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EFFECT OF YIELD STRENGTH RATIO OF LONGITUDINAL REINFORCING BAR ON DUCTILITY OF R/C BEAM YIELD HINGE

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ABSTRACT

The objective of this study is to demonstrate by a simple mathematical model and tests of reinforced concrete cantilever beam, that usage of longitudinal reinforcement with high yield ratio close to unit lead to tensile fracture of longitudinal reinforcement after yield of reinforcing bar if it is used for yield hinge and subjected to large plastic hinge rotation. Yield strength ratio is here defined as the ratio of tensile strength to yield strength. Three 1/2 scale lightly reinforced concrete cantilever beams specimens were made of high strength concrete and high strength reinforcing steel. The specimens were subjected to statically cyclic loading with increasing amplitude to failure by displacement control. The parameters of the specimens included (1) yield strength ratio of longitudinal reinforcing bars (90%,75%) and (2) with or without reinforcing bar coupler at flexure critical section. It is concluded that reinforcing bar with high-yield strength ratio may sometimes jeopardize the ductile behavior of plastic hinge, because rupture of reinforcing steel occurs due to the concentration of strain within its hinge region.

KEYWORD

Yield strength ratio; High-strength reinforcing bar; High-strength concrete

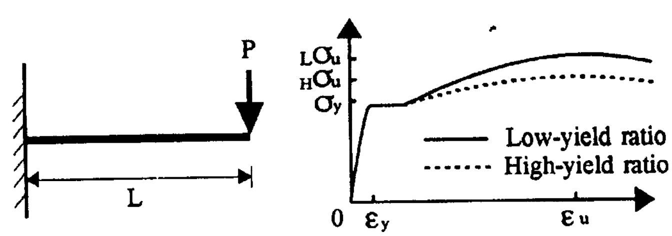
INTRODUCTION

Recently, high strength bars with yield strength of 50 MPa or higher had been investigated in Japan as a part of a national project which aims developing innovating technology for enhancing the range of reinforced concrete structure application including sky scraper with high strength materials [AOYAMA 1996]. General tendency of the high strength steel bar is that the yield strength ratio of higher strength bars is higher and sometimes close to 1.0, and its tensile rupture strain is smaller than ordinary mild steel. So it is necessary for structural designer to understand the influence of the particular characteristics of high strength reinforcing bars how it affects the strength and ductility of R/C members. In particular the effect of high yield strength ratio on the ductility of R/C beam yield hinge is important, if they are used in structures constructed in high seismic risk region. But they are not well known. The failure mode of R/C member due to tensile fracture of longitudinal bars is never observed if ordinary strength deformed steel bars with normal quality is used and if it is used in a building structural member with ordinary size. It may be attributable to rather low yield strength ratio of the ordinary strength deformed bar. Kato [KATO 1988] investigated of the ductility of H-shape steel section beam under moment gradient subjected to large plastic deformation. He concluded if the steel with high yield strength ratio is used for the flange, concentration of tensile strain is accelerated in a critical section, the length of the plastic hinge zone decreased, and the plastic rotation performance is jeopardized. This fact is widely recognized within the community of the researcher and designer of steel structure. An analogous result for R/C member is expected ; i.e. if extremely high yield strength ratio steel is used for longitudinal reinforcing bar, tensile rupture of the bar may occur. However, few research were conducted on the effect of yield strength ratio on the fracture of longitudinal bars in R/C members. The JIS (Japanese industrial standard) has no specification for the yield strength ratio limits in its standard specifying the quality of deformed bar for R/C. In Europe, CEB-FIP Model Code provides an upper limit of 87% as yield strength ratio for the reinforcing bars used in buildings [CEP-FIP 1993]. One of the principles of earthquake resistant design of a structure is to avoid any brittle failure so that ductile member could dissipate seismic energy input. Therefore, it is important to prevent any brittle failure including tensile fracture.

In this paper, first of all, effect of high yield strength ratio of reinforcing bar on member's ductility is tried to be discussed with simple mathematical model, then the results of tests of three R/C cantilever beams are reported. The parameters of the tests is (1) yield strength ratio of longitudinal reinforcing bar and (2) with or without of mechanical joint coupler. R/C structure require reinforcing bar joint. Highest feasible joint method for the high strength steel is a mechanical coupler with threaded deformed reinforcing bar. Couplers are usually placed at small stress region. But placing of couplers at a critical section sometimes increase productivity if used combined with precast concrete element. In the test, effect of the coupler on the behavior was also investigated.

YIELD STRENGTH RATIO OF REINFORCING BAR AND DUCTILITY OF MEMBER

Usually, tensile rupture mode is difficult to observe at ordinary seismic tests of R/C cantilever beams even if it is subjected to large displacement reversals. One of the reason is the large ultimate tensile strain of ordinary reinforcing bar, sometimes larger than 20%. Another reason is low yield strength ratio around 0.6 to 0.7. The characteristics ensure large hinge zone length and large plastic rotation capacity. The fracture of a longitudinal reinforcing bar is affected by two factors (1) the ultimate tensile strain of reinforcing bar and (2) then concentration of tensile strain at flexural critical section. With respect to the latter factor, (1) yield strength ratio and (2) bond deterioration are also concerned. In order to explain the difference caused by the factors, hereafter we use the cantilever R/C beam as generic parts of moment resisting frame structure as shown in Figure 1(a) with length L with concentrated load at the beam end.

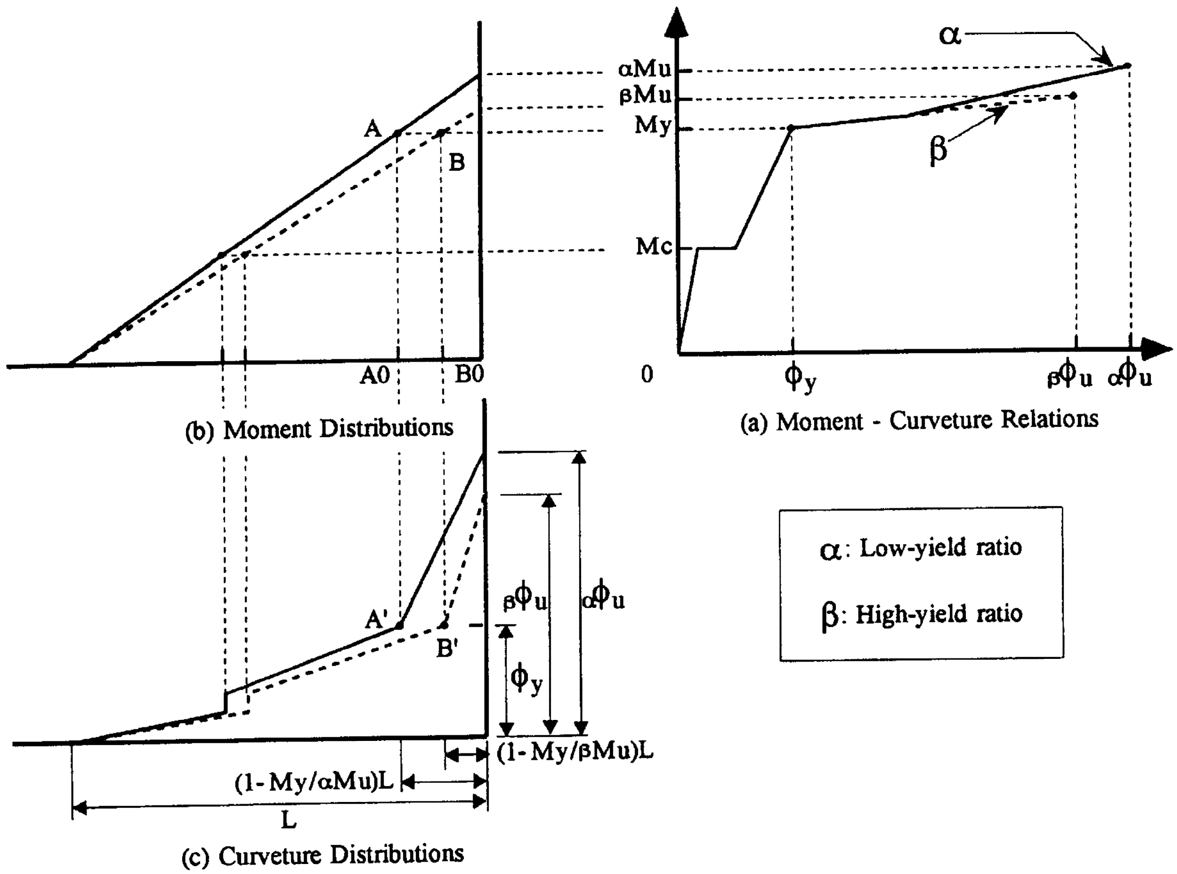


(a) Beam (b) Reinforcement Stress-Strain relation

Figuer 1. Simple Mathematical Model

<u>Beam with longitudinal reinforcing bar with perfect bond</u>

Let assume two beams with same geometry and same reinforcement arrangement for



Figuer 2. Moment - Curveture Response of Cantilever Beams

comparison. The only difference is in stress-strain relation of longitudinal reinforcing bar. One beam uses reinforcing bar of a high yield strength ratio and the other uses low yield strength ratio reinforcement. Figure 1(b) depicts the two types of stress-strain relation of reinforcing bars. It is assumed that the both type of reinforcement have the same the yield strength σ_y and the same uniform elongation ε_u. The yield strength ratio of reinforcing bar in α (solid line), and β (break line) respectively. The value α is assumed to be smaller than β ($\alpha < \beta$). For the flexural analysis of section Navier's assumption is used. The displacement of beam end at which steel strain reached uniform elongation ε_u at flexural critical section are calculated and compared. Figure 2(a) compares a of two kinds of M-ϕ relation of the two beams. Apparently, these two beams have same yield moment M_y. However, the ultimate moments of the two beams; αM_u and βM_u are in relation of $\alpha M_u > \beta M_u$. With respect to the curvatures $\alpha\phi_u$ and $\beta\phi_u$ at the ultimate strength, $\alpha\phi_u$ is slightly larger than $\beta\phi_u$. This can be derived from the fact that with a larger maximum strength, the neutral axis move from compression end to tension end, resulting in decrease of the moment arm length. Figure 2(b) shows the moment distribution along the axis when the tensile strain of reinforcing bar reaches a uniform elongation ε_u in the critical section. Figure 2(c) shows the curvature distribution. From these figures, the length of the yielded section is given by $(1\text{-}M_y/\ \alpha M_u)L$ and $(1\text{-}M_y/\ \beta M_u)\,L$ respectively; thus, it is concluded that the length of the plastic zone become smaller with increase of yield strength ratio. In other word, tensile strain concentration is predicted in the beam with high strength ratio reinforcing bar. The displacement of the end of the cantilever beam is given by integrating the curvature distribution in Figure 2(c) along the member axis. So it is also concluded that the beam end displacement increases if the yield strength ration is larger. Let consider an extreme case where the yield strength ratio equal to unity. The bending moment starts to decrease just after the beam yields. If the larger displacement is induced, after the reinforcing bar reaches an uniform elongation in the critical section, the bending moment decreases, with necked reinforcing bar, and elongation concentrates at the critical section, ultimately leading to rupture of the bar at the critical section. With this model, it is possible to explain the reason why the plastic zone length is affected by yield strength ratio and resulting in decrease of ductility in cantilever beam which uses high yield strength ratio reinforcing bars.

Beam with longitudinal reinforcing bar with imperfect bond

In the case of an imperfect bond between reinforcing bar and concrete, the above mentioned model is too simple to model the reality. The same argument are not possible because Navier's assumption is not applicable. When reinforcing bar yields, tensile strain suddenly increases and bond decreases due to reduction of bar diameter under Poissin's effect. Then mechanical bond between concrete and reinforcing bar ribs become weaker. The reduced bond stress and bond-slip prevent from increasing of the concentration of strain. Pull out of the reinforcing bar generally increases the member deflection. As a result, beam with reinforcing bar of poor bond are insensitive to high yield ratio. On the contrary to that, beam with good bond may easily reaches a rupture limit strain of longitudinal bar and show brittle failure mode of rupture. Typical case of good bond beam is the combination of (1) high strength concrete, (2) high yield ratio reinforcement, and (3) low tensile reinforcing ratio.

EXPERIMENT OF R/C CANTILEVER BEAMS

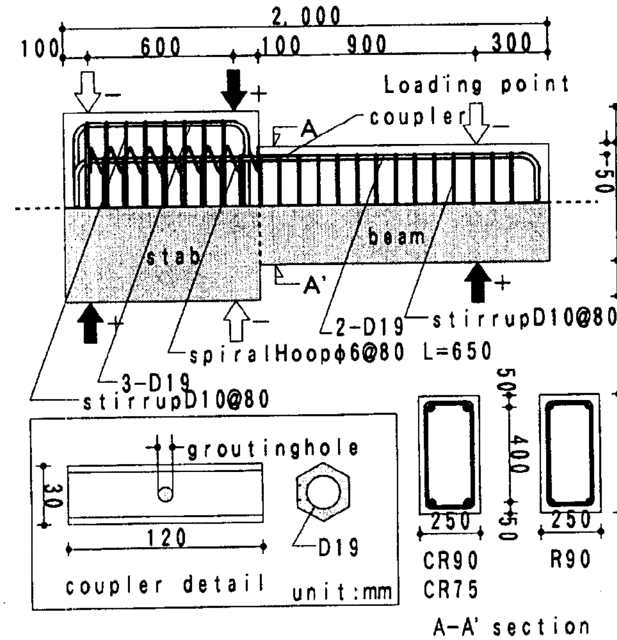
Summary of the experiment

Three 1/2 scale cantilever beams specimens are prepared. Parameters used are (1) yield strength ratio of longitudinal reinforcing bar; 90%,75% and (2) with or without mechanical couplers for splicing reinforcing bars. The mechanical properties of materials are listed in Table 1. The geometry of specimen and the arrangement of reinforcing bar are shown in Figure 3. Three specimen have common geometry and the same reinforcing bar arrangement. The specimens CR90 and R90 use deformed bar D19 with 89.6% of yield strength ratio. The specimen CR75 uses deformed bar D19 with 74.9% of yield strength ratio. Figure 4 show the stress-strain relation of the two kinds of longitudinal reinforcing bar. With regard to the specimens CR90 and CR75, longitudinal reinforcing bar is spliced by mechanical coupler in the critical section. Considering a minimum requirement of building code for tensile reinforcement ratio, 2-D19 (tensile reinforcing bar ratio 0.48%) was selected for tensile reinforcement. The ratio of span to (effective) depth ratio was chosen to be 1.8, and a sufficient amount of lateral reinforcing bars are provided to prevent a shear failure under a large deformation. The longitudinal reinforcing bar placed was screwed

Table 1. Mecanical Properties of Materials

	SPECIMENS		
	CR90	R90	CR75
Wide by Depth (mm)	250 × 500		
Longitudinal Reinfocement Bar	2-D19 (upper) , 2-D19 (lower)		
Area (cm^2)	2.72		
Tensile Reinforcement ratio (%)	0.48		
Yield Strength (MPa)	726		659
Tensile Strength (MPa)	798		872
Tensile Strain (%)	9.0		11.0
Yield ratio (%)	91.0		75.6
Expand ratio (%)	11.7		11.5
Stirrup	D10 @80		
Web Reinforcement ratio (%)	0.72		
Tensile Strength (MPa)	733		
Coupler	with	without	with
Ratio of Sapan to Depth ratio	1.8		
Concrete Compressive Strength (MPa)	67		

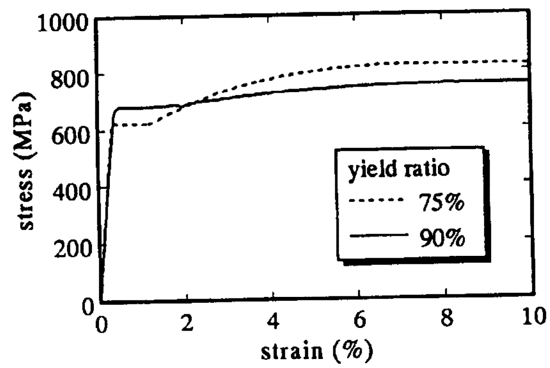
deformed bars of about 700 MPa yield strength and the concrete compressive strength is about 70 MPa. Cyclic reversed load with increasing amplitude is applied by displacement control at loading point. Loading history is chosen so that the displacement ductility factor increases with increment of 1.0, where the yield displacement was estimated as 1.25 times of the measured displacement at which observed moment reaches 80% of the calculated yield moment obtained by flexural analysis. (1) Shear, (2) displacement of the beam end and (3) strain of the longitudinal bars were measured. For the measurement of reinforcing bar strain distribution, strain gauges were attached in the groove made along the reinforcing steel.



Figuer 3.Reinforcment Detailes

Test Results

Failure Modes ; In the Specimens CR90 and R90, with 91.0% yield strength ratio reached the maximum strength at the ductility of 2 (at member's rotation angle: R=1/82rad.). Subsequently, the peak strength decreases gradually by increasing number of loading cycle. Sudden reduction of restoring force occurred accompanied by the rupture of longitudinal reinforcing bar at the ductility of 8 or 9. It was observed through cracks that a necking of the longitudinal reinforcing bar occurred. The loading was ceased at the moment the longitudinal reinforcing bar was ruptured at a necking spot during loading in the negative direction at the ductility 8 or 9. The position of rupture for the specimens was on the stab side, at 20 to 30 mm from the critical section.



Figuer 4.Reinforcement of Stress–Strain Relation

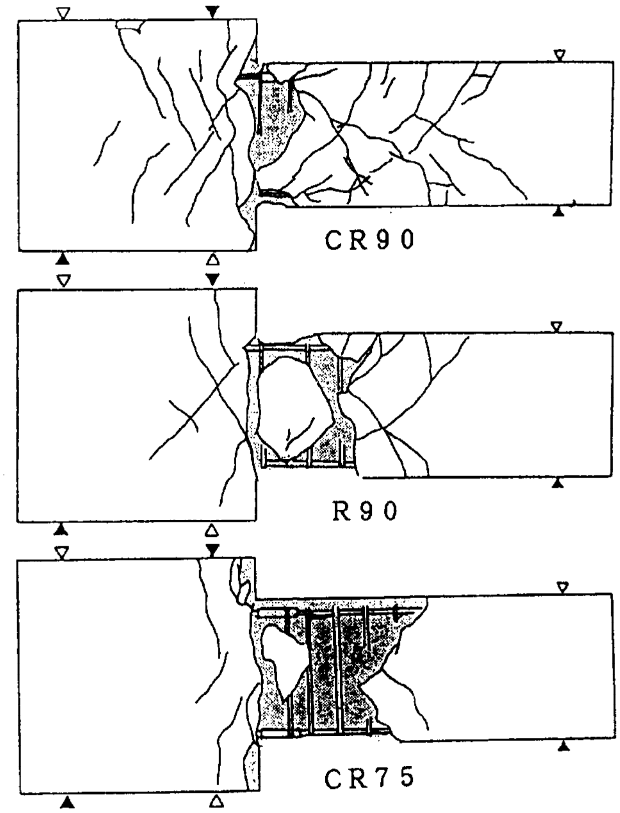
In the specimen CR75, which uses the reinforcing bar of 75.6% yield strength ratio, it reached the maximum strength at the ductility of 5(member's rotation angle; R=1/25 rad.). The width of cracks in the critical section was enlarges along with increase of the deformation. At the ductility more than 6, the yield strength decreased bit by bit, but there was no rupture for the longitudinal reinforcing bar. loading ceased at the ductility 10, because of the limit of stroke of hydraulic jack. No rupture of the longitudinal reinforcing bar.

Crack Pattern ; Figure 5 shows the crack pattern after the tests. Concrete damages of cracking and spalling of cover concrete were concentrated in the vicinity of the critical section of the Specimen C90. For the specimen R90, its damage was also concentrated in the vicinity of critical section. But the crack pattern were slightly different from that of the specimen CR90. Development of wide crack was observed at the location of 150 mm from the critical section towards the member's free end. Contrary to that, in the specimen CR75, cover concrete spalled off thoroughly. It means large plastic hinge zone were developed in the Specimen CR75.

Hysteresis ; The restoring force characteristics are shown by the relation of the beam-end-displacement vs. beam shear in Figure 6. The specimens CR90 and R90 with yield strength ratio of approximately 90%, show gradual degradation of strength due to cyclic loading after the bending yield reached. On the contrary to that, the specimen CR75 with about 75% yield strength ratio shows stable hysteresis with small degradation until reaching rotation angle of 1/20 rad.

Figure 7 compares the envelope curve of the hysteresis in positive direction, to compare the influence of steel couplers on the yield strength. The difference of two specimens CR90 and R90 is regarded due to the existence of couplers . Yield strength of specimen R90, is slightly larger than the specimen CR90. On the other hand, the negative direction loading envelopes exhibits a contrary trend.

Ductility of the member and reinforcing bar ; Strain readings are plotted on the curves of the restoring force in Figure 8. The strain value is measured at its ductility of 1,4,6,8 and 10. There was no remarkable difference in the ductility of the member. However, when the reinforcing bar strain increases further with a same displacement (or ductility) at the beam end, the tensile strain of the longitudinal reinforcing bar in the critical section become larger as the yield ratio increases. Figure 8 shows a relation between the strain of the



Figuer 5.Crack Pattern after Test of Specimens

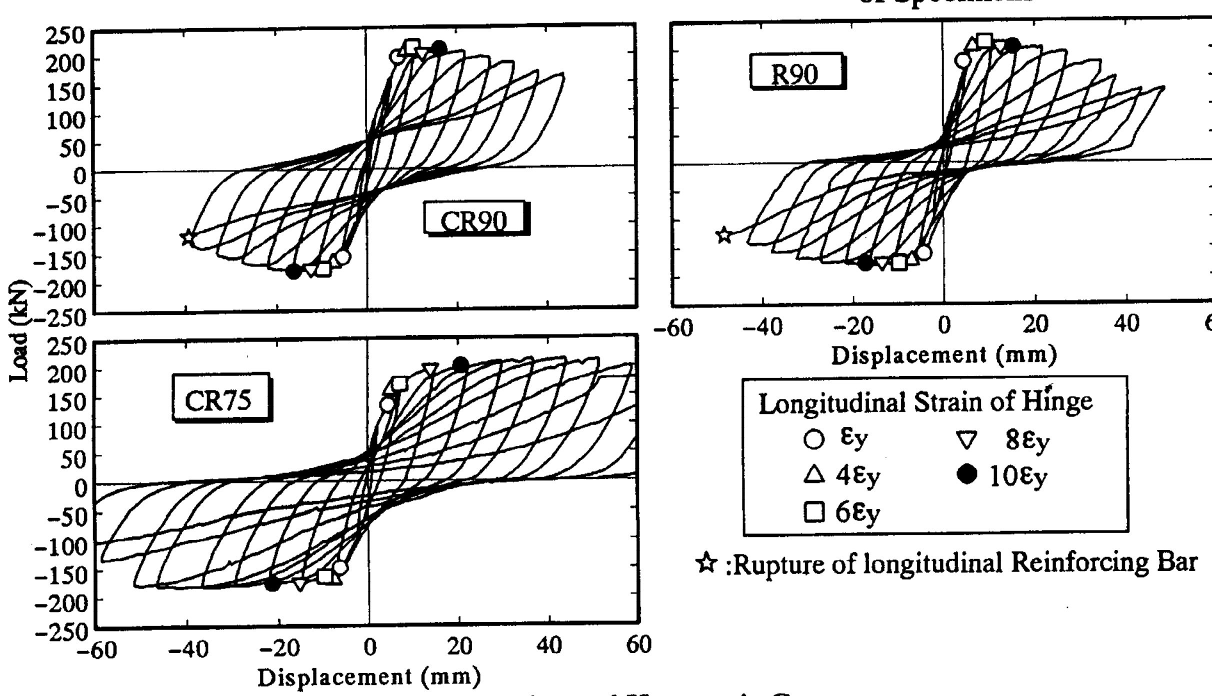


Figure 6.Hysteresis Curve

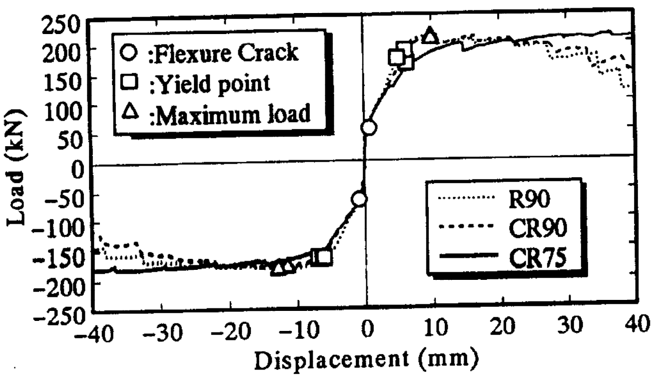


Figure 7. Envelope Curve of Hysteresis

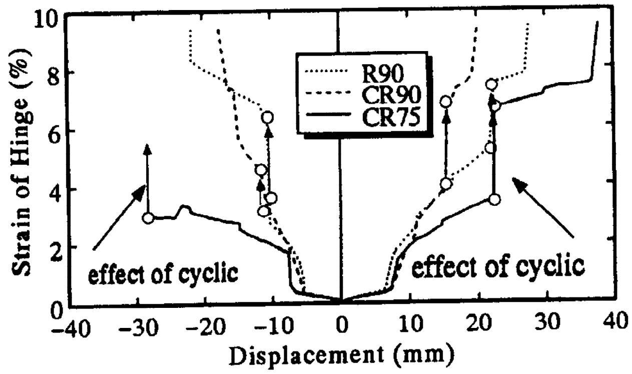


Figure 8.Strain of Critical section

longitudinal reinforcing bar at critical section by a strain gauge and the displacement at the beam end . Suddenincrease of strain is observed when it exceeds about 3%. In the case of the specimens CR90 and R90, this sudden increase of strain occurs earlier.

Strain distribution in the reinforcing bar ; Figure 9 shows the tensile strain distribution of the longitudinal reinforcing bar. They are strains readings at a beam end displacement of 24 mm in the positive direction. Clear peak of tensile strain is observed in the vicinity of the critical section. The strain on the stab side is larger than that of the beam end side. For the specimens CR90 and R90, The peak of strain is higher than that of Specimen CR75. The specimen CR75 has smaller peak value of plastic strain and strain distributed in a wider area on the both sides of the coupler. This means that a hinge zone length is larger in the specimen CR95.

DISCUSSION

The test results shows that in the case of the reinforcing bar with a yield strength ratio of approximately 90%, the maximum load reached earlier, at ductility factor 2 or 3, then it decreased gradually as deformation increases, and finally, the reinforcing bar ruptured. From several observation including peak of strain distribution of the longitudinal reinforcing bars, reinforcing bar necking and a spilling off of cover concrete, It is concluded

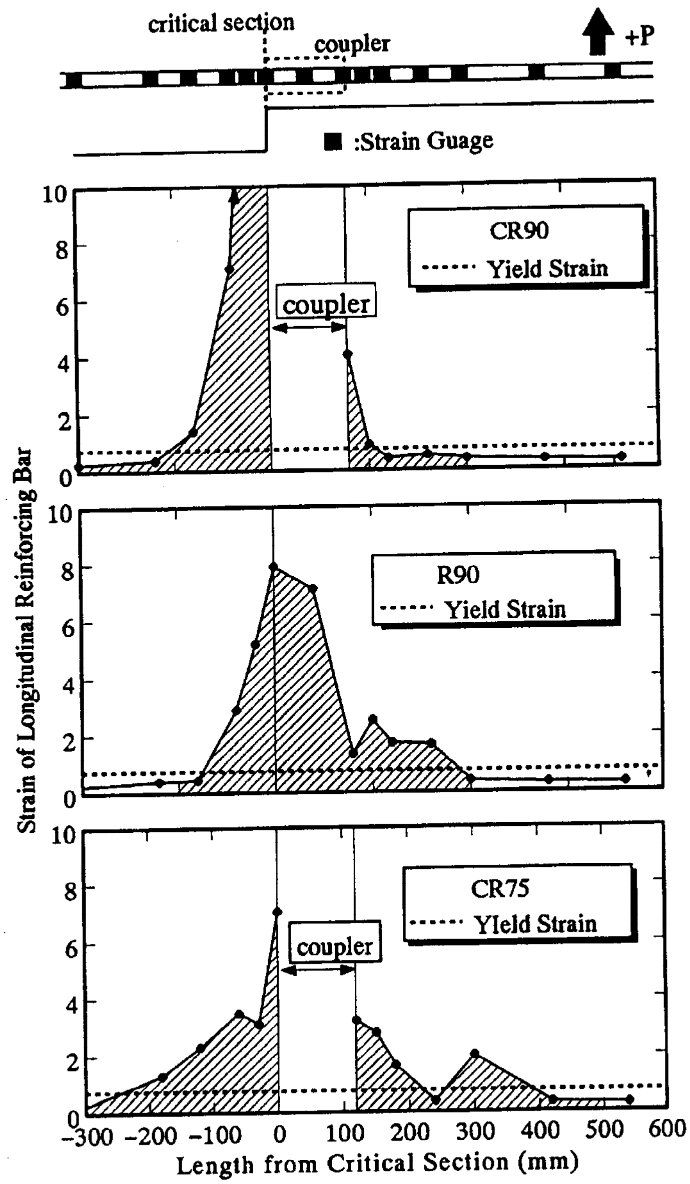


Figure 9. Strain of Distrbution of Longitudinal Reinforcing Bar

that concentration of damages was enhanced by high yield strength ratio and it caused earlier decrease of residual strength and rupture of reinforcing bar. Because the test was done only two levels of yield strength ratio, further research is indispensable to have enough data to determine a permissible level of yield strength ratio. For the time of being, it is important for a structural engineer to provide certain upper limit for yield strength to each project on our judgment, if high strength bar are used in a real application.
Cyclic loading history is used for the test assuming a seismic loading. In the test, increase of strain of the reinforcing bar seemed to be accelerated due to the cyclic loading. It means loading history may have some influence on the strain concentration. Further study on the effect of loading history is also important.

CONCLUSION

If the reinforcing bar of a high yield strength ratio is placed in the member having a moment gradient, plastic deformation concentrates in the vicinity of the critical section, causing the strength degradation prematurely and the reinforcing bar to be ruptured. In order to prove this prediction obtained by a simple model by flexural analysis, three 1/2 scale of R/C cantilever beam were subjected to a reversed cyclic loading of increased amplitude to study the two parameters (1) yield strength ratio of reinforcing bar and (2) reinforcing bar coupler. The following conclusions are derived,

1 It is concluded that reinforcing bar with high-yield strength ratio may sometimes jeopardize the ductile behavior of plastic hinge, because rupture of reinforcing steel occurs due to the concentration of strain within its hinge region. Therefore, restriction of usage of longitudinal steel with relatively high yield strength ratio is strongly recommended if they are used at yield hinge where large plastic rotation is expected to avoid rupture of reinforcing bars.

2 Concentration of strain due to the existence of mechanical couplers at critical section of specimen was not so remarkable compared with the situation without the couplers.

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