

Debonding and fracture between deformed bars and early-age concrete

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ABSTRACT: The purpose of the present study is to obtain the bond characteristics of a deformed bar embedded in early-age concrete. The fundamental experiments, employing specimens with various covers of deformed bar, were conducted in order to investigate cracks around the deformed bar. The results indicated that in concrete within 1 day of age it is easy to generate internal cracks. The bond characteristics after an age of 2 days were properly evaluated by the equivalent bond stress. The increase of the slip could be induced by the damage of the concrete around the deformed bar.

1 INTRODUCTION

Cracks in concrete are undesirable for the durable concrete structure; therefore cracks must be controlled appropriately. Such cracks, however, often cannot be avoided; moreover the prevention of all cracks is not always needed for the rational design of concrete structures. Wider cracks compromise concrete structures' long-term service life, but microscopic cracks hardly influence the durability of concrete. In order to construct durable concrete structures, the width of the cracks in the concrete is the most important factor for durability.

Many high strength and massive concrete structures have been constructed in recent years. In such structures, cracks due to the volume-change in early age often are induced. Therefore controlling the crack width in early-age is an effective strategy for ensuring durable concrete structures. Crack width is dependent on the bond characteristics of the reinforcing bars embedded in the concrete. In order to estimate the crack width, the bond characteristic is normally evaluated as the relationship between local bond stress and slip of the reinforcing bar. The concrete around the ribs of the reinforcing bar is damaged by the front of the ribs when the reinforcing bar in concrete transforms. Here, concrete strength has not been developed sufficiently during the hydration period, i.e. early age. The bond strength of early-age concrete, therefore, is lower than that of the mature concrete. In other words, the early age concrete is more sensitive to the bond fracture of the reinforcing bar.

The purpose of the present study is to obtain the bond characteristics of a deformed bar embedded in

the early-age concrete. The fundamental experiments, employing specimens with various covers of deformed bar, were conducted in order to investigate cracks around the deformed bar. In the present study, such bond fracture obtained from the fundamental experiments is indicated and the bond fracture mechanism in early age is also discussed. The bond stress-slip relationship in various ages of concrete is evaluated in the present study.

2 INVESTIGATION OF DAMAGE AROUND DEFORMED BAR IN EARLY AGE

2.1 *Experimental program*

2.1.1 *Test specimen*

Test specimens in the present study are shown in Figure 1. All specimens in the fundamental experiments were made by using mortar concrete. The reinforcement was embedded at the center of the specimen. The reinforcement was a deformed bar with a diameter of 13 millimeters. The specification of deformed bar and the detail of its rib are given in Table 1 and Table 2 respectively.

Table 3 gives the mix proportion of mortar. Materials employed for the mortar were the blast furnace slag cement with a density of 3.05 g/cm^3 , sea-sand with a density of 2.60 g/cm^3 and crushed andesite rocks with a density of 2.70 g/cm^3 .

The sizes of the test specimens were set at $100 \times 400 \text{ mm}$ with various levels of cover of the deformed bar. In order to investigate the mortar damage around the deformed bar, the cover thicknesses used were 3.5 mm, 7.0 mm and 12.5 mm, and the heights(h) of the specimens were 20 mm, 27 mm

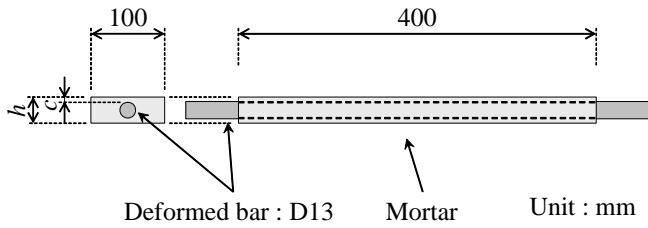


Figure 1. Test specimen

Table 1. Specification of deformed bar

Diameter	Yield point	Young's modulus
mm	N/mm ²	N/mm ²
13	295	191200

Table 2. Detail of deformed bar rib

Maximum height	Minimum height	Average interval
mm	mm	mm
1.0	0.5	8.9

Table 3. Mix proportion of mortar

Water-Cement Ratio	Water	Cement	Fine Aggregate	Admixture
%	kg/m ³	kg/m ³	kg/m ³	kg/m ³
32	207	647	1414	6.47

Table 4. Experimental parameters

Specimen	Cover of deformed bar (c)	Height of specimen (h)	Mortar age at test
	mm	mm	days
12.5-1d	12.5	38	1
12.5-7d	12.5	38	7
7.0-1d	7.0	27	1
7.0-7d	7.0	27	7
3.5-1d	3.5	20	1
3.5-7d	3.5	20	7



Figure 2. Uniaxial tension test

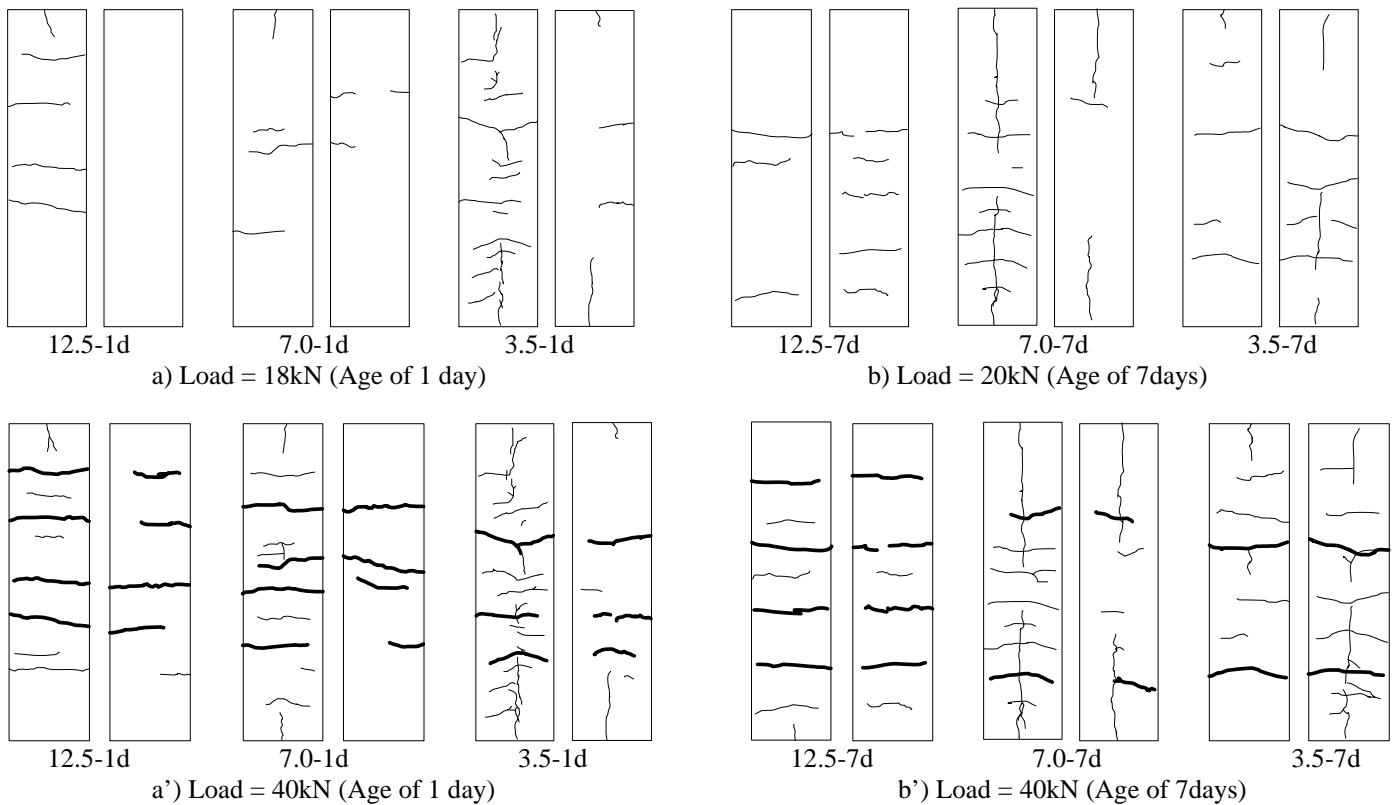


Figure 3. Crack sketch

and 38 mm respectively. Table 4 gives the experimental parameters in the present study.

2.1.2 Experimental procedure

When concrete cracking occurs due to volume change, the concrete and reinforcement are mainly

in the tensile stress field. In order to simulate such an actual stress condition, the uniaxial tension test was conducted. The test setup is shown in Figure 2. Loads were provided as high as the stress on yielding point of the deformed bar, i.e. the maximum load 40 kN. Load was gradually increased at a rate of 100 N/s.

2.2 Result and discussion

2.2.1 Crack sketch

Example of crack sketches is shown in Figure 3. The bold lines represent cracks across the cross section.

As shown in Figure 3, the specimens of 3.5-1d had many more cracks than the specimens of 7.0-1d and 12.5-1d under the same load. Most cracks in the specimens of 12.5-1d under a load of 40 kN were across the cross section. The same results were found at the age of 7 days.

2.2.2 Fracture Mode

Goto and Otsuka have reported on cracks formed in concrete around deformed tension bars (Goto and Otsuka, 1980). When the concrete and the deformed bar are subjected to an axial tension load, primary cracks shown in Figure 4(a) are often generated in the concrete. In the concrete surrounding the deformed bar, internal cracks, which do not generally appear on the surface of concrete, occur at an approximate 60° angle to the axis of deformed bar. When the deformed bar is subjected to higher stresses, some internal cracks develop to the surface of the concrete as shown in Figure 4(a). In the present paper, such a crack is called a secondary crack. The concrete around the rib of the deformed bar is damaged by the front of ribs as shown in Figure 4(b). Under higher loading, the concrete between two ribs is finally fractured with local shearing failure as shown in Figure 4(b). Cracks across the cross section illustrated in Figure 2 can be assumed to be primary cracks while the others can be taken as internal cracks.

Figure 5 shows the crack condition in a specimen of 12.5-1d. The rib-marks of the deformed bar clearly remained. Therefore, the mortar between the ribs was not sheared and the mortar in front of the ribs was not crushed.

All primary cracks were generated from the rib of the deformed bar as shown in Figure 6. Several cracks in the specimens with 3.5mm of cover over the deformed bar (3.5-1d, 3.5-7d) were generated at an angle to the vertical direction. The formation of such cracks was due to the internal cracking.

2.2.3 Interval and length of cracks

The average intervals were evaluated from the intervals of all cracks including the primary cracks and internal cracks, and the average lengths were calculated from the lengths of internal cracks. Table 5 gives the average interval and the average length of cracks under the load of 40 kN.

The specimens with thinner cover of deformed bar had many cracks, so that the average intervals in that specimen were smaller. The average lengths at the age of 7 days ranged from 60.9 mm to 66.3 mm. On the contrary, the average lengths measured in the specimens which had the thinner cover were smaller

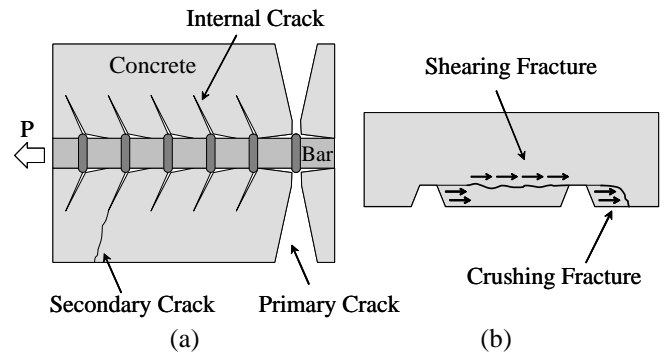


Figure 4. Fracture Modes

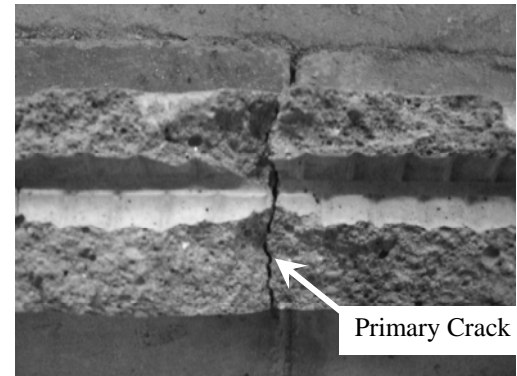


Figure 5. Crack condition in specimen of 12.5-1d

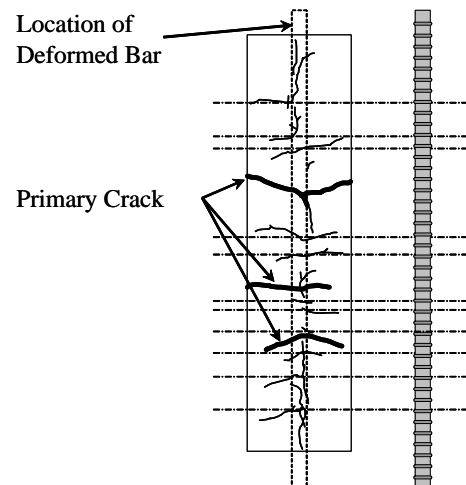


Figure 6. Location of cracks and deformed bar ribs (Specimen : 3.5-1d, Load = 40kN)

Table 5. Average interval and length of cracks

Specimen	Average interval of cracks	Average length of cracks
	mm	mm
12.5-1d	36.4	59.2
7.0-1d	30.6	51.4
3.5-1d	24.3	39.3
12.5-7d	47.1	66.3
7.0-7d	31.3	65.5
3.5-7d	31.8	60.9

at the age of 1 day. The average length in the 3.5-1d was 65% of the average length in the 3.5-7d. The internal cracks in the 3.5-1d specimen occurred at a lower load level than in the other specimens, as shown in Figure 3. These results indicate that early-age concrete (within 1 day of age) is more suscepti-

ble to the formation of internal cracks around the deformed bar.

3 LOCAL BOND STRESS-SLIP RELATIONSHIP

3.1 Experimental program

3.1.1 Loading method

The uniaxial tension tests were conducted to simulate an actual stress condition as shown in Figure 7. The jig set with the bar edge has two hinges in order to reduce the eccentric load. The maximum load was determined as 35 kN, so that the reinforcing bar did not yielded in the present study. In addition, reloading tests were conducted in order to evaluate the damage of the concrete around the deformed bar. The program of the reloading test is shown in Figure 8.

The loading and unloading process was controlled at approximately 100 N/s.

3.1.2 Test specimen

The test specimens used in this experiment are illustrated in Figure 9. The reinforcement embedded at the center of the concrete was a deformed bar with a diameter of 13 mm.

Yamao et al. indicated that the relationship between local bond stress and slip is almost equal in case of sufficient bond length, i.e. more than 25D (Yamao, Chou and Niwa, 1984). Early-age concrete is more easily damaged by the bond stress of deformed bar than is mature concrete. Therefore, the bond length employed in this study was 50 times the bar diameter, i.e. 650 mm from the center of the specimen. The un-bond zone, with a length of 130 mm, was set by covering the deformed bar with vinyl tape. Such un-bond zones had the role of preventing pullout fracture at the bond edge. Therefore, the specimen length was 1560 mm and the cross section shape was a square with side of 100 mm.

Strain gauges were attached on longitudinal ribs of the deformed bar with an interval of 65 mm beginning at the center of the specimen.

Table 6 gives the mix proportion of the concrete. The cement employed in this experiment was the blast furnace slag cement. The specified concrete strength in the present study was 24 N/mm² which is used for many civil infrastructures in Japan, and the water-cement ratio was 57 %. The detail of the reinforcement is equal to the specifications given in Table 1 and Table 2.

3.1.3 Experimental parameters

Uniaxial tension tests were carried out at 0.5, 1, 1.5, 2, 3, 7, and 28 days. In addition, compressive strength tests, split tensile strength tests and Young's modulus tests were carried out in order to evaluate the hydration degree of the concrete.

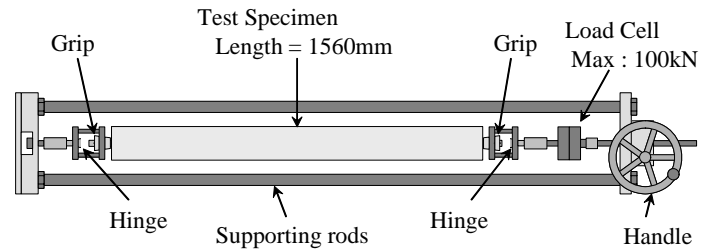


Figure 7. Test setup

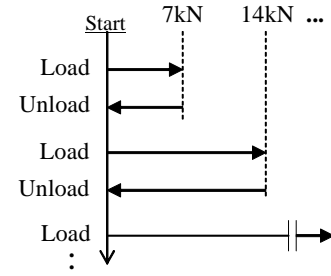


Figure 8. Program of reloading test

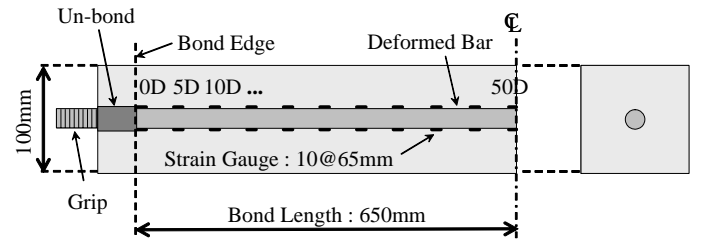


Figure 9. Test specimen

Table 6. Mix proportion of concrete

Water	Cement	Fine Aggregate	Coarse Aggregate	Admixture
kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³
165	290	812	1030	2.9

3.1.4 Local bond stress and slip

As given in Equation 1, local bond stress is evaluated from a differential function of the strain distribution in the deformed bar. In the present study, the distribution of strain was taken as 2-dimensional parabolic curves by using 3 points of the strain data (Shima, Chou and Okamura, 1987).

$$\tau = \frac{DE_s}{4} \cdot \frac{d\varepsilon_{s-b}}{dx} \quad (1)$$

where x = location from the specimen center across the length; τ = local bond stress; D = diameter of re-bar; E_s = Young's modulus of re-bar; ε_{s-b} = strain of re-bar subjected to bond stress.

The bond stresses are generally expressed as a function of slip. As given in Equation 2, slip is evaluated by integrating the difference between the reinforcement strain and the average concrete strain. Here, the average concrete strain can be obtained from Equation 3. The slip at the center of reinforcement can be assumed as zero in the case of axially loaded tension test.

$$S = \int_0^x \{\varepsilon_{s-b}(x) - \bar{\varepsilon}_c\} dx \quad (2)$$

$$\bar{\varepsilon}_c = \frac{P - \varepsilon_{s-b} E_s A_s}{E_c A_c} \quad (3)$$

where S = slip; $\bar{\varepsilon}_c$ = average strain at cross section of concrete; P = load; A_s = area of re-bar; A_c = concrete area; E_c = Young's modulus of concrete.

3.2 Strain of deformed bar subject to bond stress

The deformed bar embedded in concrete was restricted by the bonding concrete, so that the strain of the embedded bar is smaller than the strain of the un-bond region of the bar at specimen edge. Figure 10 shows an example of the relationship between stress and strain on the deformed bar embedded in concrete with various ages. Here, the ordinate represents the stress in the un-bond region of the bar; its stress-strain relation is illustrated for comparison in these figures.

Figure 10 demonstrates that the strain of the reinforcement in concrete becomes smaller as concrete strength increases. The concrete strength and Young's modulus at the age of 0.5 days were especially small, i.e. compressive strength of 0.41 N/mm², splitting tensile strength of 0.06 N/mm² and Young's modulus of 1.34 kN/mm², so that the surrounding concrete had little resistance to the slip of the deformed bar. Thus, the stress-strain curves at the age of 0.5 day were especially similar to the curve of un-bond region of the bar compared with the curves obtained from the other ages. However, primary cracks across the cross section occurred at this age. Such cracks could be induced by the friction and the chemical bond on the interface between the concrete and the deformed bar, though the mechanical resistance of deformed bar rib was especially little. This phenomenon at the age of 0.5 days occurred in the test employing the round bar (Figure 11).

Figure 12 shows the strain distribution in the reinforcement along the specimen length at various levels of un-bond bar stress. The strain at the location of cracks was increased as high as the strain of the un-bond bar. Figure 10 illustrates the various locations of cracks in every test. Thus, the bond characteristics before cracking are discussed in this study.

The distribution slope around the edge of the bond region was more inclined by the increase of the load, as shown in Figure 12. In the other region, the reinforcement strains obtained from the test were very similar to the average concrete strain estimated by Equation 3 with axial stiffness of concrete and deformed bar ($E_s A_s$, $E_c A_c$), as shown in Figure 13. Therefore, the slip between the deformed bar and the concrete is nearly equal to zero in this region.

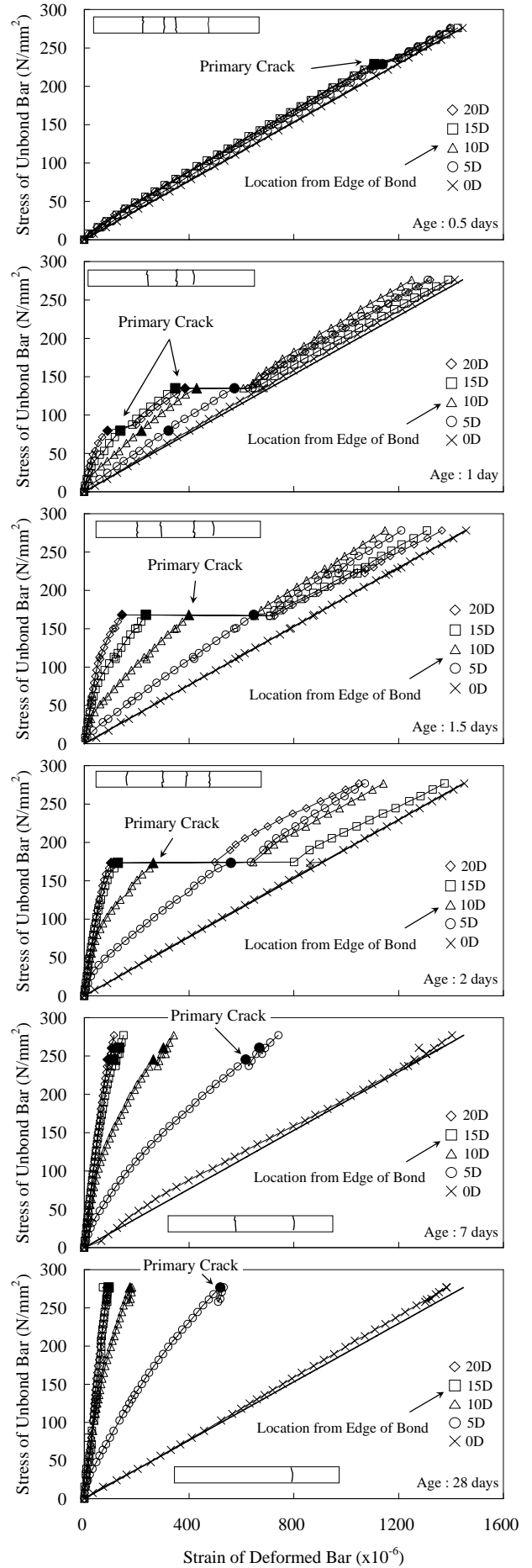


Figure 10. Strain of deformed bar subjected to bond stress (Age : 0.5, 1, 1.5, 2, 7, 28 days)



Figure 11. Primary cracks in the test employing the round bar at age of 0.5 days

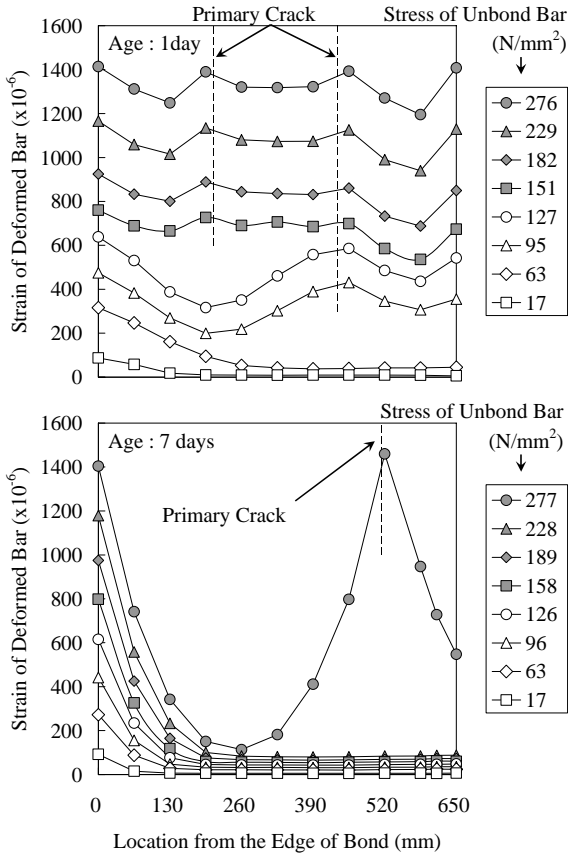


Figure 12. Distribution in deformed bar strain along the length of specimen at various levels of stress of unbond bar (Age : 1, 7 days)

3.3 Local bond stress-slip relationship

Figure 14 shows the local bond stress-relative slip relationship along the reinforcement at the age of 3 days. A relative slip (S/D , %), which means the slip per the diameter of bar, is herein employed as the lateral axis. Figure 14 indicates that the relationships between local bond stress and relative slip are greatly similar curved lines in spite of the location along the deformed bar.

Figure 15 shows the relationship between bond stress and slip at various ages of concrete. Figure 15 demonstrates that the local bond stress increases with age at the same relative slip.

In order to investigate the influence of the hydration progression of concrete, e.g. concrete strength development, equivalent bond stress is employed in this study. The equivalent bond stress is defined as the bond stress per the two-third power of the compressive strength of concrete as given Equation 4 (Yamao, Chou and Niwa, 1984).

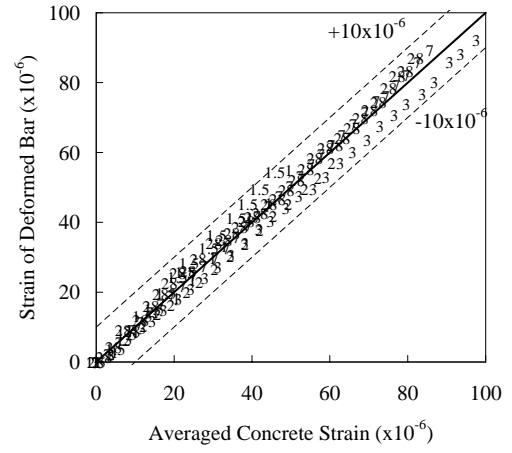


Figure 13. Relationship between average concrete strain and strain of deformed bar

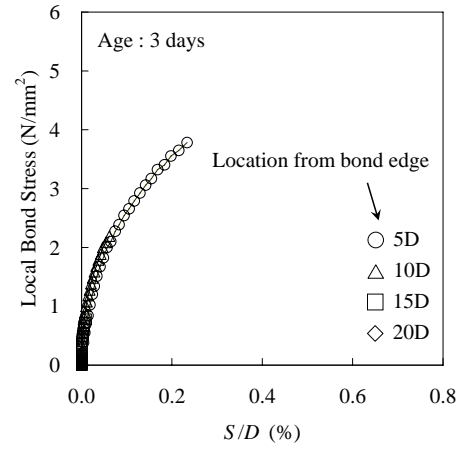


Figure 14. Local bond stress-slip relationship along the reinforcement axis (Age : 3 days)

$$\tau_{equ} = \frac{\tau}{f'_c{}^{2/3}} \quad (4)$$

where τ_{equ} = equivalent bond stress, and f'_c = compressive strength of concrete.

Figure 16 shows relationships between equivalent bond stress and relative slip at various ages of concrete. This graph indicates that the relationships showed a great amount of variation at earlier ages (1, 1.5 days) differed from the other relationships. This phenomenon implies that the bond mechanism before 2 days is different from the mechanism for ages after 2 days. As mentioned above, the concrete surrounding the deformed bar is sensitive to internal cracks before 2 days age. Thus, the concrete cannot be expected to have developed bonding characteristics at an age of 1 day, as shown in Figure 16.

In addition, the curves of the equivalent bond stress were very similar to each other after 2 days age, as shown in Figure 16. The equivalent bond stress properly evaluates the characteristics of the bond stress after 2 days. To employ the equivalent bond stress is a valid method to evaluate the bond behavior of early-age concrete.

