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Nonelastic Behavior of Axial Reinforcement Subjected to Axial and Slip Deformation at the Crack Surface

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Reports on an investigation of the mechanical characteristics across a crack of embedded reinforcement simultaneously subjected to axial and slip displacements from pure shear. In particular, the effects of shear slip displacement on slippage characteristics were investigated.

Keywords: bars; elastic limit; joints (junctions); **mechanical properties**; reinforced concrete; **reinforcing steels**; shear properties; shear stress; strains; stress-strain relationships.

Mechanical action perpendicular to a crack (slippage[1]) and that parallel to it (dowel action[2]) have traditionally been treated separately in investigations on mechanical characteristics of reinforcement embedded in concrete across crack surfaces. It has been pointed out by Suzuki et al.,[3] however, that axial forces acting on reinforcement lead to lowering of the dowel resistance. This fact suggests that dowel stress acting on reinforcement may, in turn, lower the axial resistance of the reinforcement. Lowering of the constraint of reinforcement leads to a decrease in the shear resistance of the crack surface. The dowel action of reinforcement, therefore, has a double effect of raising and lowering the shear resistance of the crack surface. This dual nature of the dowel action means that models that ignore the coupled effect of dowel and axial deformation may well give results that are on the dangerous side, giving rise to a need to construct a model of axial slippage of reinforcement under a more general deformation path (axial and slip displacement).

The purpose of the study reported was to investigate the mechanical characteristics of embedded reinforcement simultaneously subjected to axial and slip displacement from pure shear and to collect experimental data required for the construction of a general model. Investigation in particular on the effects of shear slip displacement on the slippage characteristics of the reinforcement were carried out.

PURE SHEAR TEST ON REINFORCED CONCRETE MEMBERS

Test specimens

Particulars of the test specimens used in the pure shear test conducted by the authors are given in Table 1. The test was carried out with the aim of examining the stress transfer characteristics at the concrete joint. The attention will be focused here on the behavior of the reinforcement observed in the test. The test specimens were of two types, those subjected to smoothing treatment of joints, and those subjected to chipping treatment. The results pertaining to smoothing treatment have been reported elsewhere.[4] For both types, three specimens were prepared with reinforcement ratios of 0.37, 0.74, and 1.10 percent. The observations here will be concentrated on the specimens with the reinforcement ratio of 0.74 percent. It has been confirmed that, given the same joint treatment, the specimens will show more or less the same behavior, regardless of the reinforcement ratio, and it will suffice to examine the behavior of the two representative specimens for the purpose of assessing the mechanical characteristics.

Except for the differences in the reinforcement volume at the joint, the specimens had the same configuration and reinforcement arrangement, which is shown in Fig. 1. Anchorage lengths of at least 30 diameter were established for the reinforcement traversing the joint so that the slippage characteristics would not be affected by anchorage length. In jointing the concrete, chipping treatment was provided by removing the surface mortar until the aggregate protruded

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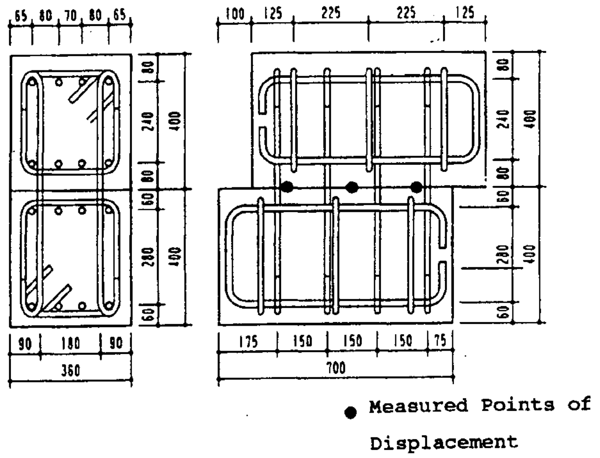


Fig. 1—Test specimen

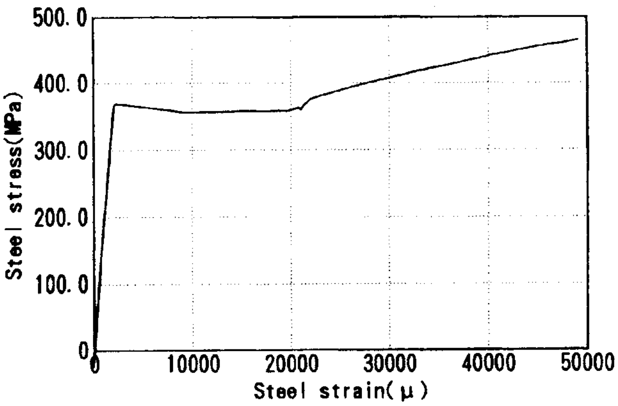


Fig. 2—Uniaxial stress-strain relationship of reinforcement

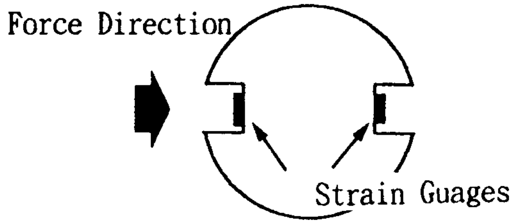


Fig. 3—Measurement of reinforcement strain

from the joint surface by several millimeters, while the joint surface was smoothed to the level expected with trowel finish in the smoothing treatment. With all the specimens, the portion of the concrete placed first was wet-cured for about 7 days before placing the second portion.

The mix strength of the concrete was 24.0 MPa and the maximum aggregate size 20 mm. The reinforcements used were D16 deformed reinforcement bars. The results of the uniaxial tension test are given in Fig. 2.

Measurement items

Care was taken to prevent the measurement of the reinforcement strain affecting the anchorage characteristics through use of reinforcing bars with grooves (width = 3 mm; depth = 3 mm). Strain gages were attached on either side of the central axis of the reinforcement bars, on both the sides of the bar placed under force, and the side opposite, for detection of both the bending and axial deformation of the bars accompanying shear displacement (Fig. 3). Strain distribution measurement was carried out by attaching strain gages to two of the joint reinforcing bars at the intervals indicated in Fig. 4. An attempt will be made to show the mechanical behavior of reinforcement subjected simultaneously to shear slip and axial displacement based on the results obtained on these reinforcing bars.

Displacement gages were positioned at three points each on either side of the specimens shown in Fig. 1 to measure the opening displacement and shear slip displacement at the joint. Since the displacement obtained in this test was that measured on the surface and as such will not be exactly the same as the average displacement of the joint cross section, the average of the measurement values was taken to be the representative displacement of the crack surface for the purpose of simplification. The deformation of the concrete was presumed to be negligible and the axial and shear displacement of the reinforcement bar was assumed to equal the opening and shear slip displacement of the joint surface.

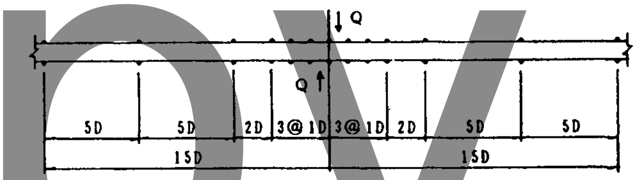


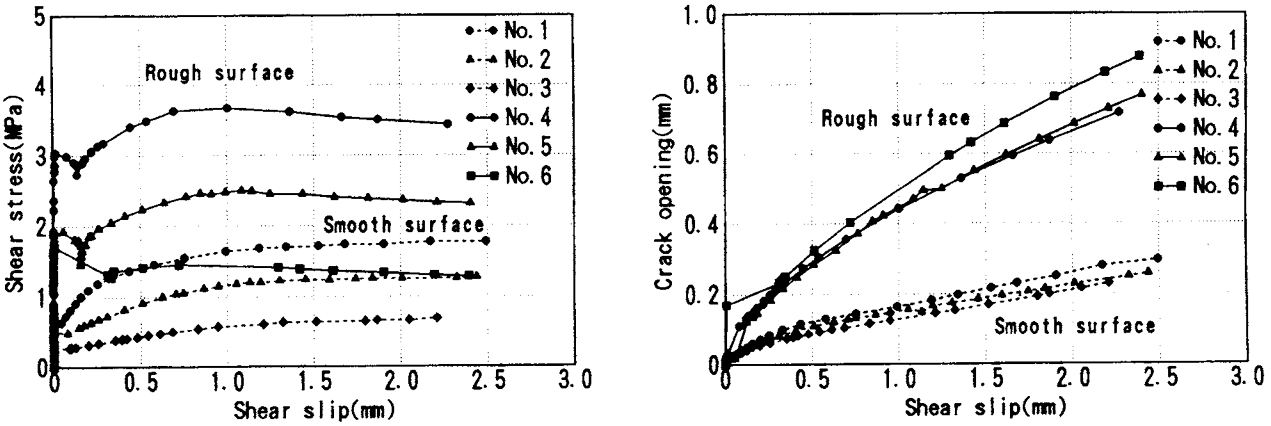
Fig. 4—Measurement positions for reinforcement strain distribution

Loading test

Loading was implemented as a part of the pushoff-type pure shear test. In pure shear tests on reinforced concrete members, either the shear force may be applied only after cracks have been created on the joint surface or it may be applied from the start. The latter method, in which the shear

Table 1—Test specimens

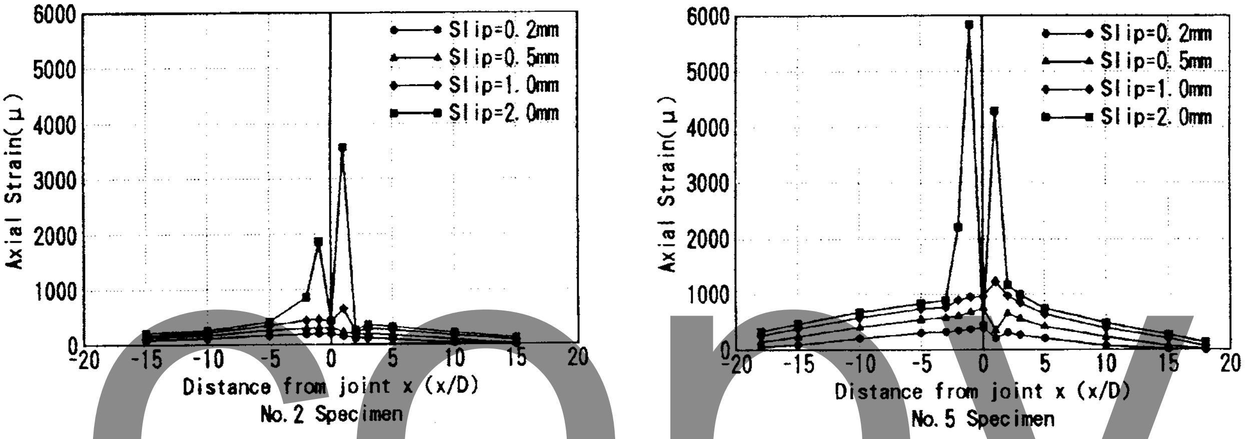
Specimen no.	Treatment	Reinforcement ratio, percent	Concrete strength, MPa	Shear area, mm^2	Bar diameter, mm	Number of bars
1	Smooth	0.37	27.3	216 x 10^3	D16	4
2		0.74	27.7			8
3		1.10	25.2			12
4	Chipping	0.37	25.1			4
5		0.74	23.9			8
6		1.10	23.2			12



(a) Shear Slip-Shear Stress Relationship

b) Shear Slip-Crack Opening Relationship

Fig. 5—Test results: (a) shear slip-shear stress relationship; (b) shear slip-crack opening relationship



(a) No. 2

(b) No. 5

Fig. 6—Axial strain distribution in reinforcement: (a) No. 2; (b) No. 5

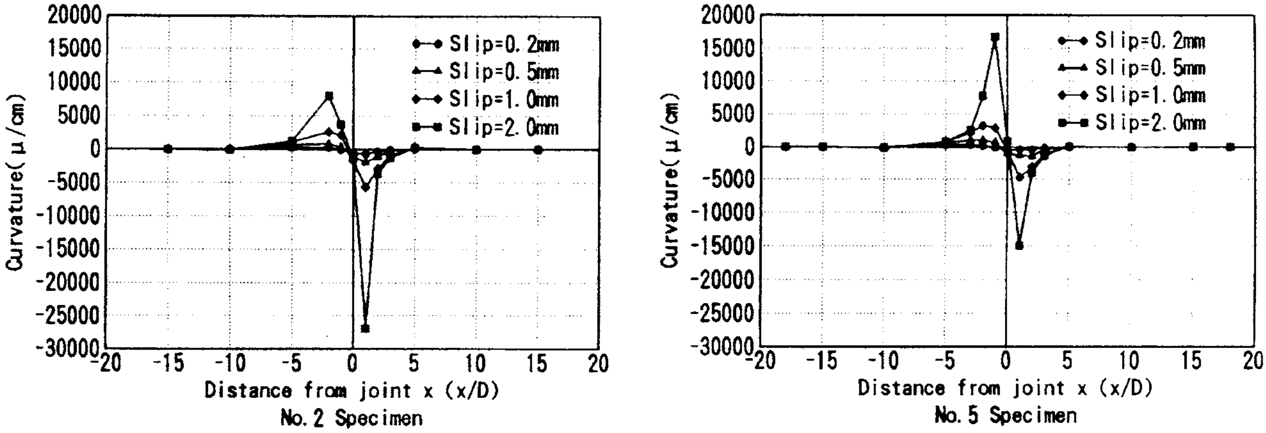
force is in effect from the start, was adopted here. Although this method is liable to result in generation of shear cracks in locations other than the joint, the fact that the joints in the test specimens here were construction joints meant that the tensile strength at the surfaces was much lower than in the rest of the concrete, and the result was that no harmful cracks were generated by the use of this method and clean openings were observed at the joints.

The shear slip displacement-to-shear stress relationships and shear slip-to-opening displacement relationships for each of the specimens are shown in Fig. 5. In all the specimens, shear slip and opening displacement did not occur until the joints opened. The considerations here will be limited to the behavior after the opening of the joints. In the test specimens subjected to smoothing treatment, the extremely small size of the bumps on the crack surfaces results in very small openings, while in those subjected to chipping treatment, opening displacements corresponding to around 40 percent of the shear is observed. A comparison of the two types of test specimens gives a clear understanding of the effects of the ratio between the shear slip and opening displacement on the behavior of the reinforcing bars.

OBSERVATIONS ON TEST RESULTS

Axial strain distribution in reinforcement bars

The distribution of the axial strain in the reinforcing bars at representative stages of the loading in test specimens No. 2 (smoothing) and No. 5 (chipping) are shown in Fig. 6. The axial strain was obtained by averaging the strain measured on either side of the reinforcing bars. With both the specimens, the axial strain showed chevron-shaped distribution when the shear slip was small, with the strain at the joints being the greatest. These distribution characteristics are the same as those obtained, for example, in the two-end pullout tests on reinforced concrete members. As the shear slip increases and the load nears its maximum value after the opening of the joint, however, the axial strain shows a sudden increase at points 1D (diameter) away from the joint (1D points) and becomes larger here than the strain at the joint. In particular, when the shear slip is found to be extremely large after the maximum load, the average axial strain at the 1D points far exceeds the yield strain, indicating the progress of yielding of reinforcing bars at the joint. It is to be noted that, despite this, the axial strain at the joint remains below the yield strain and is still found in the elastic region. This shows that the deformation characteristics of reinforcement when shear slip and axial strain coexist cannot be estimated



(a) No. 2 (b) No. 5

Fig. 7—Curvature distribution in reinforcement: (a) No. 2; (b) No. 5

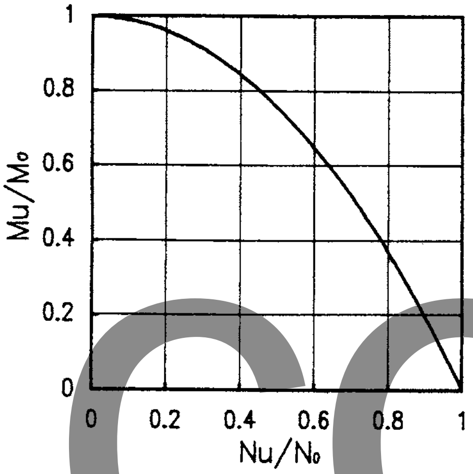


Fig. 8—M_u-N_u relationship in reinforcement

simply from the results of pullout tests under one-dimensional conditions.

Curvature distribution of reinforcement bars

The curvature distribution in specimens No. 2 and 5 is shown in Fig. 7. The curvature was obtained by dividing the values of the strain on either side of the reinforcing bar by the bar diameter. As with the axial strain, the curvature has its maximum values at the 1D points, indicating a close relationship between the axial strain and curvature distribution characteristics. It is also to be noted how both axial strain and curvature show sudden drops around the 1D points after the commencement of yielding, indicating the concentration of deformation in extremely small areas.

The exceptionally large values of the curvature at the 1 diameter point mean that the reinforcing bars cannot be regarded as one-dimensional linear members, but have to be treated as three-dimensional rod members. It is known that ultimate strengths M_u and N_u have the relationship shown in Fig. 8 in elasto-plastic reinforced concrete rod members subjected simultaneously to bending and axial forces. Reinforcing bars subjected to shear slip, too, have to be treated in the same way for the accurate assessment of their axial stress conditions. The variation of the stress conditions obtained from the measured strain at the 1D points, assuming reinforcing steel to be a completely elasto-plastic material, is shown in Fig. 9. The reinforcement at the 1D point undergoes what is more bending yield than axial yield.

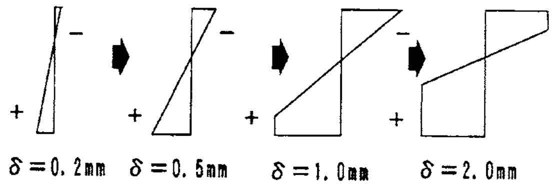


Fig. 9—Changes in reinforcement stress conditions

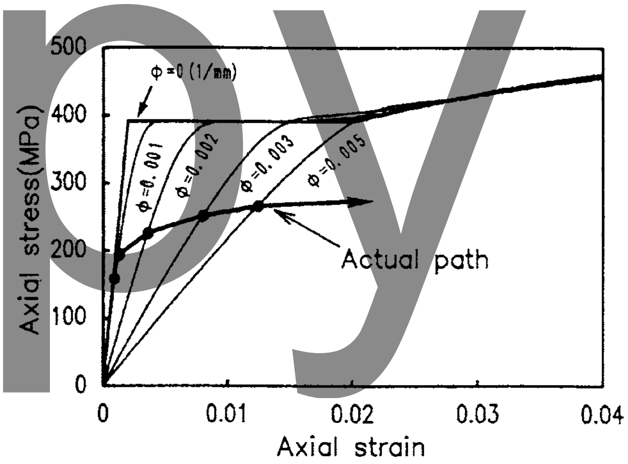


Fig. 10—Effect of curvature on stress-strain relationship

Axial strain-axial stress relationship of reinforcing bars

If the reinforcement cross sections are assumed to retain their planar composition, the average axial stress on the reinforcement cross section may be considered a function of the axial strain and curvature of the reinforcement and is shown in Fig. 10. If the deformation path corresponding to the axial strain and curvature is as shown by the bold line in Fig. 10, the effect of the bending yield will mean that the maximum value for the average axial strain of the reinforcement will be far below the uniaxial yield strength. The axial strain-axial stress relationship, as calculated from the axial strain and curvature hysteresis at the 1D points in test specimens No. 2 and 5, is shown in Fig. 11. With both test specimens, the apparent yield points are greatly reduced and found at values less than half those of the uniaxial yield stress. In the smoothing treatment, test specimen No. 2 in particular, with which the shear slip is large in relation to the opening displacement, the apparent yield points have been reduced to around one-third of the uniaxial yield stress. These observations confirm that the stress conditions of the reinforcement cannot be assessed accurately if the curvature is ignored.

Axial force distribution of reinforcing bars

Fig. 12 shows the distribution of the axial force in the reinforcement as calculated by the same method as in the preceding section, taking into account the coupling of the curvature and axial strain. There is a certain amount of dispersion in the values around the joint, suggesting a certain amount of errors in the calculations, but it can be observed that there is a tendency for the axial force to be more or less constant within 3 diameter of the joint. This is a result that is to be expected if the local fracture of the concrete around steel bars has resulted in the decrease of bond stress between concrete and steel. If the axial stress has more or less constant values, the axial strain will be largest at the point where the axial stiffness of the reinforcement is smallest. The effect of curvature resulted in a major drop in the stiffness of reinforcement at the 1D points, and this is thought to be the reason why the axial strain has its maximum value at 1diameter.

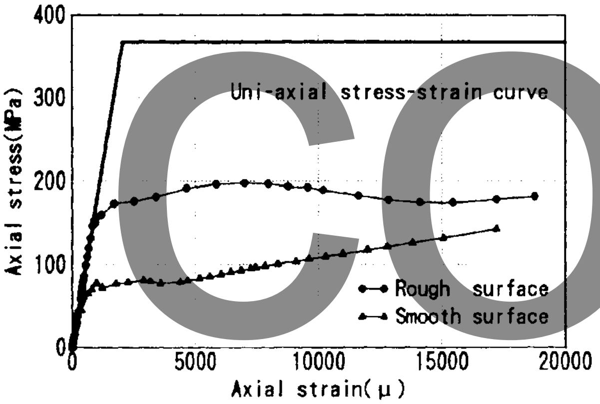


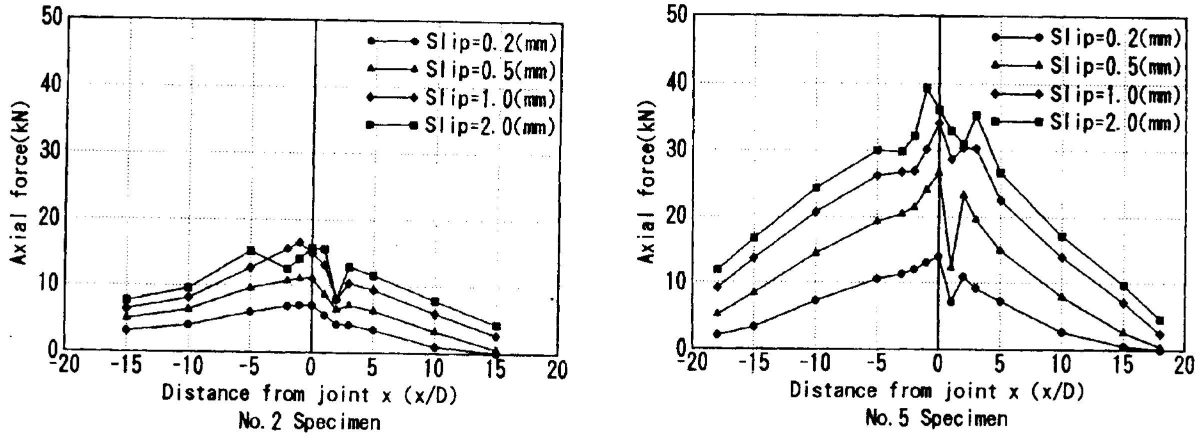
Fig. 11—Axial stress-axial strain relationship of reinforcement with curvature taken into account

Relationship between reinforcement stress and slippage

The slippage of reinforcement is obtained by integrating the axial strain of the reinforcement. In conventional models of slippage,[1,5] the plastic deformation accompanying the increase in the curvature of the reinforcements inside the concrete is ignored, and this results in the estimates for the slippage being smaller than in reality. If the continuity of the reinforcement stress and the deterioration of the bond stress around the joint are taken into account, the reinforcement stress at the joint and that at the 1D points will be more or less the same. This is an important point, which means that the limit value of the reinforcement stress at the joint will be lowered to a fraction of the reinforcement yield stress, as at the 1D point.

The reinforcement stress-slippage relationships, as obtained using the conventional model (Shin[5]) and the test values, are compared in Fig. 13. There is a relatively close agreement for the initial stiffness but both the stiffness, and the resistance become smaller in the test values than in the calculated values after the commencement of yielding. This indicates that calculation of shear resistance by a combination of the conventional reinforcement strain-slippage relationship and the concrete stress transfer model will tend to give values that are too large for the shear resistance. It has, in fact, been reported that the shear resistance is too large by several tens' percent when calculated using the discrete crack model developed by the authors,[6] despite the fact that the values for the reinforcement slippage[5] and the concrete stress transfer model[7] are accurate enough in themselves. While the causes of this error have not been explained, it is thought that the factors described previously have a major bearing on this matter.

When the symmetry of the deformation is taken into account, the reinforcement curvature at the joint position is ze-



(a) No. 2

(b) No. 5

Fig. 12—Axial force distribution in reinforcement: (a) No. 2; (b) No. 5

ro. The fact that the maximum axial stress of the reinforcement at the joint is a fraction of the uniaxial yield stress indicates that the reinforcement at the joint position remains elastic throughout its cross section. The elasticity of the axial strain of the reinforcement at the joint position does not necessarily mean that the behavior of the reinforcement slippage will be elastic. Yamada and Aoyagi[8] report that many of the test specimens ruptured under shear in their pushoff test when the reinforcement at the joint was in the elastic region. This rupture, too, may be explained by the lowering of the reinforcement stiffness with the progress of internal plastic deformation, or in other words, the reduction of the constraint on the crack opening.

CONCLUSIONS

The behavior of reinforcement embedded in concrete was extracted from the results of pure shear tests on the joint of reinforced concrete, and experimental observation was made on the nonelastic behavior of reinforcement subjected simultaneously to shear slip displacement and axial displacement. The following conclusions were drawn from this study.

1. The maximum axial strain in reinforcement embedded in concrete across a joint subjected simultaneously to shear slip and axial displacement was observed at points around 1 diameter away from the joint rather than at the joint itself, indicating the progress of internal yielding.

2. Taking into consideration the local bending of the reinforcement accompanying shear slip displacement, it was found that the preceding phenomenon could be explained by regarding the reinforcement to be an elasto-plastic body and coupling the axial strain and curvature of the reinforcement. The curvature, in particular, reduces the axial stiffness of the reinforcement and the limit value for its axial stress, indicating the importance of taking the curvature into account in models of such behavior.

3. The slippage behavior of reinforcement subjected simultaneously to shear slip and axial displacement differs greatly from that under purely tensile conditions, and it was suggested that the shear transfer resistance along the crack surface estimated using reinforcement models that ignore the effect of curvature will tend to be too large.

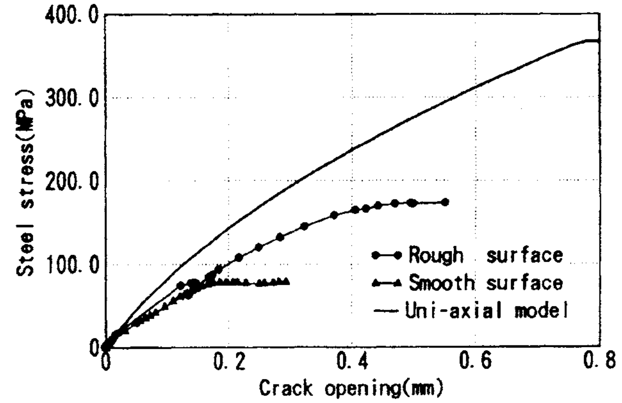


Fig. 13—Reinforcement stress-slippage relationship

CONVERSION FACTORS

1 mm = 0.039 in.
1 cm = 10 mm
1 N = 0.22 lbf
1 MPa = 145 psi

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