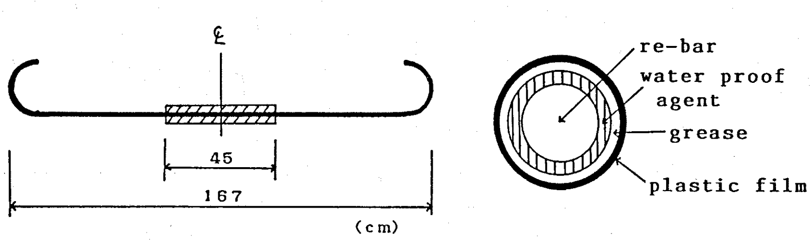

Fig. 5 "Unbond" re-bar

Four point bending test was made. Loading span length was 125 cm (moment span: 25 cm, shear span 50 cm). Loading was made monotonously. Load was measured by a load transducer (capacity of 30 tonf). Displacement under loading points, steel strain and load were recorded in the same manner as in case of the tensile test.

3. RESULTS AND DISCUSSIONS

3.1 Tensile Test

Yield strength and maximum strength of each specimen are listed in Table 5. Yield point was defined as the first bend point in a load deformation curve.

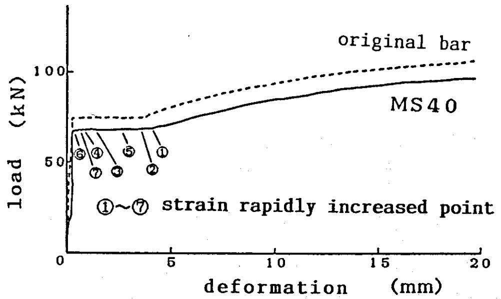

Fig. 6(a) Load-deformation curves (MS40, original bar)

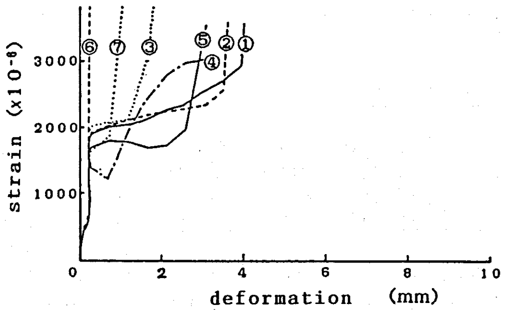

Fig. 7(a) Strain-deformation curves (MS40)

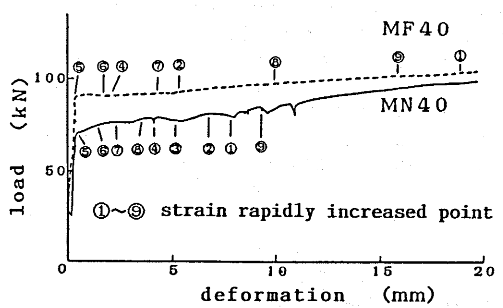

Fig. 6(b) Load-deformation curves (MN40, MF40)

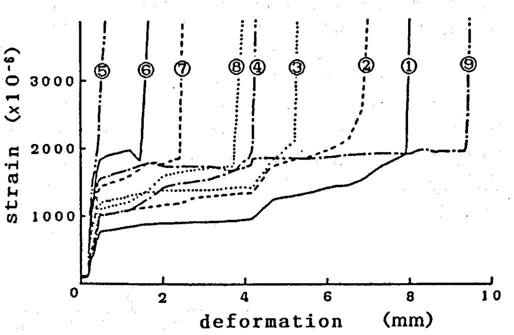

Fig. 7(b) Strain-deformation curves (MN40)

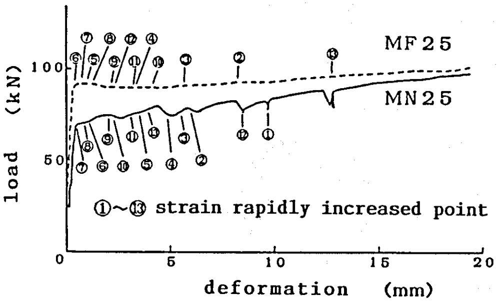

Fig. 6(c) Load-deformation curves (MN25, MF25)

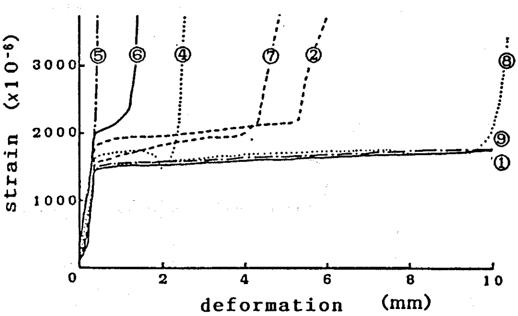

Fig. 7(c) Strain-deformation curves (MF40)

(1) Spreading process of yield zone in milling processed re-bar

Fig. 6 (a)-(c) shows the load deformation curves obtained from the tensile test of milling processed re-bars. Fig. 7 (a)-(c) also illustrates the relation of deformation and strains at various position in a re-bar. Circled number is a gage number in Fig. 2(b). Nominal yield strain was 0.0018, which was derived from yield strength and nominal Young's modulus (206 GPa). As a whole, however, steel strain increased rapidly when it was about 0.002. The point where strain incresed rapidly is considered to be the point where yielding initiated. These points were marked in Fig. 6.

In case of re-bar without cover concrete, yield zone spread immediately to the whole gage position when yield occurred at a point. After yield zone spread to all the gage positions, re-bar entered the work-hardening region and load increased. The deformation until the yield spread to all the gage positions was ca. 4 mm.

For tensile test of re-bar covered with NC and SFRC, yield of re-bar initiated at the notched position, where a crack in concrete occurred under much lower load. At the adjoining gage position, however, yield did not occur immediately. As deformation increased, yield zone spread gradually from the nearest gage point to the farthest one. Total deformation until the yield occurred at all the gage positions was 5 to 15 mm. In case with NC, several new cracks formed one after the another while defomation increased and, at that time, load dropped once suddenly. These points coincided with the points where yield initiated of re-bar at the crack position.

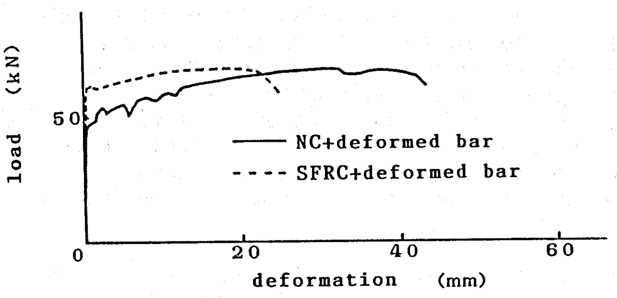

Fig. 8(a) Load-deformation curves (covered deformation re-bar)

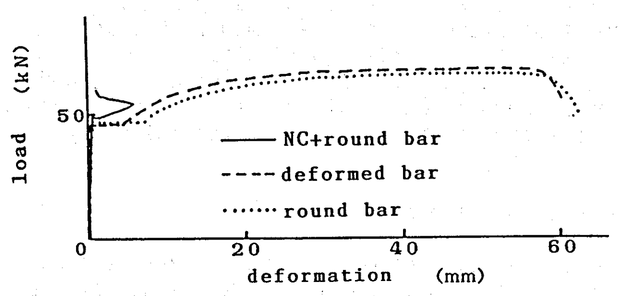

Fig. 8(b) Load-deformation curves (covered round bar, bar only)

Table 5 Results of tensile test

kind	yield load kN	maximum load kN
MN40	68.8	103.3
MN25	68.1	101.7
MF40	88.7	105.0
MF25	88.8	102.5
MS40	66.6	101.7
D16 1	73.5	113.0
2	73.8 (73.9)	112.2 (112.3)
3	74.4	111.7
P13 1	47.4	67.6
2	46.1 (46.7)	67.4 (67.8)
3	46.6	68.4
F13 1	60.8	67.6
2	63.7 (61.8)	67.7 (67.6)
3	60.8	67.4
M13 1	46.3	65.7
2	46.1 (46.3)	65.9 (65.8)
3	46.4	65.7
R13 1	46.3	65.7
2	46.1 (46.2)	65.7 (65.7)
D13 1	45.6	67.6
2	45.7 (45.6)	67.4 (66.9)
3	45.5	65.8
Φ13 1	46.3	65.1
2	46.1 (46.3)	64.7 (65.0)
3	46.4	65.1

( ) ; average

(2) Behavior under tensile test with deformed re-bar

Typical measured load-deformation curves are shown in Fig. 8 (a),(b). Yield strength of re-bar covered with NC was 2 to 4 % higher than that of naked re-bar. Ultimate strengths were, however, almost the same. In case of re-bar with NC, yield plateau did not appear, but it was clearly observed in case of re-bar without concrete. After the initiation of yielding, load increased gradually with the increase of deformation. The reason of this difference is considered to be as follows. For re-bar with concrete, there is a crack only at the notch position at the beginning of yielding. Plastic deformation caused by the yielding must be concentrated and limited only to the crack position and its mere vicinity, because except the cracked position, the load applied to the specimen is carried not only by a re-bar but by concrete section. Stresses in the rest of re-bar must be less than the yield stresses. Before the effect of yield plateau on the total elongation appears dominantly, the limited small portion will probably enter the work hardening region whereas another portion still remains in elastic region. We concluded that is why the yield plateau could not observed and load increased just after yield initiates for the re-bar with concrete. With the increase of deformation, new cracks were formed one by one in addition to the first crack. At this moment, load dropped once suddenly and yield of re-bar probably occurred at the newly formed crack position and its vicinity. The portion is likely to reach immediately to hardening region and load level returned to the level before the cracking. These process continued and the yield gradually spread over the whole length.

Yield strength of re-bar with SFRC was 30 to 40% higher than naked re-bar. Stress of SFRC at the yield of re-bar was calculated to be ca. 2.5 MPa from the above difference of the yield strengths. This value is about a half of the tensile strength obtained by splitting tensile test and corresponded to the tensile strength after the peak stress of SFRC with 1.5 to 2 % fiber addition, which was reported by Kobayashi et al [9]. In case of SFRC, there was a crack at the notch section before yielding. The cracked SFRC section, however, transmitted a certain amount of tensile force at the time of yielding. As a result, yield strength increased in case of SFRC. During the increase of deformation after yielding, no additional crack formed and only the width of the initial crack increased. With the increase of the crack width, steel fibers at the crack were broken or pulled out and the load transmitted with SFRC decreased, while, the load with re-bar increased because of work-hardening. As a whole, the load increased.

Fig. 9 (a),(b) illustrates the relation between the load versus displacement of the cross head of a testing machine; (a) for deformed re-bar, and (b) for round re-bar, with and without concrete cover. The displacement included not only the elongation of a specimen but also some slipping in gripping portion. Total displacement at breaking of a deformed re-bar is largely affected by its cover concrete. In comparison with ultimate displacement of re-bar without cover, it was about 1/2 for re-bar with NC and about 1/3 for re-bar with SFRC, and in both cases, yield plateau did not appear. This means that the deformation of deformed re-bar is largely restrained by sorrounding cover concrete.

(3) Behavior under tensile test with round re-bar

At the tensile test with round re-bar with normal concrete cover, a crack also occurred at the notched section in the early loading stage. Width of the crack increased with the increase of loading; however, another crack did not occur. Bond between re-bar and concrete completely disappeared after yielding.

In case of round re-bar with SERC, no crack was generated even at the notched section and after yielding bond between re-bar and SFRC was completely lost.

As shown in Fig. 9(b), in case of round re-bar, ultimate deformation did not change not only by the kind of cover concrete but also by whether it had cover or not. Yield plateau was observed in all the cases. After yielding, deformation of round re-bar was not restrained by cover concrete, i.e. deformation process of round re-bar after the yield is not affected by cover concrete.

3.2 Beam Test

All the beam specimen failed in flexure. Load-deflection curves of beam specimens are shown in Fig. 10 (a) to (j). The results of the tests for yield strength, measured and calculated ultimate strengths, and the ratio of measured strength to calculated one are shown in Table 6. Ultimate strength was calculated according to the Specification for Road Bridge of Japan[10].

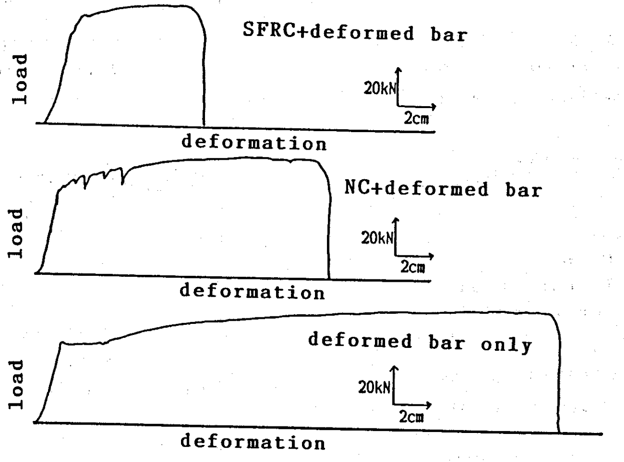

Fig. 9(a) Load-displacement curves (deformation re-bar)

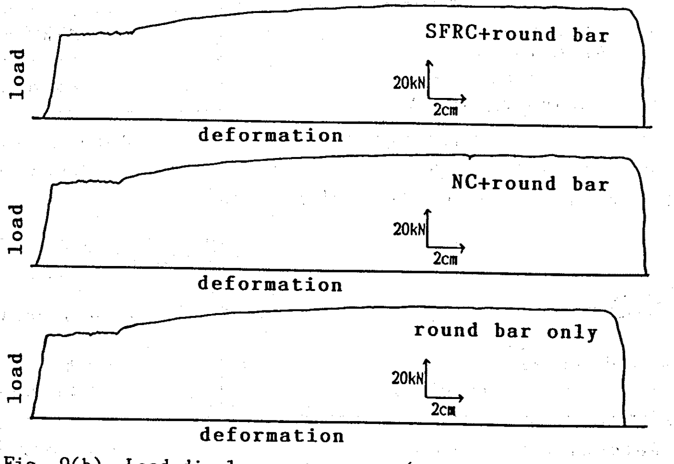

Fig. 9(b) Load-displacement curves (round re-bar)

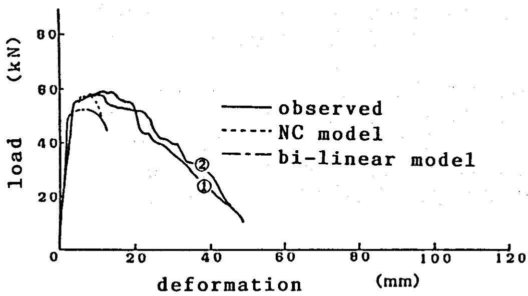

Fig. 10(a) Load-deflection curves (Beam CP0)

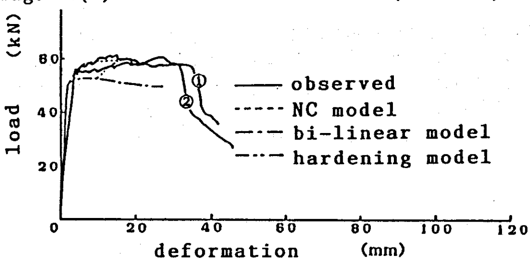

Fig. 10(b) Load-deflection curves (Beam CP10)

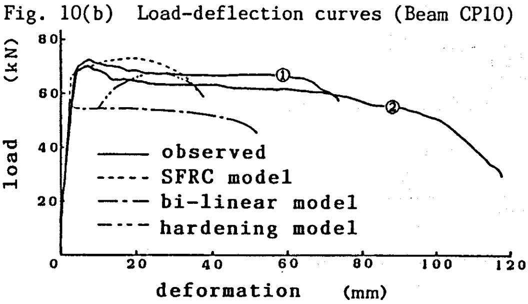

Fig. 10(c) Load-deflection curves (Beam CF0)

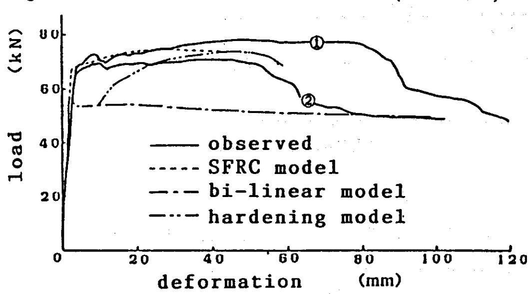

Fig. 10(d) Load-deflection curves (Beam CF10)

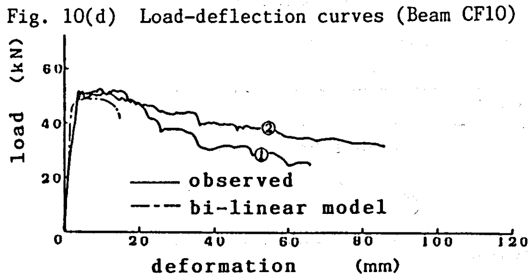

Fig. 10(e) Load-deflection curves (Beam PP0)

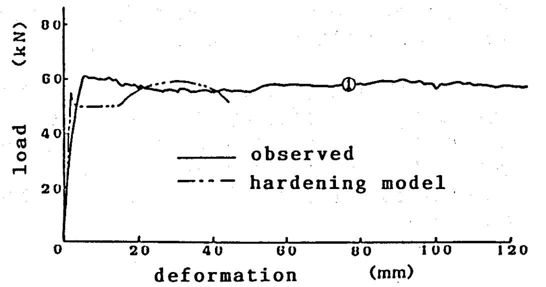

Fig. 10(f) Load-deflection curves (Beam PF0)

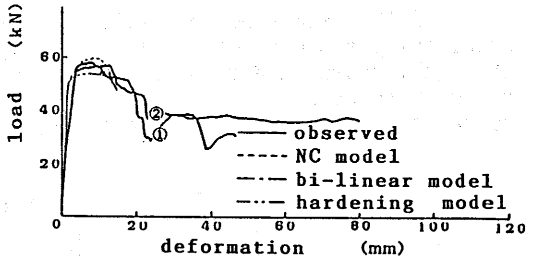

Fig. 10(g) Load-deflection curves (Beam UP0)

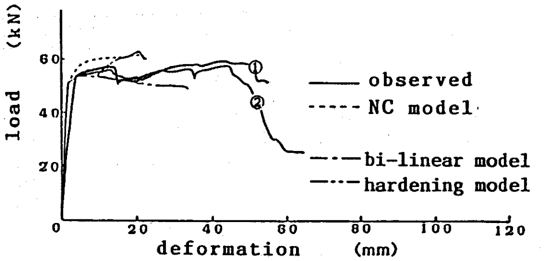

Fig. 10(h) Load-deflection curves (Beam UP10)

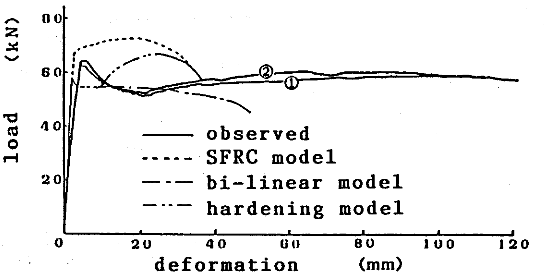

Fig. 10(i) Load-deflection curves (Beam UF0)

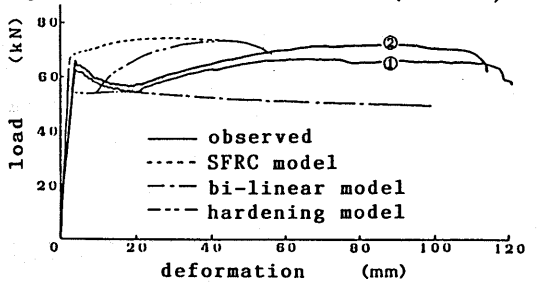

Fig. 10(j) Load-deflection curves (Beam UF10)

(1) Beams with deformed re-bar

Measured yield strength of beams with deformed re-bar and NC was about 7 % higher than calculated one, which was a little bit smaller than expected one. Probably because of the coating with epoxy resin and vinil tape of wire strain gage attached to re-bar, bond stress between concrete and re-bar was lost from the portion and deformation of re-bar after yielding occurred not only just at the position of cracking but spread to the wide portion without bond. As a result, the yield strength of beams with deformed re-bar was approximately the same as those with "unbonded" re-bar. After yielding, load increased probably because bondless portion of re-bar entered the work-hardening region. Beams with deformed re-bar and SFRC shows yield load about 25 % higher than the calculated one. After yielding, load also increased as in the case of NC.

(2) Beams with round re-bar

Measured yield strength of beams with round re-bar and NC was about 5 % larger than the calculated one. Load after yielding was almost constant and no increase in load was observed. For beams with SFRC, measured yield load was about 20 % larger than the calculated one. Load decreased gradually with the increase of deflection, while, it turned to increase when the deflection became about 50 mm. This happened perhaps because re-bar entered the work-hardening region.

(3) Beams with unbonded re-bar

After yielding, load of beams with unbonded re-bar and NC did not increase as the same as in case of round re-bar and NC and it decreased finally when crushing of compression concrete crushed. For the beams to which compression reinforcement was provided, load decreased gradually when concrete crushed, but it turned to increase when the deflection became more than about 20 mm. The increase was probably caused by the re-bar that entered the hardening region.

Table 6 Results of beam test

specimen		yield load(kN)	maximum load(kN)	calc. load(kN)	yield/calc.
CP0	1	54.8	57.9	51.1	1.07
	2	54.8	57.0		1.07
CP1	1	53.7	57.4		1.05
	2	55.2	60.1		1.08
CF0	1	66.3	71.3	52.7	1.26
	2	66.5	68.7		1.26
CF1	1	66.6	76.2		1.26
	2	64.8	69.4		1.23
PP0	1	50.8	50.8	48.5	1.05
	2	50.9	51.6		1.05
PF0	1	bond failure		49.5	—
	2	59.8	59.8		1.21
UP0	1	55.0	57.0	52.0	1.06
	2	53.1	56.0		1.02
UP1	1	52.8	58.3		1.02
	2	52.4	56.4		1.00
UF0	1	61.6	61.6	52.5	1.17
	2	62.8	63.0		1.20
UF1	1	61.8	65.5		1.18
	2	64.9	70.7		1.24

Yield strength of beams with SFRC was larger than calculated one by about 20 %. At the time of yield initiation, there was only one crack in a beam. In case of SFRC, a certain amount of tensile force will be transmitted through the crack portion even after cracking. Probably, this is the reason why the yield strength increased largely. Load decreased gradually when deflection increased. This is probably because number of fibers which were pulled out and broken increased. When deflection became about 20 mm, load incresed again also as in case of unbond re-bar with normal concrete.

4. APPLICATION TO LOAD DEFLECTION CURVE OF RC BEAMS

Observed load-displacement curves of RC beams were compared to the calculated one, where three sorts of stress-strain relation of deformed re-bar were assumed; (a) derived from the results of tensile test with NC or SFRC (to be called as tensile test model, hereafter), (b) derived from usual tensile test of re-bar itself including work hardening region (hardening model), and (c) commonly adopted in strength design (bi-linear model). These three sorts of models of stress strain relations are shown in Fig. 11. For beams with round re-bar, the calculation was made with only two sorts of models, i.e. hardening model and bi-linear one, since in this case bond of re-bar to concrete was found to have no effect on the deformation of re-bar after yielding. Stress-strain relation of concrete was obtained through the standard cylinder test and it was modeled in the calculation as shown in Fig. 12. For SFRC the relation in tension was taken into account.

Load-deflection curve was calculated through the section-dividing method using stress strain relations of concrete and re-bar. One section was divided into one hundred layers. From the conditions of equilibrium and compatibility, flexural moment versus curvature relation was obtained. Then, deflection was calculated with area-moment method. Calculated load deflection curves were added in Fig. 10. In case of CPO and PPO, calculated results with bi-linear model and with hardening model were equivalent. In every case, calculated total deflections are smaller than that observed one because the effect of shear cracking and that of yielding of re-bar in shear span are not included in the calculation. These effects have become large in the region of large deflection, in particular.

The following results were obtained for the deflection in the ordinary range (within deflection/span ratio of 1/50 -- in this case, deflection of ca. 25 mm). Calculated loads with bi-linear model were always smaller than that experimentally obtained. Yield load with hardening model was also smaller than

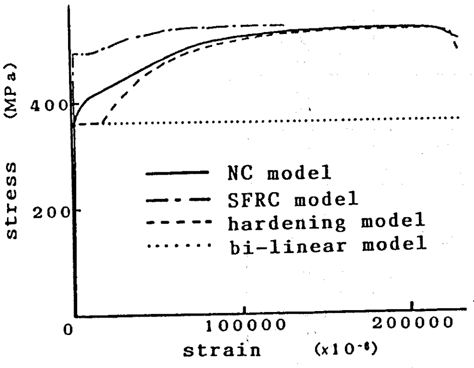

Fig. 11 Stress-strain curves of re-bar

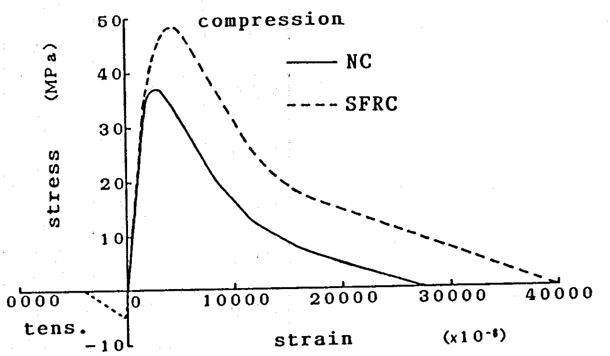

Fig. 12 Stress-strain curves of concrete

corresponding experimantal value, as same in case as bi-linear model. In this case, however, calculated curves approached to the experimental one when deflection increased. Calculated results with tensile test model coincided well with the experimental one for both cases of NC and SFRC.

5. CONCLUSIONS

Tensile tests of deformed and round re-bars which were covered by normal concrete or SFRC were conducted. In case of round re-bar, bond between re-bar and concrete was lost after yielding occurred. As a result, the test became equivalent to the tensile test of re-bar itself, and yield plateau was clearly observed where load did not increase while deformation increased. In case of deformed re-bar, since spread of yield zone was restricted by cover concrete, the yield plateau disappeared and re-bar entered work hardening region just after yielding. As a result, nominal yield point became higher than that of re-bar itself. For cover concrete with SFRC, the restriction became much larger and nominal yield point also became much larger because tensile force transmitted through concrete portion increased even when crack occurred.

Calculated load-deflection diagrams of RC beams coincided well with the observed ones when models of the stress strain relations of re-bars derived from the tensile test were used in stead of those commonly used for re-bar itself; i.e. bi-linear model or work hardening model.

In order to simulate the failure process of RC beam more precisely, tensile property of re-bar is concluded to be modeled as that with covered concrete in tension side instead of re-bar itself.References

References

[1] J.S.C.E., "Standard specification for prestressed concrete", 1978
[2] A.C.I., "Building code requirements for reinforced concrete", 1983
[3] CEB-FIP, "International system of unified standard codes of practise for structures", Vol.2, 1977
[4] BSI, "British standard structural use of concrete", Part 1, 1985
[5] S. Ban, "Study on reinforced concrete" (in Japanese), Sangyo-tosho Bo. Co., 1954
[6] M.A.Azimi, "Fundamental study on high strength concrete" (in Japanese), Doctorate Dissertation, Kyto University, 1981
[7] A.H.Mattock, L.B.Kriz and E.Hognestad, "Rectangular concrete stress distribution in ultimate strength design", Jour. ACI, Feb., 1961
[8] W.Koyanagi, K.Rokugo et al., "Failure process and energy dissipation" (in Japanese), Preprints for Annual Meeting of JSCE, Chubu Chapter, 1982
[9] K.Kobayashi, T.Uomoto et al., "Study on the flexural behavior of steel fiber reinforced concrete structural members" (in Japanese), Proc. Symposium on SFRC, JCI, 1984
[10] Japan Road Association, "Specifications for road bridges" (in Japanese), 1978