LOCAL BOND-SLIP BEHAVIOR OF DEFORMED REINFORCING BAR UNDER CYCLIC LOADING

Shuai HAO
Graduate Student, University of Tsukuba, Japan
s1420947@u.tsukuba.ac.jp

Toshiyuki KANAKUBO
Associate Professor, University of Tsukuba, Japan
kanakubo@kz.tsukuba.ac.jp

Hitomi OKAZAKI
Graduate Student, University of Tsukuba, Japan
s1420872@u.tsukuba.ac.jp

ABSTRACT: In this study, pullout bond test both for monotonic and cyclic loading is conducted for several types of deformed bars with different dimensions of lugs. The test variables are the ratio of lug height to spacing, loading history and concrete strength. The specimens are subjected to splitting test after pullout loading to observe the interface between the bars and concrete. As a result, deformation of concrete at the front of the lug is recognized. For the cyclic loading specimens, the relationship between bond stress and cumulative slip, that considers the returnable limit slip, shows a similar tendency to bond stress - slip curve of monotonic loading specimens regardless of the type of deformed bars. It is feasible to use the monotonic loading results to evaluate the bond strength under cyclic loading.

1. Introduction

Researches on bond behavior of deformed reinforcing bars have been studied so far (Sato et al., 2012). However, there are few studies on local bond behavior under cyclic loading. For example, although Morita and Kaku (1975) proposed a hysteretic model for the relationship between bond stress and slip under cyclic loading and reported the bond deterioration in the range of experienced slippage, there is no further discussion when the slippage exceeds the experienced slippage. Suzuki et al., (1985) also proposed a hysteretic model. However, bond behavior after the experienced slippage is not mentioned.

On the other hand, when the reinforcing bars in beam, column or beam-column joint are under an antisymmetric loading, they are subjected to a cyclic load with large slippage. The authors focus on bond behavior of deformed bars under cyclic loading in the case of large deformation (Okazaki and Kanakubo, 2014). As a result, the hysteretic curve can return to the one under monotonic loading even the slippage exceed the experienced slippage in a certain region. However, when it exceeds that region, bond deterioration appears remarkably. For some rib dimensions, bond stress decrease rapidly at the slip of 1/20 bar diameter. The designed capacity and ductility of reinforced concrete members may be overestimated if the bond deterioration under cyclic loading is unknown.

In this study, focusing on the local bond behavior of deformed reinforcing bars, bond test is conducted. The bond length is 4 times bar diameter and the deformed bars are originally manufactured for various type (different ratio of lug height to spacing).It can be used to investigate the influence of ratio of lug height to spacing on the bond behavior. In addition, the specimen is restricted by a steel tube to avoid splitting failure. The purpose of this study is to investigate the influence of loading history and dimensions of lugs on local bond behavior.

2. Experimental Program

2.1. Tested Deformed Bars

Table 1 and Fig.1 shows the list of deformed bars and the dimensions, respectively. The tested bar was manufactured by machining a round steel bar. Variation factors are the height of lug and lug spacing. The ratio of lug height to spacing varies from 0.05, 0.075 to 0.25 (called F050，F075 and F250, respectively). The lug dimension of F075 is similar to the normal deformed bar specified in Japanese Industrial Standard. Sectional area of those bars is defined as the equivalent area calculated by volume divided by the length. Yield strength of the bar before machining is 570MPa, and the elastic modulus is 207GPa.

Table 1 –Tested reinforcing bar

ID	Height of lug (mm)	Lug spacing (mm)	Ratio of lug height to spacing	Sectional area (mm^2)	Perimeter (mm)
F050	1.2	24.0	0.05	201	50.2
F075	1.2	16.0	0.075	204	50.6
F250	2.4	9.6	0.25	194	49.4

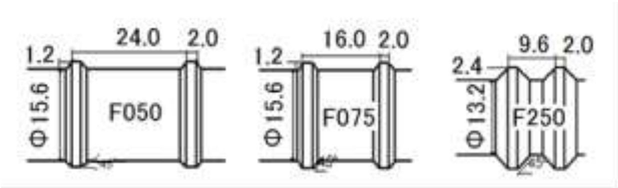

Fig. 1 – Dimensions of tested bar

2.2. Specimen

Fig.2 shows the details of the specimen. One deformed bar was set at the center of the concrete cylinder. The cylinder was confined by steel tube to avoid concrete splitting. External diameter of the steel tube is 216mm, the thickness is 5.8mm and the width is 112mm. The bond region was set as 4 times the referred deformed bar (φ16), so bond length is 64 mm. Unbond regions were set in both two sides with 24mm length.

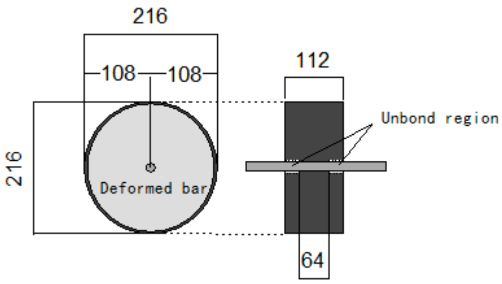

Fig. 2 – Details of specimen

2.3. Loading Method and Measurement

Loading apparatus is shown in Fig.3. The Teflon sheet and reaction steel plates with a hole of 112mm were set beside two sides of specimen. Load cells and center-hole jacks were set at both left and right sides of the specimen. Using the jack in each side alternately applied a cyclic loading. Monotonic loading was also carried out by only use one side of jack.

The measurement items are pullout load measured by load cell and the relative displacement between lateral side of specimen and the tested bar end. The slippage at free end is defined as the relative displacement measured by LVDT, which is set at the opposite side of loading direction. The loaded end slip is calculated as that the elongation of reinforcement is added to the free end slip under the assumption that bond stress distributes uniformly among bonded region.

Fig. 3 – Loading apparatus

Fig.4 shows the loading history, which is the main experimental factor. It includes a monotonic loading and three types of cyclic loading called C1, C2 and C3. C1 loading was a reversed cyclic loading and it increases gradually. Each cycle corresponds to the loaded end slip at 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0 and 8.0mm. C2 loading was a cyclic loading in only positive direction, the target slip of each cycle is same as C1 loading. The pullout load in negative direction was applied after unloading until the slip returns to 0mm. In C3 loading, bond stress was set as a target value at when the target slip reached to 0.1, 0.3, 0.5, 1.0 and 2.0mm at first time. Five cycle loadings were applied for each bond stress. Upper side of the specimen in concrete pouring was set as the reaction surface for the positive loading and the monotonic loading.

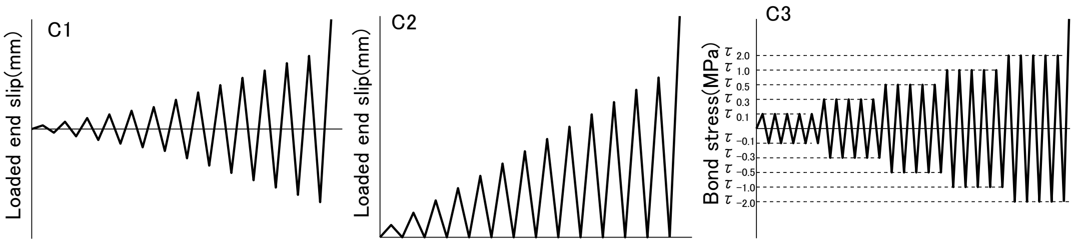

Fig. 4 – Loading history

2.4. Observation of the Interface between Bars and Concrete

Half of the specimens (concrete target strength of 13MPa and 36MPa, explained after) were subjected to splitting test to observe the interface between the bars and concrete after the loading of the target slip cycle. Fig.5 shows the photo of the splitting test.

Fig. 5 – Splitting test

2.5. Experimental Factor

The experimental factors are dimensions of rib of deformed bars, loading history and concrete target strength (13MPa, 21MPa and 36MPa). Table 2 shows the mechanical properties of concrete. Fig.6 gives the definition of ID of specimens. Specimens are listed in Table 3.

Table 2 – Mechanical properties of concrete

ID	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
C13	13.3	1.48	20.7
C21	20.9	1.97	24.9
C36	37.3	2.58	27.8

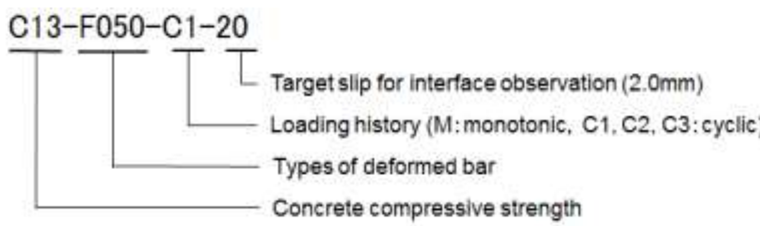

Fig. 6 – Specimen ID

Table 3 – List of specimens and test results

ID	At maximum load		ID	At maximum load				
	Bond stress (MPa)	Slip (mm)		Cycle	Bond stress (MPa)		Slip (mm)	
					+	-	+	-
C21-F050-M	24.6*	6.32*	C21-F050-C1	8	23.1	17.2	3.0	3.0
C21-F075-M	25.1*	2.05*	C21-F050-C2	9	22.5	-	4.0	-
C21-F250-M	18.7*	0.58*	C21-F050-C3	20	16.9	15.6	2.0	2.0
C13-F050-M-20	(6.27)	(2.0)	C21-F075-C1	4	16.7	13.6	0.8	0.8
C13-F050-M-40	(8.16)	(4.0)	C21-F075-C2	6	26.2	-	1.5	-
C13-F050-M-80	8.91	5.09	C21-F075-C3	16	19.1	20.4	1.0	1.0
C13-F075-M-08	(7.44)	(0.8)	C21-F250-C1	1	20.0	14.2	0.2	0.2
C13-F075-M-20	8.44	1.42	C21-F250-C2	2	21.4	-	0.4	-
C13-F075-M-40	8.44	1.74	C21-F250-C3	7	13.8	9.8	0.5	0.5
C13-F250-M-04	(6.16)	(0.4)	C13-F050-C1-20	7	(6.73)	(5.58)	(2.0)	(2.0)
C13-F250-M-08	(6.31)	(0.8)	C13-F050-C1-40	8	7.02	5.50	3.0	3.0
C13-F250-M-20	6.05	0.54	C13-F050-C1-80	8	7.81	6.71	3.0	3.0
C36-F050-M-20	(19.62)	(2.0)	C13-F075-C1-08	4	(8.16)	(4.63)	(0.8)	(0.8)
C36-F050-M-40	(24.21)	(4.0)	C13-F075-C1-20	6	7.60	4.88	1.5	1.5
C36-F050-M-80	24.71	5.50	C13-F075-C1-40	6	7.48	5.66	1.5	1.5
C36-F075-M-08	(22.49)	(0.8)	C13-F250-C1-04	2	(7.49)	(5.08)	(0.4)	(0.4)
C36-F075-M-20	24.41	1.62	C13-F250-C1-08	2	7.30	4.77	0.4	0.4
C36-F075-M-40	28.57	1.82	C13-F250-C1-20	2	7.00	5.30	0.4	0.4
C36-F250-M-04	20.30	0.21						
C36-F250-M-08	21.24	0.31						
C36-F250-M-20	20.78	0.27						

( ): For observing interface, the load terminated before maximum load appears.

*: Average value of three specimens.

Three same specimens (C13 series and C36 series) for each parameter were tested. They were subjected to splitting test to observe the interface between the bars and concrete after the loading of the target slip cycle. The target slip cycle was set as 3 stages (load increase region, just before or after the maximum load, and after the maximum load). For C13 series specimens, the loading was carried out only for monotonic and C1 loading. C36 series specimens were only subjected to monotonic loading. For C21 series specimens, three same specimens for each parameter were subjected to monotonic loading. Total number of specimens is 45.

3. Test Result

3.1. Observation of the Interface between Bars and Concrete

The photos of interface between bars and concrete after loading for C13 and C36 series specimens are shown in Fig.7 and Fig.8, respectively. For F050 and F075 deformed bars, when it reached to the target slip, the lug moved from its original position with the concave of concrete. The damage of the concrete around the front of the lug was unapparent. Some cracks took place in perpendicular to the axis direction in C13 series specimens. The crashed powder of concrete was not remarkably. The lug shape on concrete collapsed after maximum load in cyclic loading specimens. For the F250 deformed bars, there was almost no damage to the concrete before the maximum load. However, local shear failure of concrete between lugs was recognized after maximum load.

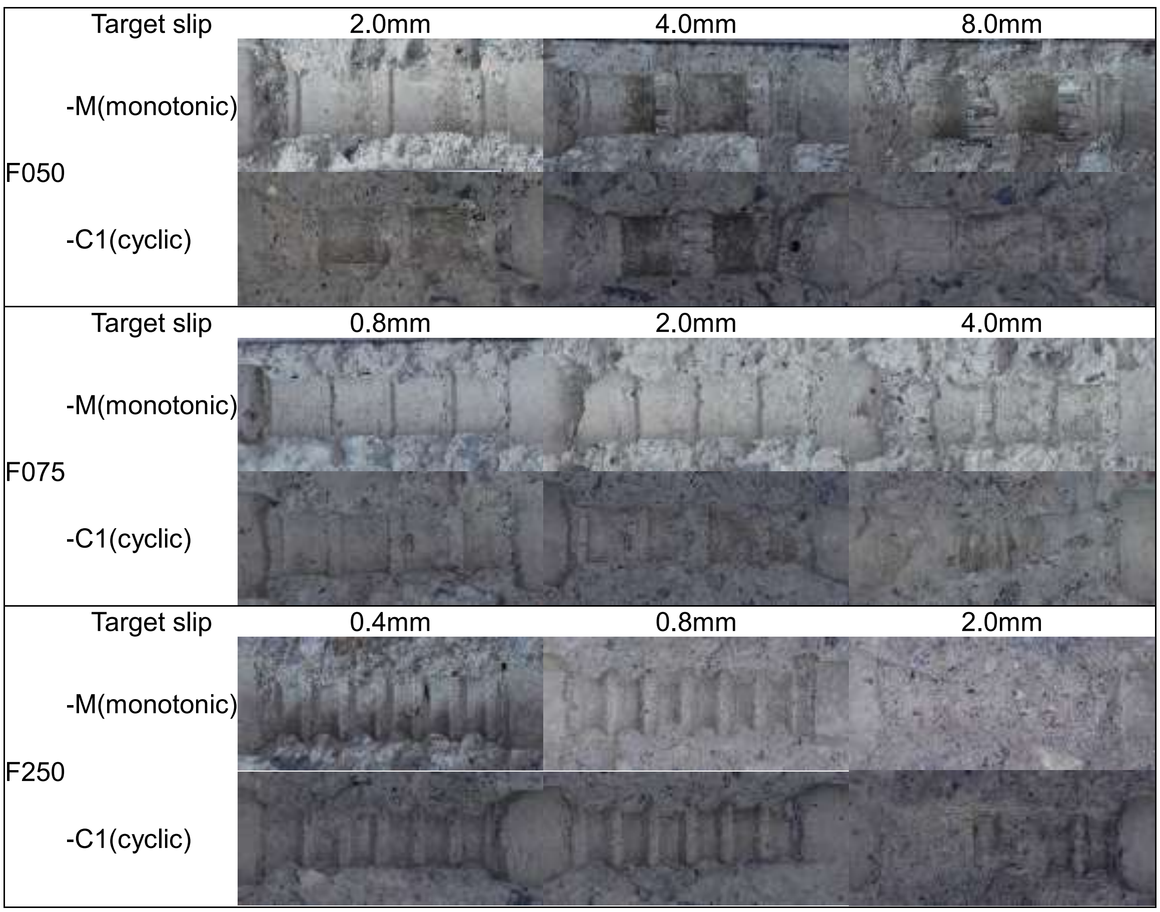

Fig. 7 – Interface between bars and concrete after loading (C13 series)

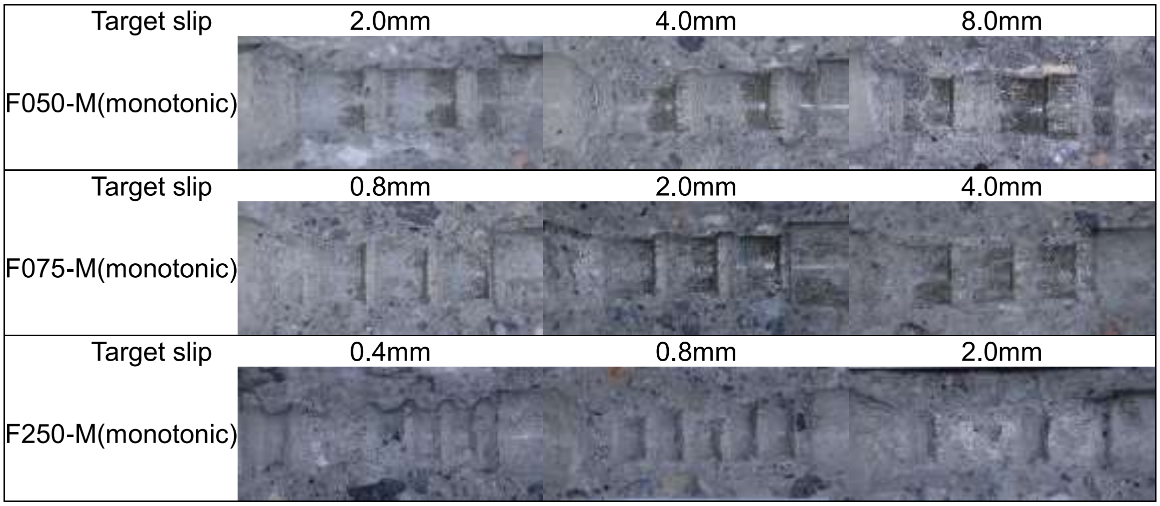

Fig. 8 – Interface between bars and concrete after loading (C36 series)

3.2. Bond Stress - Slip Relation

Relationships between bond stress and slip of monotonic loading specimens are shown in Fig.9. Although the bond stress has a large difference among the C13, C21 and C36 series of specimens, slip at maximum bond stress are almost the same. The lug spacing affects the shape of bond stress - slip curves and the slip at maximum bond stress.

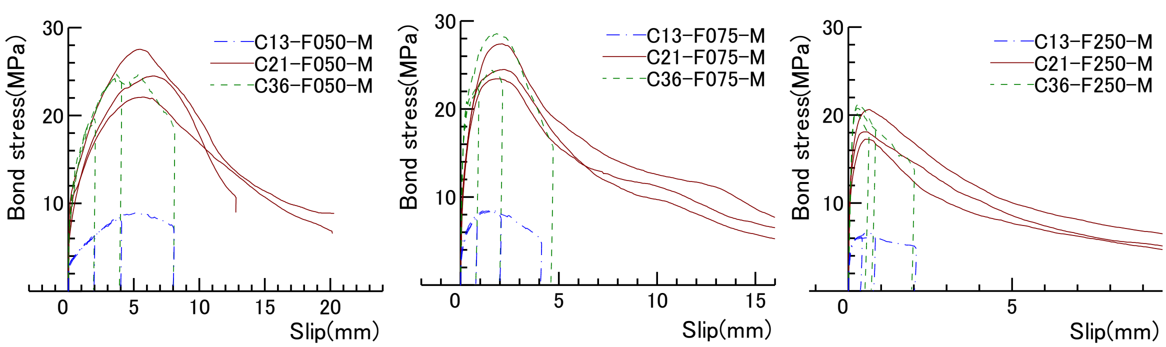

Fig. 9 – Bond stress - slip curve (monotonic loading)

Fig.10 shows the relationships between bond stress and slip by C1 cyclic loading. It can be found that the hysteretic curve can return to that by monotonic loading until slip reaches to a certain value (hereafter called “returnable limit slip”). When the slip exceeds the returnable limit slip, the bond stress drops remarkably. The returnable limit slip is not depended on concrete strength but lug spacing.

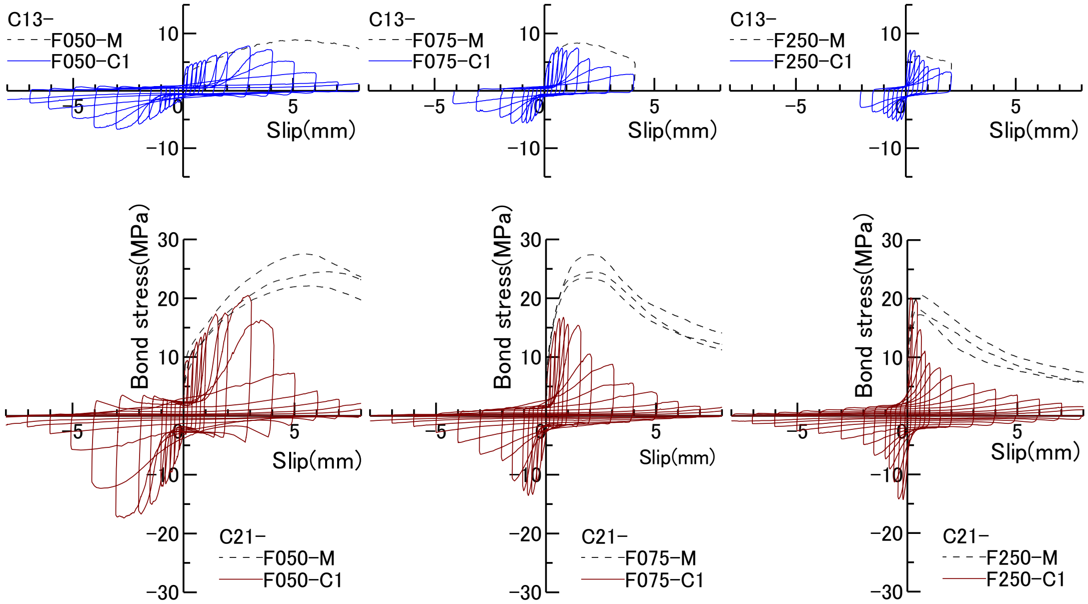

Fig. 10 – Bond stress - slip curve (C1 cyclic loading)

Fig.11 shows the envelope curves of bond stress - slip relations for C21 series specimens. The loading history affects the returnable limit slip. In addition, the bond deterioration tendency after the returnable limit slip also changes by differences of loading history. Basically, the returnable limit slip decreases with the number of reversed cycles increasing.

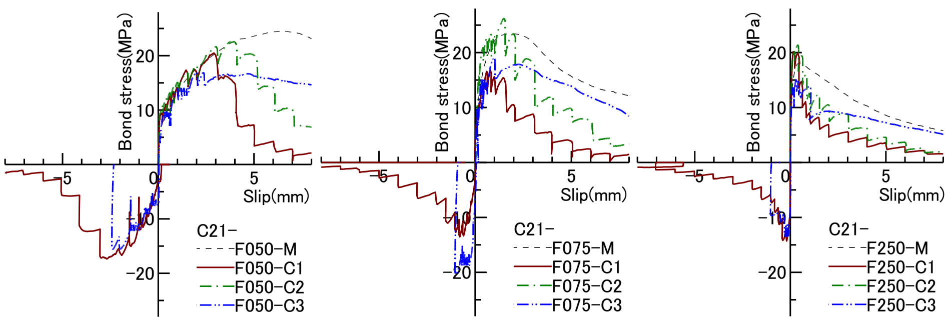

Fig. 11 – Envelope bond stress - slip curve (C21 series)

4. Evaluation by Cumulative Slip

Cumulative values are generally used to evaluate the fracture and response of materials. For those values, cumulative energy and cumulative strain are often used. As mentioned before, observing the interface between bars and concrete can find out that the lug moves from its original position with the concave of concrete. It is considered that bond deterioration occurs due to the cumulative deformation of concrete under cyclic loading.

Fig.12 shows the relationship between the cumulative slip (each peak slip is summed as the absolute value) and bond stress.

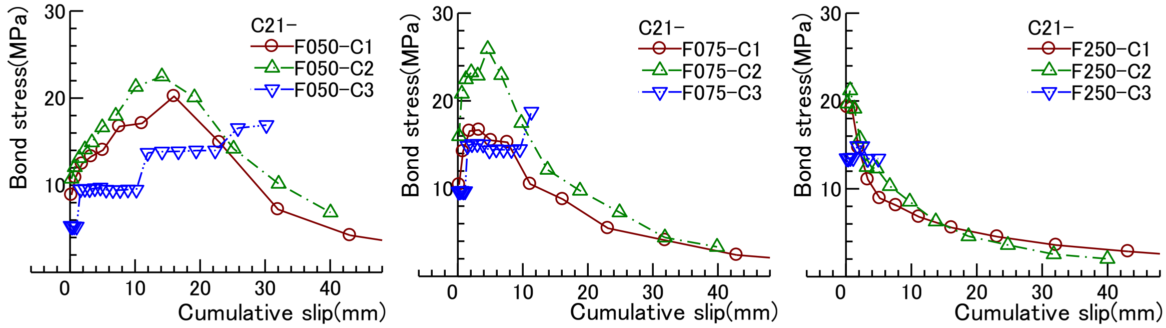

Fig. 12 – Bond stress - cumulative slip relation (C21 series)

Although the curves show a large difference among three specimens reinforced with different bars, for one bar, the curves show a similar tendency despite of difference of loading history. It is possible to use cumulative slip to evaluate bond deterioration under cyclic loading. From the result of discussion in Section 3.2, bond stress can return to that under monotonic loading until slip reaches to the returnable limit slip. It is considered that this phenomenon can be employed into the cumulative slip. The cumulative slip is calculated by sum of peak step subtracting the returnable limit slip when the peak step exceeds the returnable limit slip. Considering the effect of dimension of lug spacing, the returnable limit slip is to be equal as two thirds of the lug spacing, as the results of try-and-error. The results are shown in Fig.13. Fig.13 also includes the results of monotonic loading specimens.

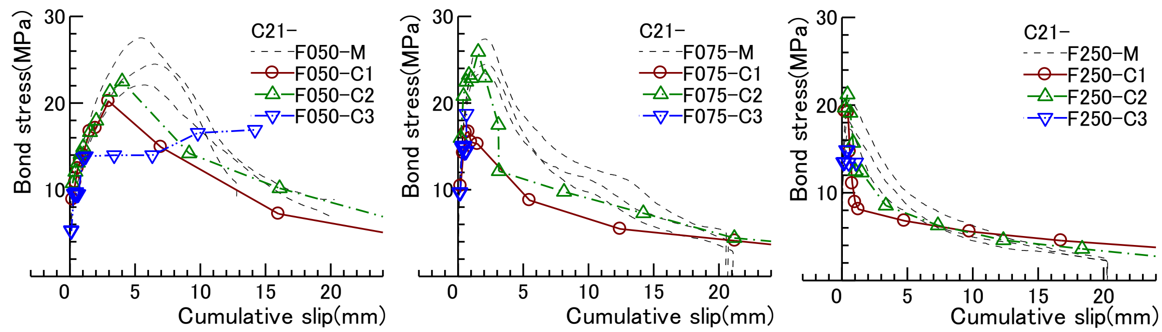

Fig. 13 – Bond stress - cumulative slip relation (returnable limit slip considered, C21 series)

The relationship between bond stress and cumulative slip, in which the returnable limit slip is considered, is similar to the one of monotonic loading specimens. It is feasible to use the monotonic loading results to evaluate the bond strength under cyclic loading.

5. Conclusion

(1) For the deformed bar with the ratio of lug height to spacing of 0.05 and 0.075, lug moved from its original position with the concave of concrete from the interface observation. For the deformed bar with the ratio of lug height to spacing of 0.25, local shear failure of concrete between lugs was recognized after maximum load.

(2) Lug spacing has a large influence on the bond stress - slip curves and the slip at maximum load.

(3) For the cyclic loading specimens, the hysteretic curve can return to the one under monotonic loading until slip reached to the returnable limit slip. Bond stress drops remarkably after the returnable limit slip and it cannot return to the curve of monotonic loading.

(4) For the cyclic loading, the relationship between bond stress and cumulative slip, that considers the returnable limit slip, shows a similar tendency to bond stress - slip curve of monotonic loading specimens. It is feasible to use the monotonic loading results to evaluate the bond strength under cyclic loading.

References

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