論文 Bond Creep Behavior of FRP Rods and Their Bond Strength after Sustained Loading

Zhongming WANG[*1], Osamu JOH[*2] and Yasuaki GOTO[*3]

ABSTRACT: The bond creep experiments of nine types of FRP (fiber reinforced plastic) rods were carried out. FRP rods tended to have the creep slip slightly greater than that of steel bar. Bond deterioration caused stress to be transferred far away from the loading end of the rod rapidly. The bond strength of the AFRP rods after sustained loading descended around 15 percent.

KEYWORDS: FRP reinforcement, pullout test, bond, slip, average bond stress, sustained loading, bond creep, bond strength, bond failure type

1. RESEARCH OBJECTIVE AND SIGNIFICATION

The bond characteristics of reinforcing rods to concrete are dependent on the mechanical properties of the rods and the concrete (e.g., the constituents, elastic moduli, Poisson's ratios, material strengths, surface configuration and size of rod, geometrical arrangements and stress conditions). The high stress level, low elastic modulus and various surface shapes of FRP reinforcements cause their bond characteristics to differ from those of steel bars and among various FRP reinforcements.

The bond between reinforcing rod and the concrete may deteriorate with time. Bond creep of the rod will occur, that means that the slip of the rod under sustained load will increase. Bond deterioration of the rods in concrete may affect the deflection, crack width and stress transfer of structural members under service loads. Hence, the problem of bond deterioration attracts extensive attention of many researchers.

An experimental program has been conducted to investigate the performance and mechanism of bond creep of FRP rods. In the program, nine types of FRP rods are subjected to the pullout test under sustained loading. It is aimed to acquire the basic data of bond creep of FRP rods and to understand the effects of material properties of the rods on bond creep. The test results are expected to deepen the cognizance on the bond of FRP rods and to aid to research on the long-term behavior of FRP reinforced structures.

*1 Department of Technology, Constec Engineering Corporation, Dr.E., Member of JCI
*2 Professor, Graduate School of Engineering, Hokkaido University, Dr.E., Member of JCI
*3 Associate professor, Graduate School of Engineering, Hokkaido University, Dr.E., Member of JCI

2. MATERIALS AND SPECIMENS

2.1 Tested FRP rods

Tested FRP rods include four types of CFRP (carbon) rods, three types of AFRP (aramid) rods, and one type of GFRP (glass) rod. The surface configurations of the rods are spirally patterned (a bundle of carbon fiber winding outfitted around the rod body), ribbed (a thin fiber thread tightly fastened to the rod surface) and braided (four braiding fiber bundles impregnated with resin). All of the rods have nominal diameters (d_b) in the range of 7.3～8.9 mm. The results of tension test on the rods are shown in Table 1.

Table 1 Details of tested rods and specimens

No	Fiber type	Surface shape	Nominal diameter d_b (mm)	Elastic modulus E_f (GPa)	Tensile strength f_f (MPa)	Embedment length l_b (mm)
1	Glass	Spiral	8.9	46.7	1240	200
2	Aramid	Deformed	8	75.3	1360	200
3	//	Spiral	8.9	73.3	1220	200
4	//	Braid	7.3	58.1	1775	175
5	Carbon	Deformed	8	125.3	1730	200
7	//	Braid	7.3	119.2	2360	175
8	//	Spiral	8.9	140.7	1690	200
9	//	//	8.9	196.1	1460	200
10	Steel	Deformed	13	196.3	699	120

2.2 Concrete

The compressive design strength of the concrete used in this experimental program is 36.0 MPa. Portland cement, washed sand and crushed gravel with a maximum size of 13mm were used. Table 2 shows the mix proportion and strength of the concrete.

Table 2 Mix proportions and properties of concrete

Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Strength σ_B (MPa)
220	379	850	887	37.4

2.3 Test specimens

Each of the test specimens for bond creep test was made with two concrete blocks at both ends of a rod [1]. The two concrete blocks were identical, and the cross section of each block measured 150x150mm, a 30mm-length unbonded segment was set at the loading end. Steel spiral hoop is provided to prevent the splitting of concrete block. Strain gauges are arranged along the rod. All the specimens were cast in a horizontal position for the rods. The details of test specimens are shown in Fig. 1.

3. TEST SETUP AND LOADING

3.1 Test setup and measurement

Bond creep test is performed using a special test apparatus as shown in Fig. 2. In the

apparatus, load is applied by a depressed steel spring. The two specimens are subjected to the load simultaneously.

Slip at free end of each specimen and the distribution of rod strain are measured. The deformation of the rod is also monitored by dial gauges.

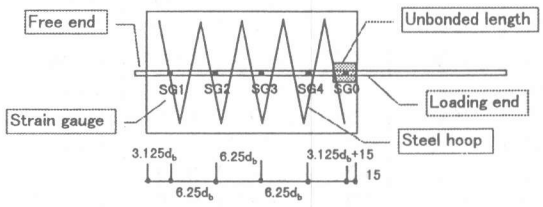

Fig. 1 Illustration of test specimen

3.2 Sustained load

Designed bond stress level, or the ratio of average bond stress of the rod under sustained load to bond strength of the rod is 0.5. The experimental load and bond stress level of each specimen is shown in Table 3. The ratios range from 0.35 to 0.59 and the average value is 0.46. The bond strengths of the rods were obtained from the results of pullout test on the specimens with the same size.

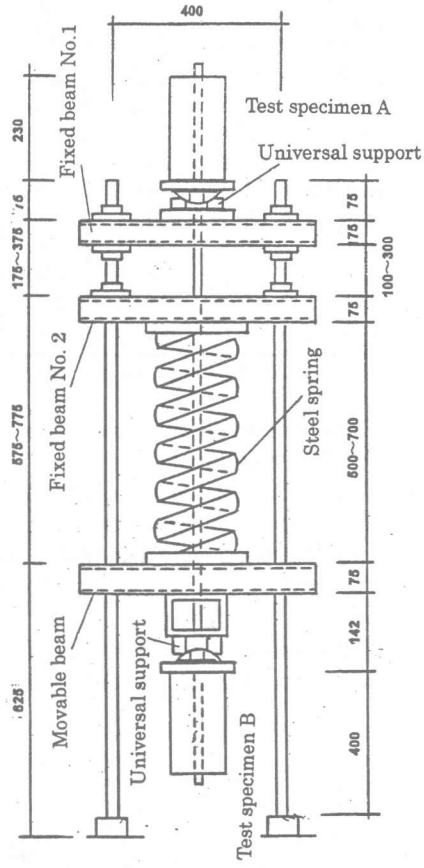

Fig. 2 Test apparatus for sustained loading

4. BOND CREEP BEHAVIOR OF RODS

Bond creep tests were carried out in a closed laboratory room. The variation of in-door temperature was between 14°C in January and 28°C in August, and the humidity between 40% in February and 70% in August. All of the tests were lasted more than 2000 hours.

4.1 Free end slip

The tests exhibited that all of the FRP rods had quite great bond creep during sustained loading. The primary test results are listed in Table 3. The instantaneous slip of a rod is the slip at the free end of specimen just after the applying of the sustained loading. The relative increase of slip is the ratio of the slip increment during sustained loading to the instantaneous slip. Fig. 3 shows the variation of the slip of rod during sustained loading.

The following results were obtained.

- While the average bond stress level of the rods was 46 percent, FRP rods tended to have great creep slip, which was around three fourths of the instantaneous slip at 2,000 hours sustained loading. More than half of the creep slip occurred within the first 24 hours. The ratio extended to 70 percent when the load was sustained up to 100 hours.

Table 3 Representative free end slip results under sustained loading

Specimen	Rod spec.	Sustained Load (kN)	Bond stress (MPa)	Bond strength (MPa)	Instantaneous slip (mm)	Increase of slip (mm)			
						24 h	100 h	1000 h	2000 h
1	2	3	4	5	6	7	8	9	10
BL97-1	GF-S_p	20.50	3.67	9.37	0.15	0.032	0.041	0.062	0.068
BL98-2	AF-R	22.54	4.48	7.55	0.10	0.068	0.092	0.120	0.13
BL97-3	AF-S_p	20.00	3.58	9.29	0.26	0.047	0.062	0.081	0.088
BL97-4	AF-B	20.01	4.99	8.41	1.38	0.52	0.69	0.95	1.04
BL98-5	CF-R	25.05	4.98	9.25	0.48	0.14	0.19	0.25	0.26
BL97-7	CF-B	20.02	4.99	10.73	0.78	0.26	0.32	0.44	0.47
BL98-7	CF-B	20.01	4.99	10.73	0.43	0.24	0.29	0.35	0.35
BL97-8	CF-S_p	22.01	3.94	11.30	0.068	0.050	0.067	0.098	0.11
BL97-9	C_xF-S_p	24.50	4.38	9.71	0.29	0.058	0.070	0.070	0.064
BL98-9	C_xF-S_p	24.57	4.39	9.71	0.076	0.040	0.053	0.070	0.073
BL98-10	SD	25.02	5.11	—*	0.16	0.054	0.074	0.10	0.11

* Lack of test data for steel bar.

- Greater creep slip occurred in the test samples that had smaller instantaneous slip, such as BL97-8 and BL98-9.
- The average instantaneous slip of the FRP rods was more than two-times greater than that of the steel bar. However, the average value of creep slips of the FRP rods was only slightly greater than that of the steel bar. The ratios of the average creep slip of the FRP rods to that of the steel bar were 1.19 in the first 24 hours and 1.09 after 2,000 hours.
- The test results could not exhibit the significant effects of material properties of the rods on bond creep slip characteristics of the rods.

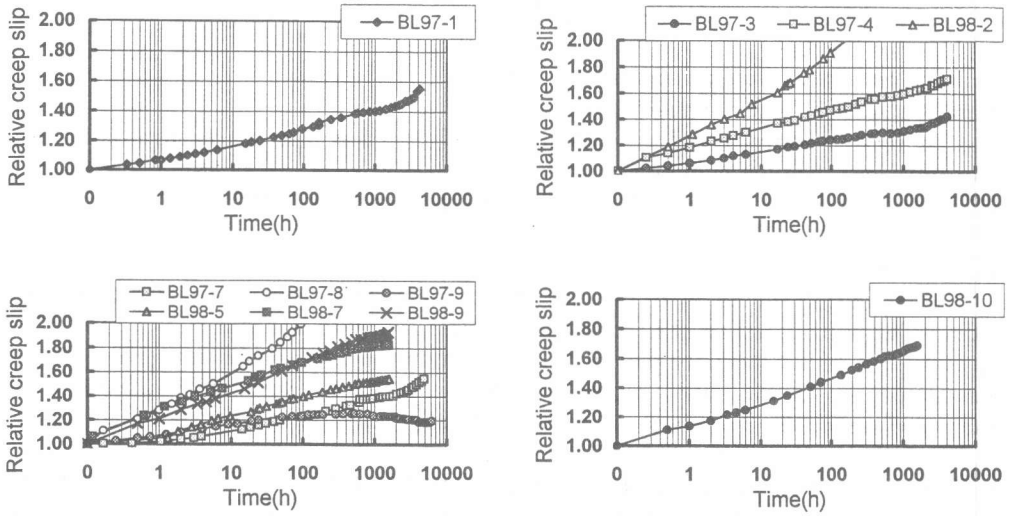

Fig. 3 Bond creep slips of tested rods

4.2 Strain within bond creep test specimen

There were four strain gauges arranged in the embedded rods of each bond creep specimen (see Fig. 1). The time-dependent variations in strains of the rod measured by strain gauges SG2 and SG4 are shown in Fig. 4. Gauge SG2 was placed at a distance of nine-times the rod diameter away from the free end, and SG4 was placed at a distance of three-times the rod diameter away from the loading end.

The following results were obtained.

- Under sustained loading, there was a continuous increase in the strain of the rod within its embedment length. The rate of increase in stress of the rod near the free end (SG2) was higher than that near the loading end (SG4) during the early period of loading. However, after 2,000 hours of sustained loading, the rate of increase in strain was similar along the entire embedment length. For all of the FRP rods, the stresses measured by gauge SG2 were 1.17 at 24 hours, 1.21 at 100 hours and 1.23 at 1,000 hours. During the same period, the stresses measured by gauge SG4 were 1.10, 1.13 and 1.20, respectively.
- Strain gauge SG1, which was the nearest gauge to the free end of the rod, recorded the greatest rate of increase in stress for most of tested specimens, particularly for the spiral-patterned rods. The deterioration of the bond caused stress to be transferred far away from the loading end of the rod rapidly.
- Sixty-five percent of the time-dependent stress increment in the part of the rod near the loading end and 85% in the part of the rod near the free end occurred within the first 100 hours after the start of loading. Stress tended to cease the increase with time after 1,000 hours in almost all of the rods.
- A great difference in the rate of increase of rod stress was not observed among different types of FRP rods.

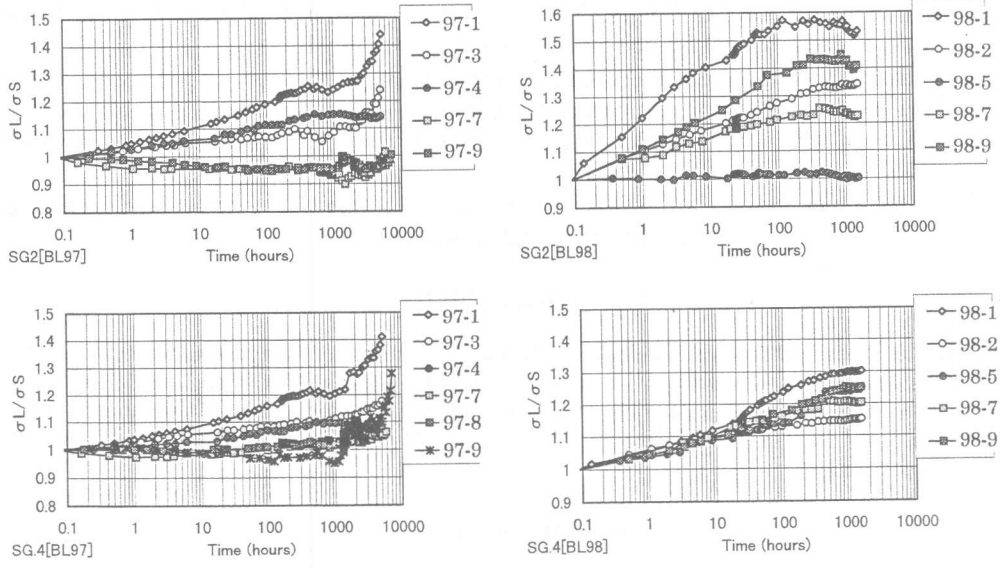

Fig. 4 Variation of strains within bond creep test specimens

5. BOND STRENGTH OF RODS AFTER SUSTAINED LOADING

Pullout test was conducted for a part of the specimens after bond creep test. Table 4 showed the maximum average bond stresses of the test specimens. Comparing to the test results of the same rod without sustained loading history, almost the same bond strength was found for the specimens of the GFRP and CFRP rods. However, for both types of AFRP rods, the bond strength descended around 15 percent after sustained loading.

Table 4 Bond strength results of rods in pullout test

Specimen	Rod spec.	Failure Load P_{max} (kN)	Maximum bond stress $\tau_{bu,L}$ (MPa)	Bond strength τ_{bu} (MPa)	$\frac{\tau_{bu1}}{\tau_{bu}}$
BL97-1	GF-S_p	51.65	9.24	9.37	0.99
BL97-3	AF-S_p	45.58	8.15	9.29	0.88
BL97-4	AF-B	27.28	6.80	8.41	0.81
BL97-7	CF-B	45.95	11.45	10.73	1.07
BL97-8	CF-S_p	65.12	11.65	11.30	1.03
BL97-9	C_xF-S_p	56.85	10.17	9.71	1.05

6. CONCLUSIONS

(1) While the average bond stress level of the rods was 46 percent, FRP rods tended to have great creep slip, which was around three fourths of the instantaneous slip at 2,000 hours sustained loading.

(2) The average instantaneous slip of the FRP rods was more than two-times greater than that of the steel bar. However, the creep slip of the FRP rods was only slightly greater than that of the steel bar.

(3) Under sustained loading, there was a continuous increase in the strain of the rod within its embedment length. The deterioration of the bond caused stress to be transferred far away from the loading end of the rod rapidly.

(4) Sixty-five percent of the time-dependent stress in the part of the rod near the loading end and 85% in the part of the rod near the free end occurred within the first 100 hours after the start of loading. Stress tended to cease the increase with time after 1,000 hours in almost all of the rods.

(5) The bond strength of AFRP rods descended around 15 percent after sustained loading. However, the GFRP and CFRP rods did not.

ACKNOWLEDGMENTS

This study was accomplished in Hokkaido University. The authors are grateful to Mr. A. Kitaro, for his kind support in laboratory work, and to study staff, Messrs. Z. Y. Wang and M. Noguchi. The reinforcing rods used in this study were manufactured by Nippon Steel Corporation, FiBEX Corporation, and Kumagai-Gumi Corporation. The authors would like to thank all of them for their generous contribution.

REFERENCES

[1] AIJ, "FRP Reinforced Concrete: Properties and Design", Gihodo, July 1995, pp.46-48