BOND BEHABIOR BETWEEN DEFORMED ARAMID FIBER-REINFORCED PLASTIC REINFORCEMENT AND CONCRETE

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ABSTRACT :

Recent years, Fiber-Reinforced Plastic (FRP) reinforcement has been utilized for concrete structures expecting its high durability to corrosion and insulation property. In this study, pullout loading test and tensile loading test is performed to investigate the bond behavior between AFRP reinforcement and concrete. The test parameters are cross sectional size of concrete block, elastic modulus and nominal diameter of AFRP reinforcement. The test results of pullout loading test show that bond behavior is influenced by surface figure of AFRP reinforcement. The results of tensile loading test show that crack width depends on elastic modulus. Tension stiffening behavior of AFRP reinforcement is almost same in spite of the type of AFRP reinforcement.

KEYWORDS: Pullout loading test, tensile loading test, bond stress-slippage relationship, local bond behavior, tension stiffening behavior, crack width

1. INTRODUCTION

Generally, steel reinforcing bar is used as reinforcement of concrete structures. However, it is a serious problem that corrosion of steel reinforcing bar occurs due to cracking. Moreover, since steel reinforcing bar is became magnetized, it is difficult to use in medical facility or semiconductor factory. Therefore, in recent years, Fiber-Reinforced Plastic (FRP) reinforcement has been utilized for concrete structures expecting its high durability to corrosion and insulation property. Typical types of FRP are Carbon Fiber- Reinforced Plastic (CFRP), Glass Fiber-Reinforced Plastic (GFRP) and Aramid Fiber-Reinforced Plastic (AFRP). Because CFRP are became magnetized, GFRP generally has a problem in alkali resistance. AFRP has been expected to be applied to concrete structures. Reinforcement of concrete structures is expected to bear the tensile force and gives enough capacity and ductility to concrete members. It is necessary to have a good unification between reinforcement and concrete to lead these objectives. It is well known that the unification of reinforcement and concrete is depended on bond characteristics of the local part of reinforcement and concrete.

In this study, pullout loading test is performed to evaluate the bond behavior of AFRP reinforcement. The test parameters are cross sectional size of concrete block, elastic modulus and nominal diameter of AFRP reinforcement. Further, tensile loading test is performed by using specimens with length of 1680mm to inquire the influence of unification between reinforcement and concrete.

2. PULLOUT LOADING TEST

2.1. Specimen

An example of specimen is shown in Figure 1.The cross section of a specimen is 80mm x 80mm, 100mm x 100mm and 120mm x 120mm. Height is 100mm. Ordinary steel reinforcing bar (D10) or AFRP reinforcement is used in the center of concrete block. The nominal diameter of AFRP reinforcement is ϕ 6.0, 7.0 and 13mm. The coupler is used at the loading end of reinforcement to grip reinforcement by the chuck of testing machine. Bond length is 4 times of the reinforcement diameter. List of specimen is shown in Table 1. The test parameters are cross section of concrete block (80mm x 80mm, 100mm x 100mm and 120mm x 120mm), type of reinforcement (TE, TO and reinforcing bar) and nominal diameter (6.0mm, 7.0mm, 13mm and D10).

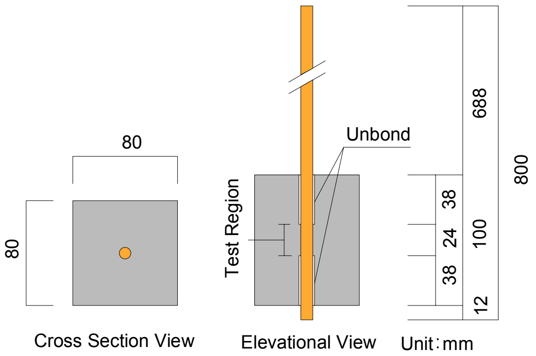


Figure 1 Example of specimen

Table 1 List of specimen

No.	Specimen name	Cross section (mm)	Type of reinforcement	Diameter (mm)	No.	Specimen name	Cross section (mm)	Type of reinforcement	Diameter (mm)	No.	Specimen name	Cross section (mm)	Type of reinforcement	Diameter (mm)
1	P-80TE-F6.0	80 X 80	TE	ϕ6.0	11	P-100TE-F6.0	100 X 100	TE	ϕ6.0	21	P-120TE-F6	120 X 120	TE	ϕ6.0
2	P-80TE-F7.4			ϕ7.4	12	P-100TE-F7.4			ϕ7.4	22	P-120TE-F7.4			ϕ7.4
3	P-80TE-F13-1			ϕ13	13	P-100TE-F13-1			ϕ13	23	P-120TE-F13-1			ϕ13
4	P-80TE-F13-2				14	P-100TE-F13-2				24	P-120TE-F13-2			
5	P-80TE-F13-3				15	P-100TE-F13-3				25	P-120TE-F13-3			
6	P-80TO-F6.0		TO	ϕ6.0	16	P-100TO-F6.0		TO	ϕ6.0	26	P-120TO-F6.0		TO	ϕ6.0
7	P-80TO-F7.4			ϕ7.4	17	P-100TO-F7.4			ϕ7.4	27	P-120TO-F7.4			ϕ7.4
8	P-80SD-D10-1		Reinforcing bar	D10	18	P-100SD-D10-1		Reinforcing bar	D10	28	P-120SD-D10-1		Reinforcing bar	D10
9	P-80SD-D10-2				19	P-100SD-D10-2				29	P-120SD-D10-2			
10	P-80SD-D10-3				20	P-100SD-D10-3				30	P-120SD-D10-3			

2.2 Employed Material

The shape of AFRP reinforcement is shown in Figure 2. Surface figure of TE and TO is deformed rod and TE-F13 is double spiral structure. The mechanical properties of concrete are shown in Table 2. The tensile test result for steel reinforcing bar is shown in Table 3. Table 4 shows the characteristic properties of AFRP reinforcement.

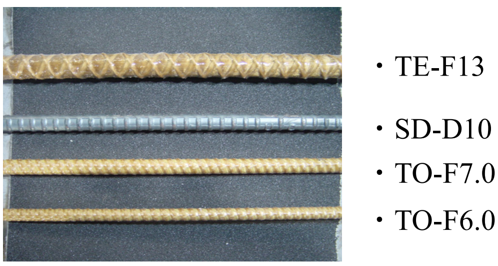


Figure 2 Shape of AFRP reinforcement

Table 2 Mechanical properties of concrete

Compressive strength(MPa)	Elastic modulus(GPa)	Tensile splitting strength (MPa)
28.6	26.8	2.44

Table 3 Tensile test result for steel reinforcing bar

Tension strength(MPa)	Yield strength(MPa)	Elastic modulus (GPa)
931	752	197

Table 4 Characteristic properties of AFRP reinforcement

Type		Diameter(mm)	Effective cross section area(mm^2)	Elastic modulus (GPa)
TE	ϕ 6.0	6.43	28.3	53.0
	ϕ 7.4	7.88	42.4	
	ϕ 13	13.1	133	
TO	ϕ 6.0	6.43	28.3	90.0
	ϕ 7.4	7.88	42.4	

2.3 Method of Loading

The method of loading is shown in Figure 3. The specimen is set on steel plate with a hole which diameter is the half of sectional size of specimens. The specimen is subjected to monotonic loading for pulling out the reinforcement. Teflon sheet is inserted between specimen and the steel plate to not restrict lateral displacement of concrete block. Measurement items are tensile load and reinforcement slippage at free end.

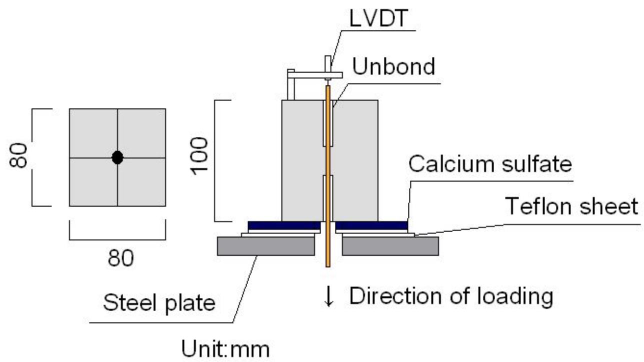


Figure 3 Method of pullout loading test

2.4. Test Results

2.4.1 Failure pattern

The damage of AFRP reinforcement after loading is shown in Figure 4. No.5, 6, 7, 16 specimens failed by splitting of concrete. Slipping out of reinforcement was observed in other specimens. In these specimens, surface fibers which forms deformed shape of AFRP reinforcement were chipped off due to friction with concrete.

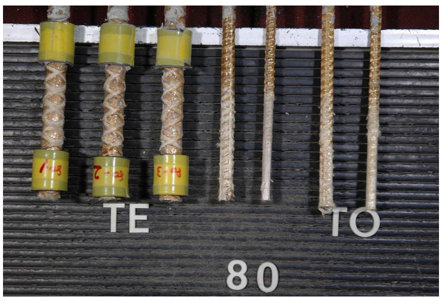


Figure4 Damage of AFRP reinforcement after loading

2.4.2 Bond Stress and slippage

The test results are summarized in Table 5. Figure5 shows bond stress-loaded end slippage relationship. Bond stress is calculated by Eq2.1. Assuming that bond stress distribution in the bond section is constant, loaded end slippage is calculated by adding elongation of reinforcement to the free end slippage obtained by LVDT.

$$\tau_b = \frac{P}{\psi \times l_b} \qquad (2.1)$$

τ_b : bond stress(N/mm^2) P : tensile load(N)
ψ : reinforcement perimeter(mm) l_b : bond length(mm)

The maximum bond stress ranges from 11.47 to 22.36 N/mm^2. In any case of cross section of a specimen, the steel reinforcing bar (D10) showed the largest value. Bond stress increases again after the maximum bond stress. It is considered that concrete and ribs of reinforcement is engaged again. Comparing TE and TO of ϕ 6.0 specimen at each cross section of concrete, TO shows a gentle decrement after the maximum bond stress. On the other hand, TE shows large dropping of bond stress. This is considered that rapid failure occurs at matrix of AFRP surface.

Table 5 Pullout loading test results

Specimen name	Bond stress (N/mm^2)	Slippage at loaded end (mm)	Specimen name	Bond stress (N/mm^2)	Slippage at loaded end (mm)	Specimen name	Bond stress (N/mm^2)	Slippage at loaded end (mm)
P-80TE-F6.0	12.05	0.341	P-100TE-F6.0	11.47	0.477	P-120TE-F6.0	12.11	0.488
P-80TO-F6.0	16.89	1.389	P-100TO-F6.0	15.90	1.647	P-120TO-F6.0	15.12	1.481
P-80TE-F7.4	12.83	1.773	P-100TE-F7.4	15.20	1.696	P-120TE-F7.4	15.40	1.867
P-80TO-F7.4	12.93	1.812	P-100TO-F7.4	14.78	1.683	P-120TO-F7.4	12.55	1.846
P-80TE-F13-1	11.88	1.109	P-100TE-F13-1	11.65	2.336	P-120TE-F13-1	13.62	1.702
P-80TE-F13-2	12.08	0.897	P-100TE-F13-2	14.12	1.298	P-120TE-F13-2	16.04	2.392
P-80TE-F13-3	12.30	1.279	P-100TE-F13-3	12.54	1.702	P-120TE-F13-3	14.15	2.198
P-80SD-D10-1	22.02	0.620	P-100SD-D10-1	17.01	0.534	P-120SD-D10-1	20.02	0.625
P-80SD-D10-2	19.88	0.604	P-100SD-D10-2	19.46	0.628	P-120SD-D10-2	20.48	0.589
P-80SD-D10-3	22.36	0.630	P-100SD-D10-3	18.90	0.902	P-120SD-D10-3	20.43	0.638

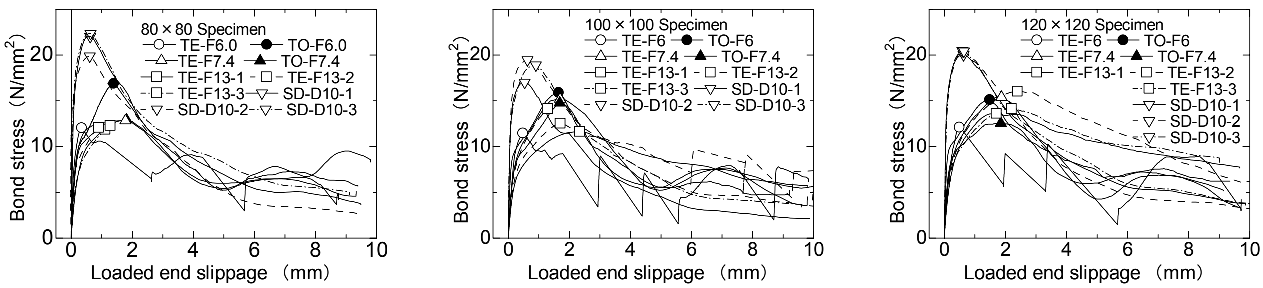


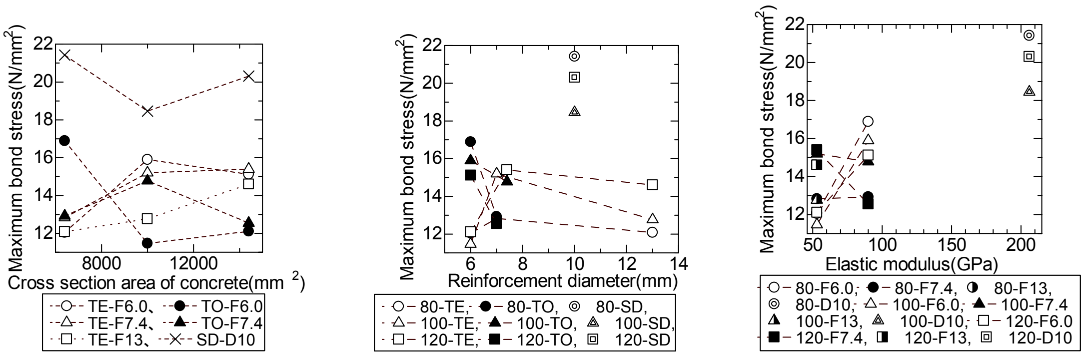
Figure 5 Bond stress versus loaded end slippage curve

2.4.3 Maximum bond stress and fracture energy

Comparisons of maximum bond stress in each parameter are shown in Figure 6. The clear relation between maximum bond stress and parameters can not be recognized.

Fracture energy-slippage relationship is shown in Figure 7. Fracture energy is calculated as an area of bond stress-slippage curve until focused slippage. The results of specimen No.3, 4 and 5 are not included because of splitting failure. In any case of cross section of a specimen, the steel reinforcing bar (D10) shows the largest fracture energy even if the slippage is small. On the other hand, the specimen of TE-F6.0's fracture energy is small in totally. In other reinforcement, the significant difference by types of reinforcement or cross section of concrete was not observed.

From the test results, in reinforcement of AFRP, the maximum bond stress is not affected by cross section of concrete, diameter of reinforcement and elastic modulus largely if rapid failure dose not occur at matrix of AFRP surface. Therefore, it is considered that the local maximum bond stress obtained by pullout loading test is depended on the bearing action with surface figure of reinforcement between concrete.



(a) cross section area of concrete (b) reinforcement diameter (c) elastic modulus

Figure 6 Comparison of maximum bond stress with each parameter

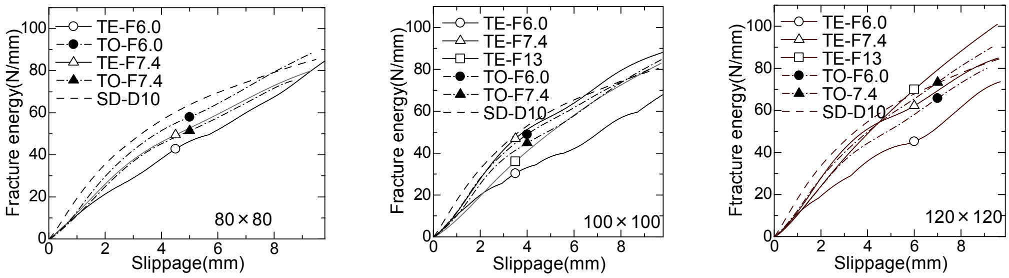


Figure 7 Fracture energy-slippage relationship

3. TENSILE LOADING TEST

3.1. Specimen

An example of specimen is shown in Figure 8. The cross section of a specimen is 80mm x 80mm, 100mm x 100mm and 120mm x 120mm. Length is 1680mm and steel reinforcing bar (D10) or AFRP reinforcement is used in the center of concrete block. The nominal diameter of AFRP reinforcement is ϕ 6.0, 7.0 and 13. The couplers in both ends of reinforcement are set to grip reinforcement by the chuck of testing machine. As shown in Figure 8, the sectional number is defined as A to H with intervals of 200mm from the position of 40mm of specimen ends. List of specimen is shown in Table 6. The same concrete and reinforcements are utilized with pullout loading test.

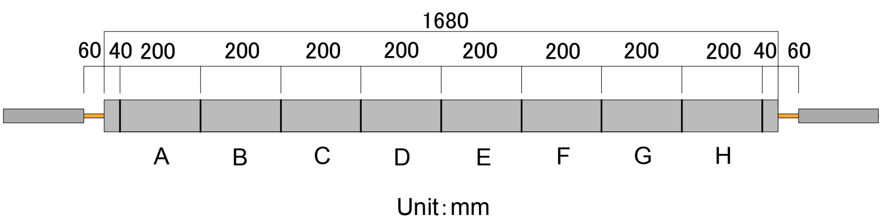


Figure 8 Example of specimen

Table 6 List of specimen

No.	Specimen name	Cross section (mm)	Type of reinforcement	Diameter (mm)	p_g^* (%)	No.	Specimen name	Cross section (mm)	Type of reinforcement	Diameter (mm)	p_g^* (%)
31	T-80TE-F6.0	80x80	TE	ϕ6.0	0.44	43	T-120TE-F6.0	120x120	TE	ϕ6.0	0.20
32	T-80TE-F7.4			ϕ7.4	0.66	44	T-120TE-F7.4			ϕ7.4	0.29
33	T-80TE-F13			ϕ13	2.08	45	T-120TE-F13			ϕ13	0.92
34	T-80TO-F6.0		TO	ϕ6.0	0.44	46	T-120TO-F6.0		TO	ϕ6.0	0.20
35	T-80TO-F7.4			ϕ7.4	0.66	47	T-120TO-F7.4			ϕ7.4	0.29
36	T-80SD-D10		Reinforcing bar	D10	1.11	48	T-120SD-D10		Reinforcing bar	D10	0.50
37	T-100TE-F6.0	100x100	TE	ϕ6.0	0.28	40	T-100TO-F6.0	100x100	TO	ϕ6.0	0.28
38	T-100TE-F7.4			ϕ7.4	0.42	41	T-100TO-F7.4			ϕ7.4	0.42
39	T-100TE-F13			ϕ13	1.33	42	T-100SD-D10		Reinforcing bar	D10	1.33

* Sectional area of reinforcement divided by sectional area of concrete

3.2 Method of Loading

The monotonic tensile loading are applied. Measurement items are load, crack width by LVDTs which are assembled both sides of specimen and whole deformation of specimen by LVDTs. The positions of LVDTs are shown in Figure 9. The tensile loads at the crack occurring and crack patterns are also recorded.

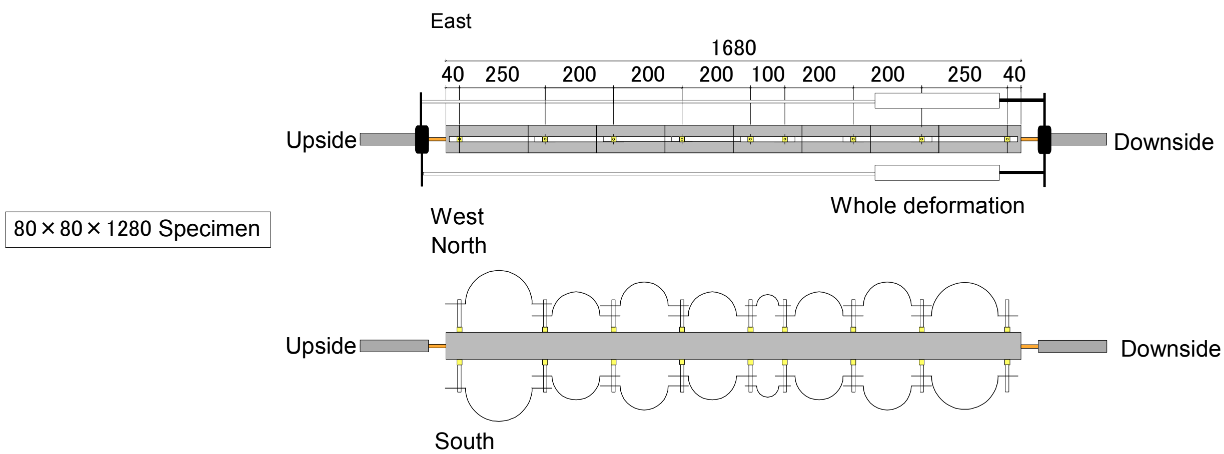


Figure9 Position of LVDT

3.3 Test Results

3.3.1 Failure progress

Tensile loading test results are shown in table 7. The failure progress was categorized into two patterns. The first one is that a crack around the bottom end of specimen took place and then cracks around the center of the specimen with almost equal interval took place. The second one is that a crack around the bottom end took place as same as first one then the next crack occurs around the opposite end of specimen, and cracks by turns by the upper and lower positions toward the center of specimen. Finally, both crack patterns reached nearly same ones from the center. The final crack number decreases with increases of sectional area of specimen. It is considered that initial crack loading of concrete increases with increase the cross section of concrete. Therefore, the number of crack decrease. In the case of the specimen at the same cross section area, the number of crack tends to increase and crack spacing is smaller when reinforcement diameter is larger. However, the specimen with steel reinforcing bar has difference tendency. Even if the diameter is 10mm which is smaller than ϕ13, the number of crack is same or bigger than ϕ13 specimen.

Table 7 Tensile loading test results

No.	Specimen name	Number of crack	Crack spacing (mm)	Initial crack (kN)	No.	Specimen name	Number of crack	Crack spacing (mm)	Initial crack (kN)	No.	Specimen name	Number of crack	Crack spacing (mm)	Initial crack (kN)
31	80TE-F6	8	187	17.52	37	100TE-F6	4	336	23.13	43	120TE-F6	1	840	28.37
32	80TO-F6	8	187	14.81	38	100TO-F6	4	336	19.23	44	120TO-F6	nothing	—	—
33	80TE-F7.4	14	112	17.23	39	100TE-F7.4	7	210	21.11	45	120TE-F7.4	4	336	34.76
34	80TO-F7.4	7	210	17.22	40	100TO-F7.4	6	240	23.07	46	120TO-F7.4	3	420	34.46
35	80TE-F13	11	140	14.32	41	100TE-F13	13	120	25.79	47	120TE-F13	10	153	35.96
36	80SD-D10	22	73.0	12.53	42	100SD-D10	14	112	18.09	48	120SD-D10	4	336	40.21

3.3.2 Tension stiffening behavior

Tensile loading and whole deformation relationship is shown in Figure 10. In the case of AFRP reinforcement, whole deformation is calculated by using Eq.3.1 in order to subtract the elongation of reinforcement at the region from concrete edge and the coupler. For steel reinforcing specimen, elongation of this region is evaluated by the tension test results of bare reinforcement considering elastic-plastic behavior.

$$\delta_w = \frac{\delta_1 + \delta_2}{2} - \frac{P \cdot 120}{a_b \cdot E_b} \qquad (3.1)$$

δ_1, δ_2 : deformation by LVDT (mm), P : tensile load(kN)

a_b : sectional area of reinforcement(mm^2), E_b : elastic modulus of reinforcement (GPa)

The tension stiffening behavior was recognized in all specimens. The pseudo tensile force carried by concrete (P_{inc}) is defined as the tensile load which is calculated by subtracting the load carried by bare reinforcement from the obtained tensile load under the same whole deformation. P_{inc}-whole deformation relationships is shown in Figure 11. For all specimens, P_{inc} increases with decreases of the reinforcement ratio. It is considered that ratio of tensile load carried by concrete increases by increase of the sectional area of concrete. Comparing with TE-F13 and SD-D10 in a 120mm x 120mm specimen, P_{inc} of SD-D10 is larger than TE-F13 in the same deformation. Considering the local bond behavior of TE-F13 and SD-D10, the fracture energy of SD-D10 is larger than TE-F13 in small slippage. It is considered that these differences of local bond behavior affects tension stiffening behavior.

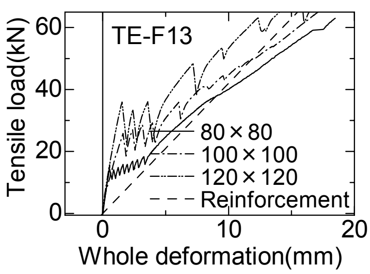


Figure 10 Tensile loading-whole deformation curve

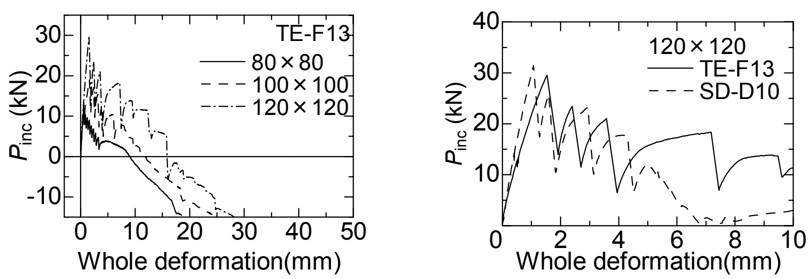


Figure 11 P_{inc}-whole deformation curve

3.3.3Crack width

Tensile load-crack width relationship is shown in Figure 12. In this figure, the crack width measured in B section is plotted and the curve shows until second crack occurring in the same measurement section. The remarkable difference is not observed by the difference of cross section of specimen. The test result of the pullout loading test that the local bond behavior is not influenced by cross section of specimen holds this phenomenon. The crack width of SD-D10 and TE-F13 at the same load is small. The clear difference is not observed in other specimens. It is considered that large elastic modulus, and good local bond behavior of SD-D10 lead small crack width. In the case of TE-F13, it is considered that a sectional area of reinforcement is larger so that crack width is controlled. The difference in other specimen's is not so large even if the elastic modulus is different.

Reinforcement strain-crack width relationship is shown in Figure 13. It is considered that crack width at the same reinforcement strain is almost equal when reinforcement shows similar local bond behavior.

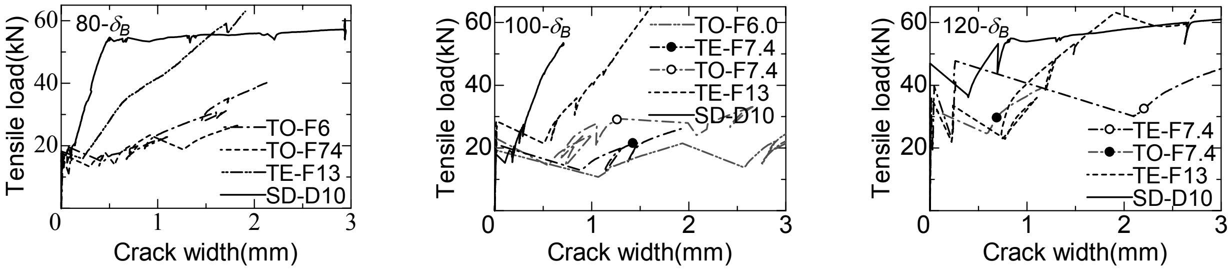


Figure 12 Tensile load- crack width relationship

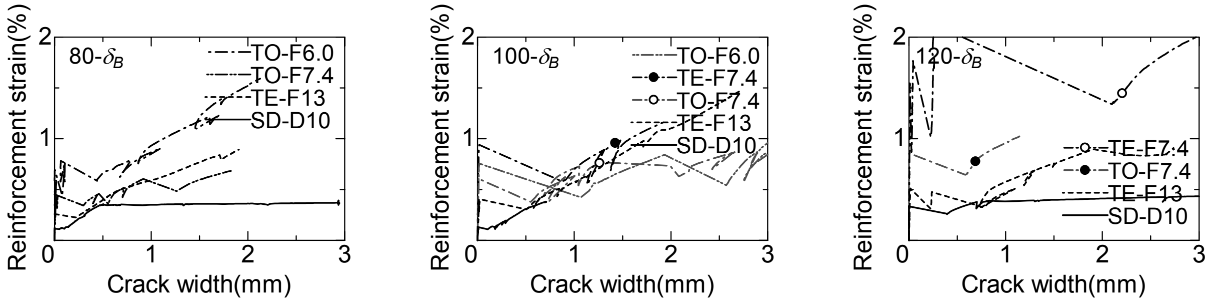


Figure 13 Reinforcement strain-crack width relationship

4. CONCLUSIONS

From the test results, the following are summarized.

(1) The local maximum bond stress obtained by pullout loading test is depends on the bearing action with surface figure of reinforcement between concrete.

(2) The tension stiffening behavior is recognized in the tensile loading test. The behavior is influenced by the local bond behavior of reinforcement.

(3) Crack width at the same reinforcement strain is almost equal when reinforcement has similar local bond behavior.