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BOND CHARACTERISTICS IN POST-YIELD RANGE OF DEFORMED BARS

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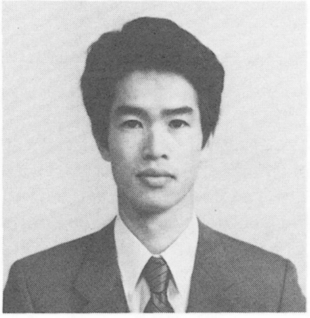
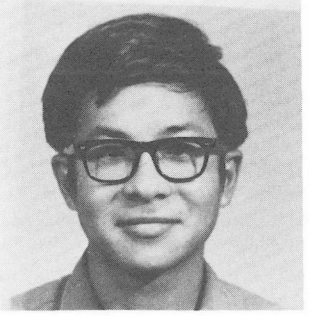


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SYNOPSIS

Bond characteristics in post-yield range of deformed bars were investigated by means of the pullout test with long embedment. A bar was embedded in massive concrete in order to have no effect of splitting cracks and unbonded region was set at the loaded end to avoid the effect of the end of concrete block. The bond stress at a location along a bar decreases suddenly as yielding of the steel is attained at that point. The slip at loaded end after yielding of steel is mostly controlled by the location along the bar where the steel bar yields. The bond-slip relationship in post-yield range depends on the stress-strain properties of a bar characterized by yield strength, length of yield plateau and stiffness in strain hardening range. The lower bond stress and the difference of bond-slip relationship in post-yield range can be explained by the analysis using the unique bond-slip-strain relationship previously proposed by the authors.

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1. INTRODUCTION

Bond characteristics between steel bars and concrete in post-yield range of steel give some important influence on the behaviour of beam-column joints (1) or bridge piers (2) because of the pullout effects of longitudinal bars. The tension stiffening effect resulted from the bond action affects the behaviour of reinforced concrete panels remarkably even in post-yield range (3). The bond characteristics also influence the flexural rigidity of reinforced concrete flexural members in post-yield range as they do in elastic range. The influence of the bond on the behaviour of panels or flexural members becomes more remarkable if their reinforcement ratios are small.

The bond characteristics in post-yield range of steel bars must be known to estimate the behaviour of reinforced concrete structures subjected to strong earthquakes. Many formulated bond-slip relationships have been proposed (4). However, all of them are for in elastic range and no investigation exists on the bond model expressing the bond stress in post-yield range quantitatively. Morita and Kaku (5) reported the bond behaviour of beam reinforcement in beam-column joint, but it was within the limits of the observation of plastic length. Hassan and Hawkins (6) developed the model for predicting the pullout of an anchored steel bar even in post-yield range by means of the modeling of bond stress distribution along the bar, but the bond stress distribution was assumed without any measurement. Viwathanatepa et al.(7) got data of bond stresses in post-yield range of steel in addition to the data before the yielding from bond tests for beam-column joints, but they did not discuss about the bond behaviour in post-yield range. Tada and Takeda (8) carried out the bond tests in post-yield range in the investigation of beam-column joint, but they did not reach to generalization of different bond behaviour which depends on the condition. Ueda et al.(9) used a bond-slip relationship obtained from tests in elastic range to predict the load-pullout relationship for reinforcing bars extending from beams into exterior columns and subjected to inelastic loading. Murayama et al.(10) investigated the bond-slip and stress-strain relationships in post-yield range of reinforcing bars embedded in massive concrete, but they did not formulate the relationship.

The object of this research is to investigate how the bond property changes due to yielding of a steel bar and to establish a formulated model to express the bond property in post-yield range of the steel bar. The authors (11) clarified the difference of strain affected the bond-slip relationship and proposed a bond-slip-strain relationship model. According to this model, stress, strain and stiffness of a steel bar at a certain slip should be dependent on the stress-strain properties of the bar, and is considered to be applicable to the post-yield range.

2. EXPERIMENTS

2.1 Specimen

In this research, well controlled pullout tests based on the previous experiments (11,12,13) were carried out. In case of investigation on the change of bond property due to the difference in yielding of steel, splitting cracks should be avoided. This was done by embedding a steel bar in massive concrete.

Pullout test was used in the experiment. The specimen and apparatus are as shown in Fig.1. A steel bar was arranged vertically in the center of the concrete cylinder specimen having diameter of 50cm. This diameter was determined

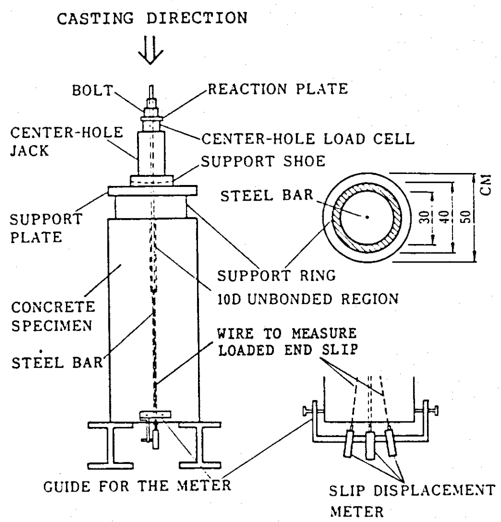


Fig.1 Specimen and testing apparatus.

to be large enough to inhibit the splitting crack and to make stress in concrete cylinder small and uniform. The embedment length was decided to be 50D, 50 times of the bar diameter, which was long enough to cause no free end slip when the pullout force exceeded the yield strength of steel. The unbonded region of 10D was set at the loaded end to prevent the effect of the loaded end region of the concrete specimen.

2.2 Experimental Condition

The main parameter was the property of steel, that was the stress-strain relationship in post-yield range. Three kinds of steel with different specified yield strength of 30, 50 and 70 kgf/mm^2, which are denoted by SD30, SD50 and SD70 in Table 1, were used. These special high strength bars were provided by Sumitomo Metal Industries Co.Ltd.

Table 1 Property of specimen

Specimen No.	1	2	3
Steel bar	SD30	SD50	SD70

2.3 Steel Bars and Concrete

The measurement of steel strain along the bar is the most important work in the experiment. If ordinary steel bars had been used, ribs of the bar should have been removed to attach strain gauges resulting in reduction of the cross-sectional area of the bar. To solve this problem, the screw-shaped deformed bars without longitudinal rib were used. Bar size was 19mm in diameter, referred as D19.

Table 2 gives the properties of steel bars. The bar diameter used in the analysis was determined by dividing the measured volume obtained from the submerged weight by its length. The measured stress-strain relationships of the

Table 2 Properties of steel bar

Steel bar	SD30	SD50	SD70
Diameter of bar D, mm	19.5	19.5	19.5
Young's modulus Es, GPa	190	190	190
Yield strength fy, MPa	350	610	820
Initial strain of strain hardening εsh, %	1.65	1.40	0.60
Tensile strength fu, MPa	540	800	910

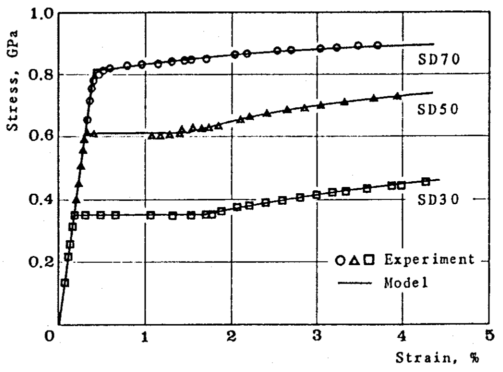


Fig.2 Stress-strain curves of steel bar.

steel bars are plotted in Fig.2. The stress-strain relationship used in the analysis was represented by the following equations as shown by solid line in Fig.2.

$$\sigma = E_s \cdot \varepsilon \qquad (\varepsilon < \varepsilon_y) \tag{1}$$

$$\sigma = f_y \qquad (\varepsilon_y < \varepsilon < \varepsilon_{sh}) \tag{2}$$

$$\sigma = f_y + (1 - e^{(\varepsilon_{sh} - \varepsilon)/k})(1.01 f_u - f_y) \qquad (\varepsilon > \varepsilon_{sh}) \tag{3}$$

where

$$k = 0.032(400/f_y)^{1/3} \tag{4}$$

σ : stress, MPa
ε : strain
fy : yield strength, MPa
fu : tensile strength, MPa
εsh : initial strain of strain hardening.

The concrete with same mix proportion was used for all specimens. The maximum size of aggregate was 25mm and the water-cement ratio was 70%. The tested compressive strength f'c was 19.6MPa.

2.4 Description of Test

Foil resistance strain gauges having length of 5mm were attached on the opposite faces at basically an interval of 5D, 5 times the steel bar diameter, in order to measure the strain distribution along the embedded bar. In order to investigate the strain distribution at the post-yield range in detail, the spacing was arranged to be 2.5D near the loaded end where the steel bar would yield.

Two stainless wires having diameter of 0.3mm were used to measure the loaded end slip as shown in Fig.1. The top of the wires was adhered to the opposite faces at the loaded end of the bar with solder. The wires extended to the bottom of the specimen through concrete and connected to electrical displacement meters. The wires were inserted through a plastic tube covered by a metal pipe so that the wire was free from bonding to concrete.

The bar was fixed centrically along the cylindrical form which was set vertically. Concrete was cast in vertical direction parallel to the embedded bar.

Axial load was applied by a centerhole jack set the direction of the bar. The direction of tensile load applied to the bar was opposite to the casting direction of concrete. The loading rate was controlled by the strain measurement at the loaded end. It was about 100 micro strain per minute before yielding of steel bar and about 1000 micro strain per minute after yielding. In addition to the measurement of strains and the loaded end slip, the free end slip and the force applied were measured by a displacement meter and a load cell, respectively.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Strain Distribution

The measurements of strain at each location along a bar were shown in Fig.3. The measured strain was derived from the average value of two gauges at each location. The strain distributions can be expressed by continuous smooth curves in elastic range of steel. However, the strain distribution is not smooth in the region where the steel bar yields and the strain approaches the one from which the strain hardening starts. Immediately after the yielding of steel at a location along the bar, the strain at that location should jump up to the initial strain of strain hardening as shown in Fig.3. The reason is that the difference of steel stress at minute length along a bar is produced certainly at the location where the steel bar yields because the bond stress has some value as long as the slip exists. The strain distributions in strain hardening range are smooth similar to those in elastic range.

The location where the steel bar yields must be determined in order to calculate the precise slip in post-yield range. However, the spacing of gauges were so large that the location of yielding can hardly be determined from the experiment. The distance from the loaded end to the yielding location, l_p, is assumed by using the strain at two measured points nearest to the yielding location in elastic range and in strain hardening range as shown in Fig.4. That is, the yielding location is determined to be the average of two locations, x_e and x_p, where the strain distribution lines extended straight from the elastic range and the strain hardening range to the yield strain ε_y and the initial strain of strain hardening ε_{sh}, respectively. The values of the two locations, x_e and x_p, in the experiment agreed well. This indicates that the strain distribution curves in elastic and in post-yield range are close to linear lines.

The strain distribution curves in elastic range and in post-yield range were obtained by connecting every three neighboring points including the coordinates

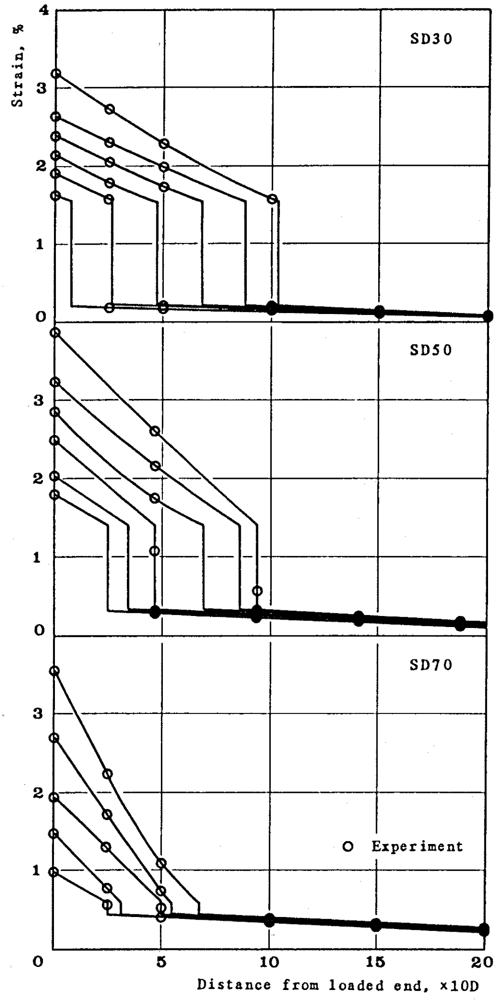


Fig.3 Measured strains and assumed strain distribution.

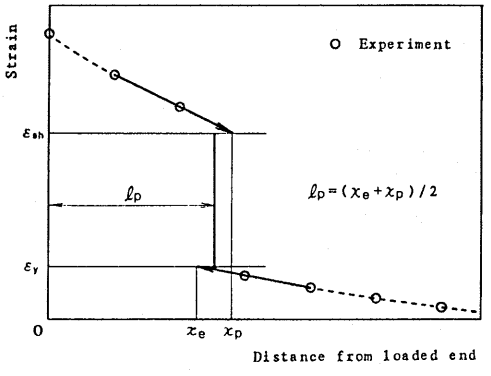


Fig.4 Method to determine the location where steel bar yields.

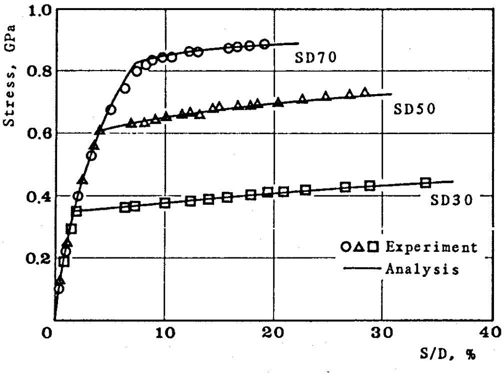


Fig.5 Relation between slip at loaded end measured by wire and pullout force.

at the yielding location, (lp, εy) and (lp, εsh), with 2nd degree polynomial equations.

The slip and the bond stress at each location along a bar can be calculated by using the assumed strain distribution mentioned above. The calculated slips at the loaded end, obtained from integration of the assumed strain distribution, are compared with the slips measured by wire in order to verify whether this assumed strain distribution is correct or not. Relationship between the loaded end slips measured by the wire and steel stresses of the bar at the loaded end are shown in Fig.5. The slips increased dominantly in the post-yield range independent on the strength of steel. Table 3 gives the comparison of the loaded end slips from the calculation with those from the experiment. The calculated results agree with the experimental results. It is considered that the strain distributions assumed by the method mentioned above express well the

Table 3 Comparison of calculated results of loaded end slip with experimental ones

Specimen								
Specimen No.1 (SD30)	ε_0(%)		1.70	1.91	2.14	2.39	2.63	3.20
	S/D (%)	Calculation	3.7	6.9	10.5	14.9	19.6	24.8
		Experiment	2.7	7.3	10.0	15.6	19.4	26.6
		(Cal/Exp)	1.38	0.95	1.05	0.95	1.01	0.94
Specimen No.2 (SD50)	ε_0(%)		1.81	2.04	2.50	2.87	3.26	3.90
	S/D (%)	Calculation	7.8	9.8	12.8	17.7	22.6	27.6
		Experiment	8.2	10.0	13.1	18.4	22.5	28.2
		(Cal/Exp)	0.95	0.98	0.97	0.96	1.01	0.98
Specimen No.3 (SD70)	ε_0(%)		1.00	1.50	1.95	2.70	3.59	
	S/D (%)	Calculation	9.2	10.9	13.8	16.5	20.2	
		Experiment	8.8	10.5	12.9	16.4	19.1	
		(Cal/Exp)	1.04	1.04	1.06	1.00	1.06	

ε_0 : Strain at loaded end

actual strain distributions.

3.2 Distribution of Slip, Stress and Bond

The slip or bond stress distribution along a bar can be calculated from the strain distribution. In this research, the slip is defined as the displacement at the point concerned of the bar from the fixed point in concrete. According to this definition, the internal slip at any point is calculated by taking the summation of the integration of strain function from the free end to the point concerned and the free end slip. The free end slip is always zero in this experiment so that the local slip is calculated by Eq.(5).

$$S=\int \varepsilon dx. \qquad (5)$$

The local bond stress at any location along a bar is proportional to the slope of the steel stress distribution curve at that point. At any point, the bond stress is expressed as

$$\tau=\frac{D}{4}\frac{d\sigma}{dx} \qquad (6)$$

where D is the bar diameter and $d\sigma/dx$ is the slope of the stress distribution curve. The stress distribution is converted from the strain distribution by using the stress-strain relationship of steel expressed in Eqs.(1), (2) and (3).

Examples of the distributions of steel strain, slip, steel stress and bond stress along the bar in each specimen are illustrated in Figs.6 to 8. The slip increases greatly in post-yield range. It is indicated that the distance from the loaded end to the yielding location affects the loaded end slip considerably. In regard to the distribution of steel stress, its slope in post-yield range is smaller than that in elastic range. From this result, it is recognized that the bond stress in post-yield range becomes much lower than that in elastic range as shown in the bottom parts of Figs.6 to 8. The degree of decreasing of bond stress caused by yielding of steel has tendency to be larger as the strength of steel is lower.

3.3 Bond-Slip-Strain Relationship

The bond-slip relationships of each specimen are shown in Fig.9. In the elastic range, the bond-slip relationship is independent on the locations along a bar in case of the condition that the slip is zero where the strain is zero (11). This is observed even in post-yield range as shown in Fig.9. However, the bond-slip relationship of each specimen is different from each other. The obvious distinction is the slip at which the bond stress drops down. The range of slip which holds the high bond stress is wider with higher strength of steel bar. The bond stress in the post-yield range is almost constant with increasing of the slip for SD30 and SD50. For SD70, the bond stress has the tendency to decrease with increasing of the slip. This difference of the bond-slip relationship in post-yield range is considered to be caused by the differences of the initial strain of strain hardening and the stiffness at strain hardening range. In other words, the bond-slip relationship in post-yield range depends

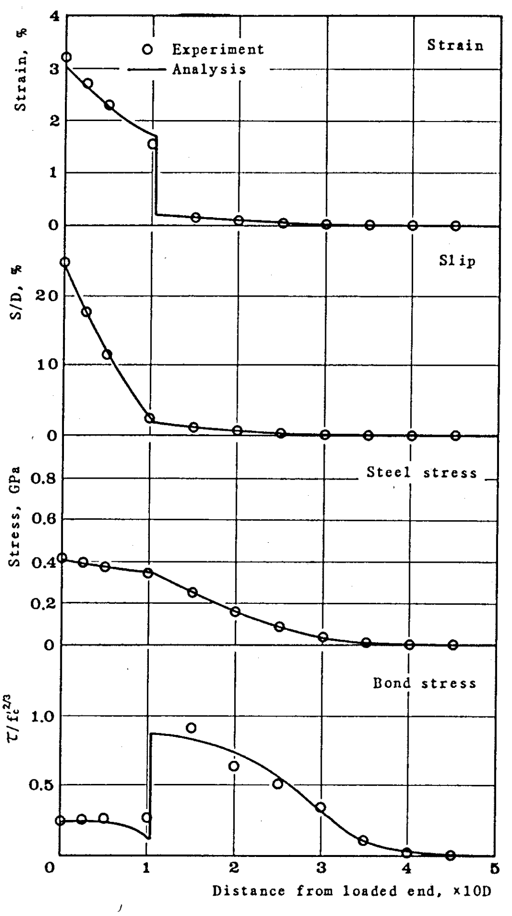


Fig.6 Distributions of steel strain, slip, steel stress and bond stress along the bar (SD30).

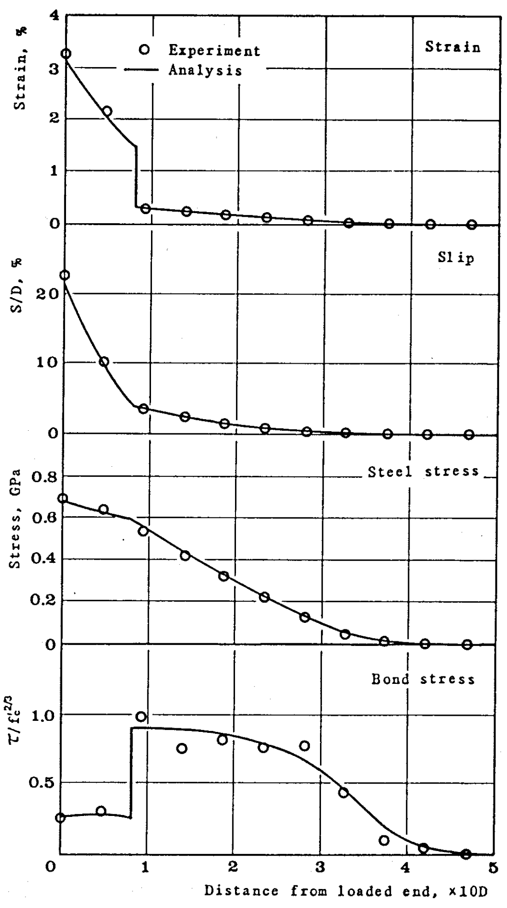


Fig.7 Distributions of steel strain, slip, steel stress and bond stress along the bar (SD50).

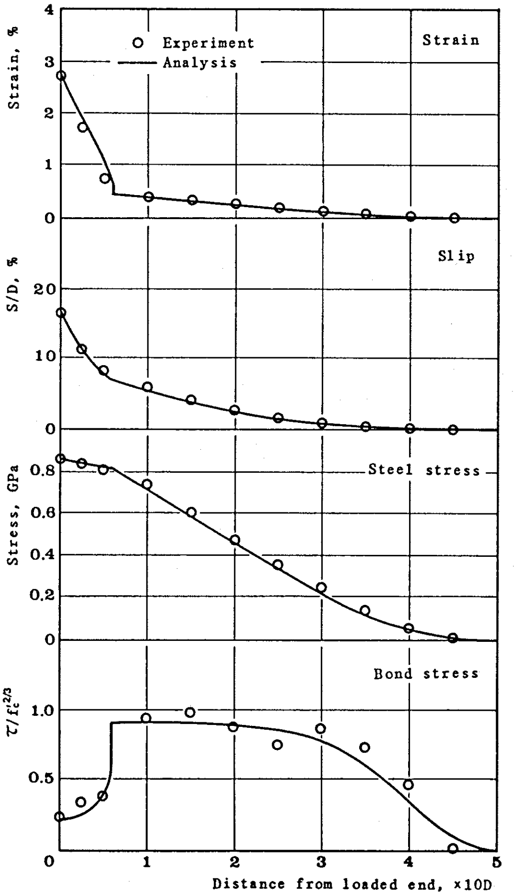


Fig.8 Distributions of steel strain, slip, steel stress and bond stress along the bar (SD70).

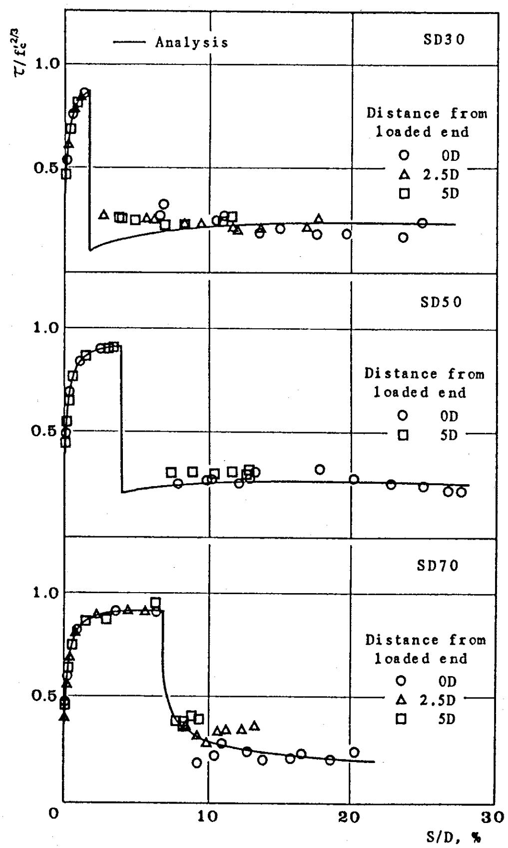
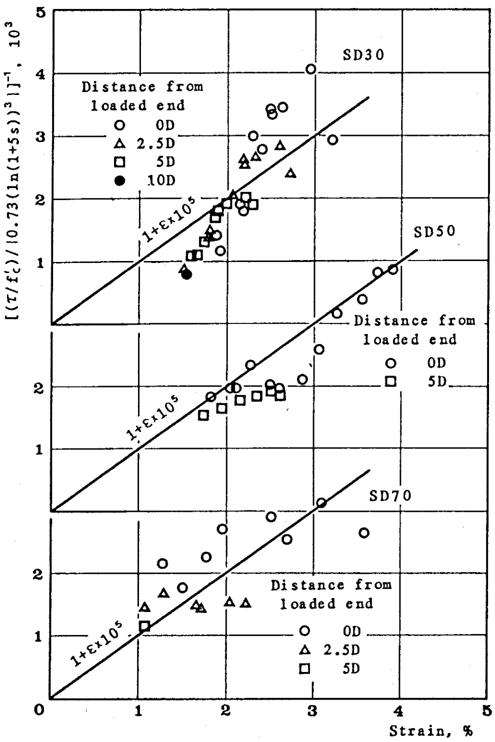


Fig.9 Bond-slip relationship in post-yield range.

on the stress-strain relationship of steel.

These phenomena are all anticipated by the bond-slip-strain relationship proposed by the authors (11). The bond-slip-strain relationships in post-yield range of each specimen are shown in Fig.10. It is indicated that the bond-slip-strain relationship which holds good in elastic range also holds good in post-yield range independent on the properties of steel.

The calculated distributions of steel strain, slip, steel stress and bond stress along the bar in each specimen are also shown in Figs.6 to 8. The analytical results agree quite well with the experimental results. In the analysis the degree of dropping down of the bond stress becomes larger as the difference between the yielding strain and the initial strain of strain hardening is larger. This analytical phenomenon agrees with the experimental results. The bond stress in post-yield range decreases gradually in Specimen SD70. This is because the difference between the yielding strain and the initial strain of strain hardening is small and the increment of strain is smaller than the increment of slip.



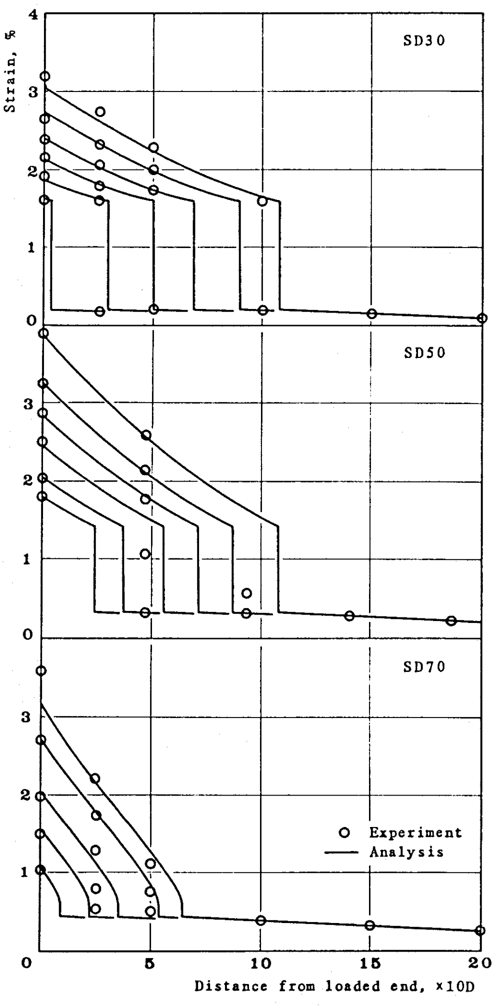


Fig.10 Bond-slip-strain relationship in post-yield range.

Fig.11 Comparison between measured strain distribution and calculated strain distribution using bond-slip-strain relationship.

The bond-slip relationships of each specimen are demonstrated in Fig.9. The analytical bond-slip relationships using the bond-slip-strain relationship are added to Fig.9. The analytical results agree well with the experimental results. The analysis using the bond-slip-strain relationship expresses the variance of the slip at yielding and the bond-slip relationship in post-yield range with the difference of properties of steel.

In order to verify the accuracy of the bond-slip-strain relationship, the experimental results measured directly from the tests are compared to those calculated using the bond-slip-strain relationship. The analytical relationships between the loaded end slip and the pullout force are added to Fig.5. The analysis agrees well with the experimental results. Fig.11 shows the comparison of the analytical strain distribution with the experimental results. It is indicated that the accuracy is good. The difference between the experimental results and the analysis near the yield strain in SD70 is considered to be caused by the difference between the actual stress-strain relationship and the assumed one. In conclusion, the bond-slip-strain relationship has good accuracy even in the post-yield range of steel.

The relationship between the tensile stress or strain and slip of a steel bar can be obtained numerically by using the bond-slip-strain relationship. For the practical use, the relationship between the pullout force and slip of the steel bars anchored in a footing can be obtained with consideration of the effect of lower bond stress near the loaded end.

4. CONCLUDING REMARKS

(1) Immediately after the steel bar yields at a location along the bar, the strain at that location jumps up to the one from which the strain hardening starts.

(2) The slip at the loaded end after yielding of steel is mostly controlled by the location along a bar where the steel bar yields.

(3) The bond stress in post-yield range is much lower than that in elastic range and decreases suddenly with the yielding of steel.

(4) The bond-slip relationship in post-yield range depends on the stress-strain properties of steel such as yield strength, strain from which strain hardening starts and stiffness at strain hardening range.

(5) The bond-slip-strain relationship obtained from the test in elastic range is applicable to post-yield range. The facts of (3) and (4) can be expressed by the analysis using the unique bond-slip-strain relationship.

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