- Technical Paper -

AN EXPERIMENTAL STUDY OF BOND STRENGTH AGAINST LOW-CYCLE REPEATED LOAD

Ichiro KURODA[*1], Sokpor CHHAY[*2], Yoshihito YAMAMOTO[*3] and Nobuaki FURUYA[*4]

ABSTRACT

This research is aimed at grasping bond strength between deformed bars and concrete subjected low-cycle (up to 10^0 to 10^1 cycles) repeated load. Intention of the study is to find whether the repeated load of significant level worsens the ultimate bond strength or not. Pullout tests were conducted for D10 and D16 bars. A conclusion is obtained that such loading does not necessarily affect the bond strength but does increase the slip of re-bars.

Keywords: deformed bar, bond strength, repeated load, bond- slip relation

1. INTRODUCTION

It is needless to say that bond strength between re-bars and concrete plays a very important role for RC structures. One of the recent research directions has been to establish bond-slip relation, whose famous example was described in “CEB-FIP Model Code 1990” [1], and monotonic loading which means that a gradually increasing load is given to a member for once is assumed in this code.

In Japan, “Design Rules and Explanations for Railway Structures (Concrete Structure)” [2] gives a warning that “Article 11.10: Bond of re-bars. Influence of decrease of bond of longitudinal re-bars on the bearing and deformation capacity of members shall be considered, depending on necessity as for the case of earthquake, etc.” However, this specification is set mainly to the bond cracks. Both “Standard Specification for Concrete” by Japan Society of Civil Engineers [3] and “Specifications for Highway Concrete Bridges” by Japan Road Association stand on an assumption that bond can be considered not to be broken at first when re-bars which satisfy Japanese Industrial Standards are used and when bond strength (f_{bok}) by the next formula in [3] is assumed.

$$f_{bok} = 0.28 f'_{ck}{}^{2/3} \text{ MPa} \quad (1)$$

f'_{ck} : specific compressive strength of concrete

However, when we think behaviors of RC members under very severe load such as earthquake for instance, the bond strength of deformed bars begins to decrease by accumulation of minor slip which are results of low-cycle (in our definition, 10^0 to 10^1 times) fatigue by initial tremor due to the P-wave, and then members receive the maximum seismic load by the following S-wave afterwards.

Regarding this, a few researches have been done yet, and as far as we can find, the reference [4] and [5] dealt with the theme from relatively same view point. Especially in [5], bond-slip relation under repeating loading was investigated, and it was reported that combination of the bond up to 75% of the ultimate strength (1/1.33 P_{max}) and repeated loading up to 10,000 cycles did not lower the residual bond strength and also the path of bond-slip relation finally agreed with the path of monotonic loading.

In order to assess correctly the behavior that does not belong to high-cycle (a typical example will be a range of 10^4 to 10^6 times or more) fatigue, about which many design rules have been already established, we think that knowledge of this “residual bond strength after initial slip” is necessary, and we placed this point as a main target of our research.

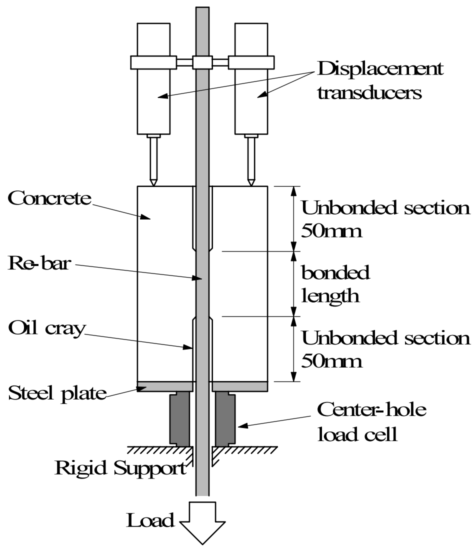

Fig. 1 Pullout test

*1 Associate Prof., Dept of Civil and Environmental Eng., National Defense Academy, Dr. E., JCI member
*2 Student from Cambodian Army, Graduate School of Eng., National Defense Academy
*3 Research Associate, Dept of Civil and Environmental Eng., National Defense Academy, M. E., JCI member
*4 Prof., Dept of Civil and Environmental Eng., National Defense Academy, Dr. E., JCI member

Table 1 Summary of Experimental results

Data No.	Diameter	Bond length	Loading method	Compressive strength (MPa)	Tensile strength (MPa)	τ_{max} (MPa)	$\tau_{max,r}$ (MPa)	τ_{max} or $\tau_{max,r}$ ÷ f_t	Slip at $\tau_{max,r}$ (mm)	Slip at final stage (mm)	P_{max} or $P_{max,r}$ (kN)	$P_{0.2}$ or $P_{0.3}$ (kN)	P_{max} or $P_{max,r}$ ÷$P_{0.2}$ or $P_{0.3}$	$P_{max,r}$÷P_{max}
1	D10	2 ϕ (20mm)	Mono.	27.9	2.4	8.1		3.38	0.70		4.87	3.95	1.23	1.00
2			$P_{0.2}$ X 5				7.9	3.30	0.40	0.31	4.76	4.30	1.11	0.98
3			$P_{0.2}$ X 20				7.5	3.13	0.63	0.34	4.50	3.53	1.27	0.92
4		2 ϕ (20mm)	Mono.	20.1	2.2	8.4		3.82	0.55		5.02	4.77	1.05	1.00
5			$P_{0.3}$ X 5				8.2	3.73	0.60	0.44	4.91	4.62	1.06	0.98
6			$P_{0.3}$ X 20				8.4	3.82	0.65	0.53	5.04	4.65	1.08	1.00
7		5 ϕ (50mm)	Mono.	24.5	2.0	6.2		3.10	0.70		9.30	7.40	1.26	1.00
8			$P_{0.2}$ X 5				5.9	2.95	0.66	0.29	8.90	6.90	1.29	0.96
9			$P_{0.2}$ X 20				6.2	3.10	0.80	0.57	9.40	8.23	1.14	1.01
10		5 ϕ (50mm)	Mono.	20.1	2.2	8.5		3.86	0.73		12.82	10.00	1.28	1.00
11			$P_{0.3}$ X 5				8.7	3.95	0.89	0.36	13.08	10.88	1.20	1.02
12			$P_{0.3}$ X 20				8.7	3.95	0.69	0.49	13.02	11.22	1.16	1.02
13			$P_{0.2}$ X 302				8.0	3.64	1.10	1.04	12.00	10.29	1.17	0.94
14	D16	3.1 ϕ (50mm)	Mono	33.3	3.4	11.3		3.32	0.51		28.12	24.09	1.17	1.00
15			$P_{0.2}$ X 5				11.2	3.29	0.73	0.32	27.98	20.66	1.35	0.99
16			$P_{0.2}$ X 5 *				8.9	2.62	0.57	0.42	22.15	23.96	0.92	0.79

Note : * … Splitted failure (others are pull-out failure).

The following notations will be used in this paper; P_{max}: Maximum load in simple monotonic loading, $P_{0.2}$ or $P_{0.3}$: Load when first slip becomes 0.2mm or 0.3mm and is used as upper control during repeated loading, $P_{max,r}$: Residual maximum load in final pullout after $P_{0.2}$ or $P_{0.3}$ was repeatedly given up to designated cycles and "r" implies residual, τ_{max}: Bond strength corresponding to P_{max} and $\tau_{max,r}$: Bond strength corresponding to $P_{max,r}$.

2. RESEARCH PROGRAMS

2.1 Loading Method

Pullout test as shown Fig. 1 was employed. The monotonic loading test was conducted at first to measure P_{max} and bond-slip relation. As the next, $P_{0.2}$ or $P_{0.3}$ was repeatedly given in one direction for 5, 20 or 302 times, and then $P_{max,r}$ was measured in the final pullout.

At first, we planed to use 0.7~0.8 P_{max} as the upper control value of the repeated loading (the method used in [5]). However, we have no way to previse P_{max} of a particular specimen before actual loading and some specimens directly went into final pullout. So, we changed the upper control to $P_{0.2}$ or $P_{0.3}$ where the bond-slip relation enters into non-linear state but still keeps some margin against the peak. The number of repeating of 5 or 20 was decided to simulate the low-cycle fatigue mentioned in Chapter 1. And, the number of 302 intended to go over the peak of bond-slip relation (target: 10^3), but it was accidentally stopped there because manual control overrun the upper control load ($P_{0.2}$) and the specimen thus went into the final pullout.

2.2 Materials

(1) Re-bars

JIS specified D10 or D16 re-bars of SD295 are used.

Table 2 Variance of τ_{max}(MPa)

Data No.	Individual Values			Average
1	**<u>8.1</u>**	9.0	7.1	8.1
4	8.2	**<u>8.4</u>**		8.3
7	**<u>6.2</u>**	7.0	6.3	6.5
10	**<u>8.5</u>**			8.5
14	**<u>11.3</u>**	11.1	13.1	11.8

Note: underlined data appeared in the Table 1

(2) Concrete

Mix condition for the concrete is: the maximum size of aggregate (crushed lime stone) = 20mm, W/C = 60%, s/a = 46%, unit quantity of water and cement = 169kg and 282kg, respectively. Actual strength of the concrete is given in Table 1. Our tensile strength was measured by the splitting test method. A main reason of variance of the strength is difference of the age at time of experiment.

(3)Specimen

Specimens have cross section of 100mm x 100mm, in which a re-bar is embedded at the center with the bonded length of 2ϕ (ϕ: diameter of re-bar), 3.1ϕ or 5ϕ. Two unbonded sections with length of 50mm each were provided, which was same to the method used in [5]. Concrete was cast when the re-bar and a surrounding steel form lied horizontally, which means that obtained bond strength can be affected by bleeding water entrapped below the re-bar.

3. TEST RESULTS AND CONSIDERATIONS

3.1 Summary of test

Table 1 shows summary of types of the specimens and their test results. The quantity of each test was 3 to 1, but combinations of best fit (degree of similarity of graphs for bond-slip relation is high) between the monotonic and repeated loadings are

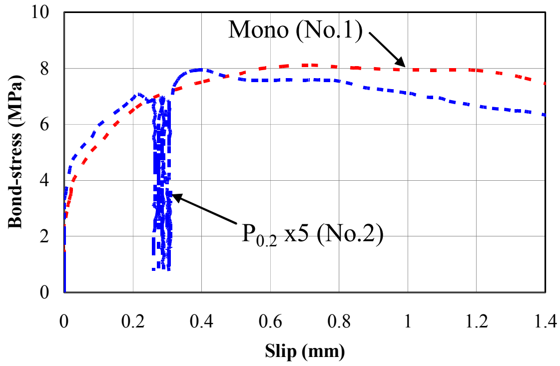

Fig.2　Bond vs. slip (D10 – bond 2ϕ)

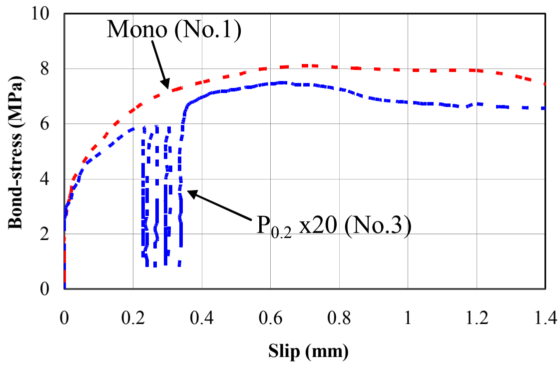

Fig.3　Bond vs. slip (D10 – bond 2ϕ)

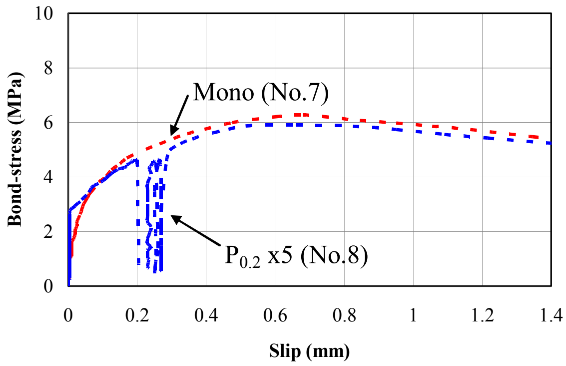

Fig.4　Bond vs. slip (D10 – bond 5ϕ)

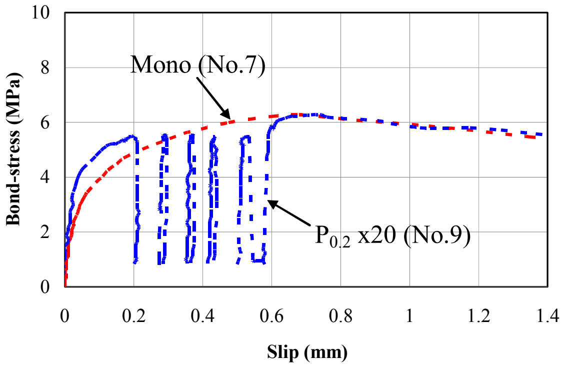

Fig.5　Bond vs. slip (D10 – bond 5ϕ)

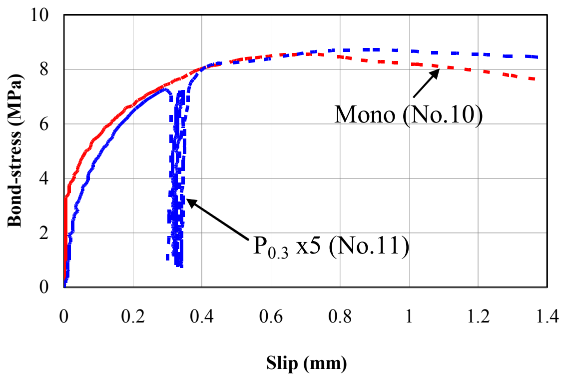

Fig.6　Bond vs. slip (D10 – bond 5ϕ)

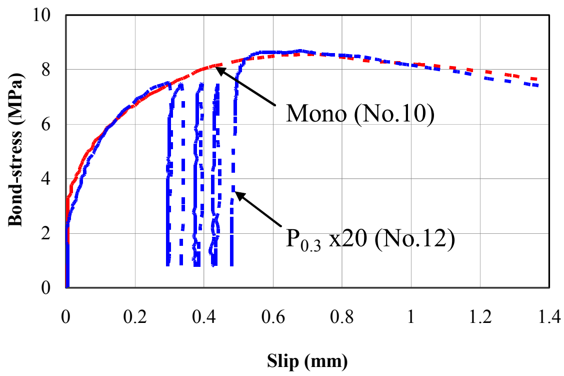

Fig.7　Bond vs. slip (D10 – bond 5ϕ)

selectively shown in Table 1, because the bond strength, its occurring slip (slip at τ_{max}) and the entire shape of the curve are expected to be near between the two loading methods.

However in such destructive tests which seem to be strongly influenced by the tensile strength of concrete (f_t), some scatter is unavoidable. So, degree of the scatter regarding to τ_{max} is shown in Table 2. And, the ratios of τ_{max} or $\tau_{max,r}$ divided by f_t are distributed from 2.62 to 3.95 as being seen in Table 1. By the way, these ratios are bigger than what are expected from both Eq.1 and the following estimation formula for the tensile strength of concrete given in [3].

$$f_{tk} \;=\; 0.23\, f'^{\,2/3}_{ck}\ \text{MPa} \tag{2}$$

By Eq.2, the tensile strength of 33MPa concrete which was strongest in our experiment is calculated to be 2.4 MPa (relatively good agreement to our result), and the Standard Specification seems to expect that the ratio (bond strength vs. tensile strength) becomes around 0.28/0.23 = 1.2.

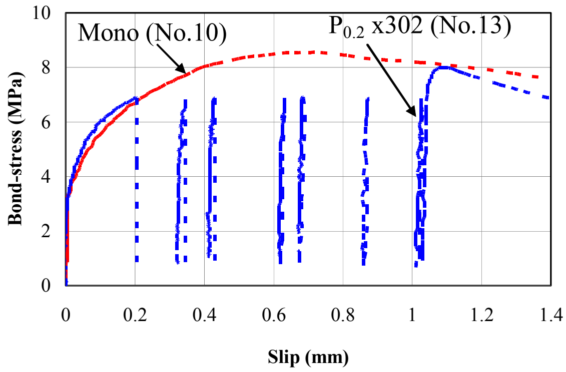

Fig.8 Bond vs. slip (D10 – bond 5ϕ)

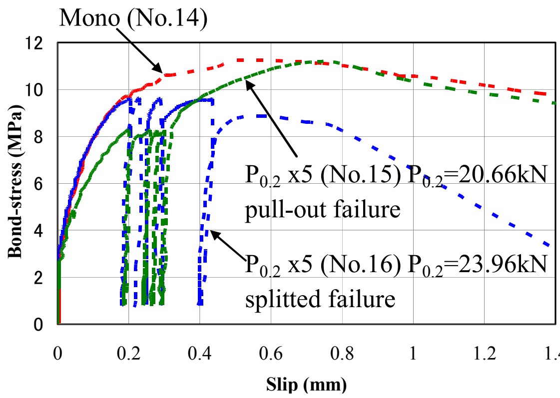

Fig.9 Bond vs. slip (D16 – bond 3.1ϕ)

3.2 Bond-slip relation

Fig. 2 ~ 9 show typical bond-slip relations. These are basically similar to the relations specified in [1] or other literatures, though [3] does not give specific relation. In Fig.2, for example, No.1 data shows the result of monotonic loading while No.2 data shows that $P_{0.2}$ was repeated for five times and then the final pullout was conducted. When the cycle of repeated loading is higher than five, the plots in halfway are omitted otherwise the graphs are totally painted over. In Fig. 2 ~ 9, the combination of monotonic loading and repeated loading was individually selected for each group of the specimens which were classified in Table 1, because different groups were made of different concrete cast in other dates, which fact resulted in different τ_{max} as seen at No.1, 7, 10 and 14.

The path of bond-slip relation observed in the repeated loading, not only in No.2 but also in other graphs finally agreed with the path of monotonic loading with the exceptions of No.3, 13 and 16. Any drop of the peak value was not found, as being reported in [5]. All specimens except No.16 showed so-called pullout type destruction.

Generally speaking, the 2ϕ bonded length showed unstable result compared with 5ϕ result, partly because the number of lugs of deformed bar embedded in 2ϕ length could change 2 to 3 and this may influence the strength. This unstable result is seen in Fig. 3 where influence of the repeated loading seems to exist. However, it may be appropriate from overall considerations about our experiment and other literatures that the influence does not exist in these experimental conditions except very harsh one as No.13.

If we roughly see, there seems to be no significant difference between D10 and D16 results though some variation due to the concrete strength exists. As for the difference between $P_{0.2}$ and $P_{0.3}$ cases, entire shape of bond-slip relation is same but the slip of the latter is usually larger, of course. An exception here is No.12 tested with $P_{0.3,}$ in which the bond strength of both monotonic and repeated loadings was higher than No.9 which was tested with $P_{0.2,}$, and less slip was thus left in No.12. The No.12 concrete has lower compressive but higher tensile as well as the monotonic bond strength than No.9 concrete as shown in Table 1, but we could not make this reason clear.

In Fig. 8 where repeated cycles reached 302 and residual slip exceeded 1.0mm, $\tau_{max,r}$ becomes obviously smaller than τ_{max}. This means that the residual bond strength is affected by repeated loading, even though this loading condition (1/1.17 P_{max} was given 302 times) was very severe compared with actual circumstances. Such drop of the peak value observed in our test was not reported in [5] despite the fact that their upper control load was set 1/1.33 P_{max} and repeated cycle was 10,000. Their specimen has dimension of 150mm x 150 mm, and a D16 re-bar was embedded with the bonded length of 2ϕ and unbonded length of 5ϕ. Their average concrete strength was 37MPa at the 28 days, and bond-slip relation does not reach the peak even when the slip exceeds 1.0mm.

The specimen No.16 in Fig.9 showed splitted failure under condition of the cover of 2.6ϕ, and $P_{max,r}$ was therefore smaller than $P_{0.2}$ (in terms of bond stress: 8.9MPa vs. 9.6MPa). Difference of this failure mode significantly affects the bond strength as summarized in [6]. This splitted failure, only one case of in our experiment so far, occurred at the final pullout after $P_{0.2}$ was given for 5 cycles. The reason of this peculiarity of No. 16 may be attributed to a fact that $P_{0.2}$ was higher than No.15 (23.96kN vs. 20.66kN), and this fact would tell that No.16 concrete having high initial stiffness was rather brittle and thus led early destruction, though both concrete belonged to the same batch.

From the above mentioned our test results, Eq.1 (but less than or equal to 4.2MPa) in the current design specification is safe enough at least for one directional loading. This formula, for example, gives the bond strength of 2.9MPa for the concrete having compressive strength of 33MPa.

3.3 Comparison of test cases

As already mentioned in section 3.1, each test result naturally contains some scatter and the concrete strength itself could not be kept constant, so let’s try to compare the results between the same group with ratios.

Fig. 10 and 11 show the ratio of $P_{max,r}$ to $P_{0.2}$ and $P_{max,r}$ to $P_{0.3}$, respectively. These ratios are thought to drop according to increase of the loading cycles, and the tendency can be visible for 5ϕ specimens. Fig. 12 compares $P_{max,r}$ to P_{max}. This ratio is also expected to decrease in accordance with increase of the loading cycles, and some results show such and the others do not. In order to make this point more clear, probably we have to make more experiments to enable us to treat with statistics manner.

3.4 Increase of residual slip

Fig.13 and 14 show relation between the residual slip and loading cycles, in which significant slip is found before 5th cycle; then stable condition with slight increase of the slip continues. A sudden rise of the slip at the end of each curve is corresponding to the final pullout, and the total slip up to the destruction is shown as “Slip at τ_{max} ” in Table 1 while the slip at the end of repeated loading is shown as “Slip at final stage”. It can be natural that the slip for 2ϕ bonded length is always larger than 5ϕ specimen.

It is also noteworthy that the relation keeps approximately linear up to 302 cycles (No.13), but the

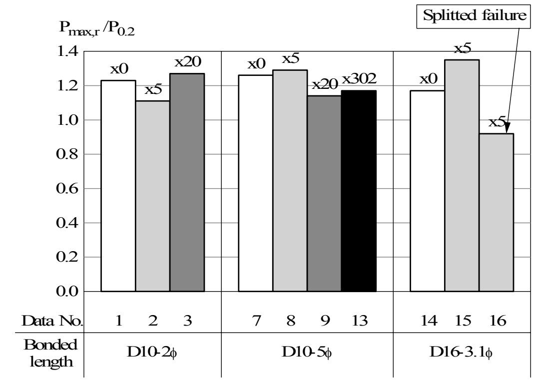

Fig. 10 Comparison of the ratio for $P_{0.2}$

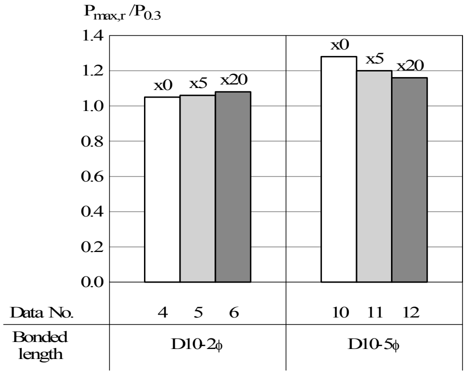

Fig. 11 Comparison of the ratio for $P_{0.3}$

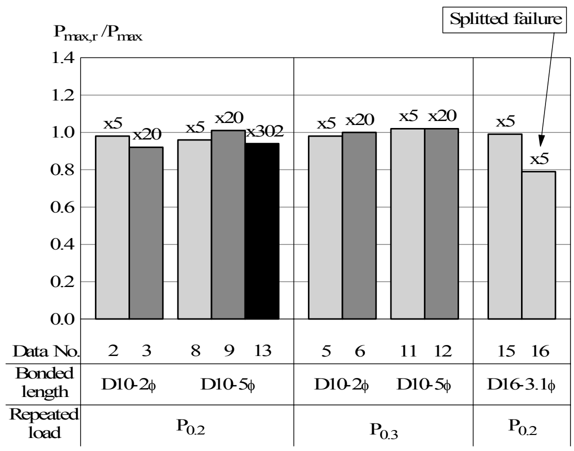

Fig. 12 Comparison of the ratio for P_{max}

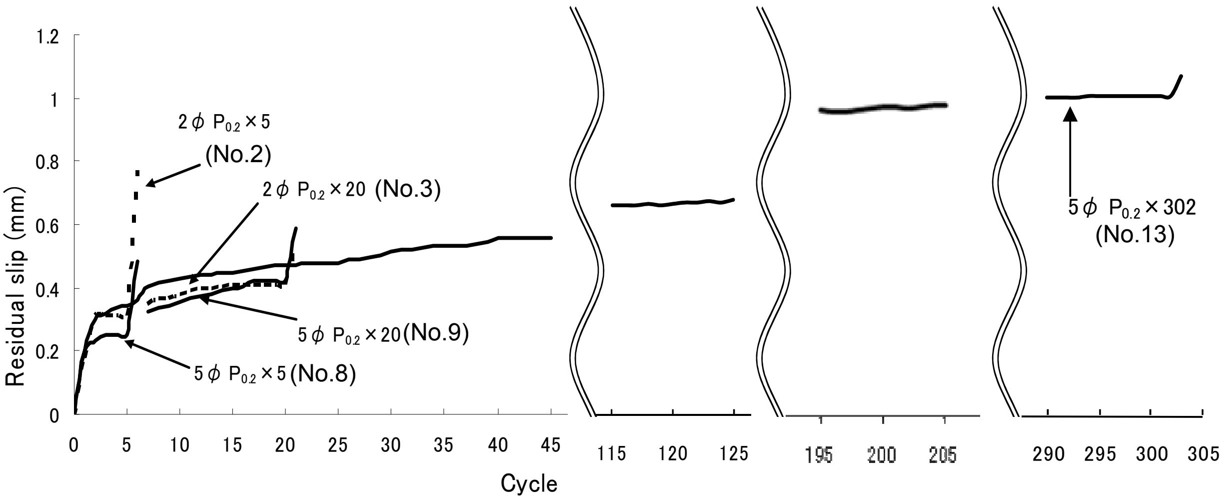

Fig.13 Residual slip vs loading cycle $P_{0.2}$

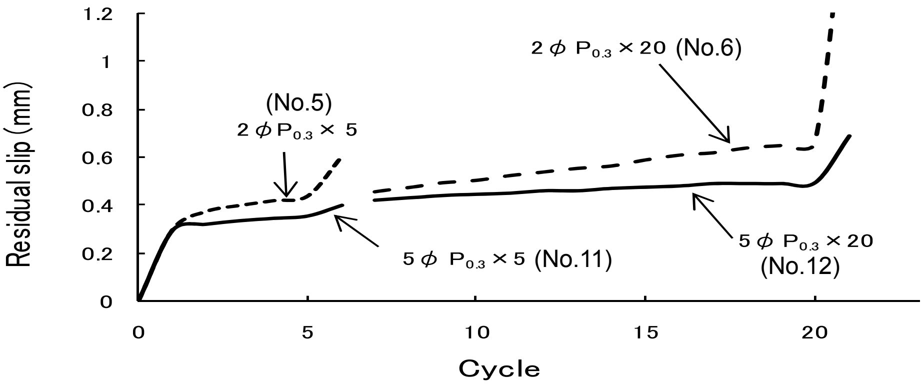

Fig.14 Residual slip vs loading cycle $P_{0.3}$

line might have gone upward if we continued the experiment for a short while. The last sudden rise of the slip by the final pullout is small (in Table 1, 1.10 – 1.04 = 0.06mm) compared with other cases (more than 0.1mm), probably because the specimen was near to an ultimate state.

4. CONCLUSIONS

We intended to understand bond characteristics under low-cycle repeated load, and monotonic pullout tests and repeated loading tests with the final pullout were conducted for specimens having the cross section of 100mm x 100mm with D10 or D16 bars embedded in. Obtained conclusions are;

(1) Giving load up to 20 times, whose magnitude was equivalent to initial slip of 0.2mm or 0.3mm (roughly equal to 75~90 % of the ultimate strength), did not lower the bond strength. But, the residual slip was accordingly increased.
(2) As for the bond-slip relation, the path observed in the repeated loading finally agreed with the path of monotonic loading, and no drop of the residual bond strength was confirmed except one case that a specimen showed the splitted failure.
(3) However, the repeated loading of $P_{0.2}$ for 302 times went over the peak and drop of the residual bond strength was observed.
(4) The current design specification seems to be safe enough against low-cycle fatigue by one directional loading.

ACKNOWLEDGEMENT

The authors acknowledge the supports by Mr. MATSUKAWA Shou (4th grade student in National Defense Academy in the year of 2008) for his contribution in the experiment.

REFERENCES

[1] CEB: CEB-FIP Model Code First Draft, (1990)
[2] Railway Technical Research Institute, “Design Rules and Explanations for Railway Structures (2004, Concrete Structure)”, pp.250, (written in Japanese)
[3] Japan Society of Civil Engineers, “Standard Specification for Concrete (2007, Structural Design)” (written in Japanese)
[4] Kazuhiko HAYASHI, et al, “Crack Characteristics around Deformed Bar in RC Members Subjected to Cyclic Load”, Proc. of JCI, Vol.29, No.3, 2007, pp.619~624, (written in Japanese)
[5] B.H. Oh, et al, “Realistic Models for Local Bond Stress-Slip of Reinforced Concrete under Repeated Loading”, J. of Structural Eng. of ASCE, Feb. 2007 pp.216~224
[6] M.H. Harajli, ”Numerical Bond Analysis Using Experimentally Derived Local Bond Laws: A powerful Method for Evaluating the Bond Strength of Steel Bars” J. of Structural Eng. of ASCE, May 2007, pp.695~705