FUNDAMENTAL STUDY ON BOND BEHAVIOR OF VARIOUS FRP RODS IN PRETENSIONED PC MEMBERS

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This paper describes and discuss the results of an experimental study on the bond characteristics of fiber reinforced plastics in concrete and the transfer length for pretensioned type prestressed concrete structures. The experimental results are then used to derive a simple relationship by using a family of curves with varying coefficient of friction μ, and poisson ratio ν against transfer length of FRP rods.

Key Words : fiber reinforced plastics, bond stress, transfer length

1. INTRODUCTION

Many extensive researches have been carried out for the practical usage of Fiber Reinforced Plastics (FRP) in the fields of academic society, design and construction industry. The synthetic continuous fibers show outstanding physical properties. Nevertheless, there are still some structural behaviors to clarify for designers to use with safety and reliability. Especially, the behaviors such as bond and transfer length which are not clarified yet, when applying FRP to PC structures.

The FRP differs with the steel in modulus of elasticity, poisson's ratio, surface condition etc. A few experimental research have been made. In this paper, the authors have focused on the transfer-bond behavior of various FRP rods. They have conducted experimental studies on the transfer length of FRP rods in pretensioned type prestressed concrete structures and the bond characteristics in concrete. The draft of testing procedures for the FRP rods outlined by the Japan Society of Civil Engineers (JSCE) is used in this research.

The purpose of this study is to estimate the transfer length of various FRP rods. To fulfill this aim and objectives, an experimental and analytical studies are made and highlighted.

The general outline of the FRP rods is shown in

Table 1-1. In the first part of this study, twelve kinds of FRP rods are used to investigate the bond character in concrete. In the second part, the transfer length of fourteen kinds of FRP rods is experimentally studied. Finally, an analytical approach on the transfer length of carbon and aramid FRP rods is made and compared with the experimental data.

2. BOND CHARACTERS OF VARIOUS FRP RODS

(1) Introduction

The bond character of FRP rods is one of the important and complex issue in prestressed concrete structures. The FRP rods are composite materials. The bonding of FRP rods to the concrete also implies to the fibers and matrix materials. In this study, the bonding of FRP rods to the concrete is outlined. As the bond strength also depends on the strength of concrete ; throughout the experiment the compressive strength will be based on the adjusted value by the factor in equation (1).

Twelve kinds of FRP rods are used in this study. The outline of FRP rods are shown in **Table 1-1**. The FRP rods used in bond experiment are marked as "B" in the remarks column. There are seven kinds of carbon, four kinds of aramid and a single kind of Polyvinyl-alcohol fiber. The matrix material for all

Table 1-1 General outline of FRP rods

Symbol	Diameter (mm)	Fiber Type	Matrix Material	Fiber Content (%)	Surface Condition	Shape	Remarks
K-C1	6	Carbon	Epoxy	61.3	Spiral		B,T
K-C2	8	"	"	61.7	Spiral		B,T
L-C1	5	"	"	50~60	Cross-Wound		B,T
L-C2	8	"	"	50~60	Cross-Wound		B,T
T-C1	5	"	"	64	Strand		B,T
T-C2	7.5	"	"	64	Strand		B,T
T-C3	12.5	"	"	64	Strand		B
K-CP	8	"	PPS	55	Stone-grain		
M-A1	6	Aramid	Epoxy	65	Braid		B,T
M-A2	8	"	"	65	Braid		B,T
M-A3	12	"	"	65	Braid		B
S-A1	6	"	V.E	65	Spiral+Rib		T
S-A2	8	"	V.E	65	Spiral+Rib		B,T
K-G1	6	Glass	Epoxy	65	Spiral		T
K-G2	8	"	"	62.5	Spiral		T
KR-V1	6	Vinylon	"	69.6	Cross-Wound		T
KR-V2	8	"	"	69.6	Cross-Wound		B

PPS=Thermo-plastic resin,　V.E=Vinyl-ester,　B=Bond,　T=Transfer Length

Table 2-1 Mix design of concrete

W(kg)	C(kg)	W/C(%)	S(kg)	G(l)kg	G(s)kg	Slump(cm)
198	330	60	849	378	568	13.3

the FRP rods is epoxy but SA type uses vinyl-ester. The tensile strength and the modulus of elasticity are tested by the authors but the diameters and cross-sections are taken from the makers. The experiments are carried out using the draft testing procedures of JSCE[1].

(2) Outline of experiment

The concrete mix-design is shown in **Table 2-1**. The test specimen is shown in **Fig. 2.1** and assemblage in **Fig. 2.2**. A universal testing machine is used for pull-out test with sensitive transducers to measure the slippage. The load versus slip data are recorded simultaneously by a data logger and a personal computer.
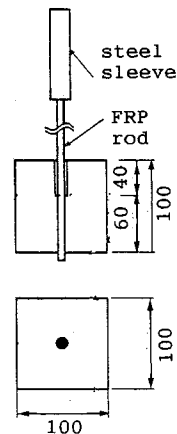

Fig. 2.1 Outline of specimen

Table 2-2 Average compressive strength of concrete at bond test

FRP rod group	LC2,KC2,MA2	SA2,KRV2,TC2	LC1,TC1,KC1,MA1,TC3,MA3
Ave. comp.strength	408 kgf/cm^2	383 kgf/cm^2	292 kgf/cm^2

transducer

rubber

15

20

machine frame

jaw-chuck

20
steel pad

(units : mm)
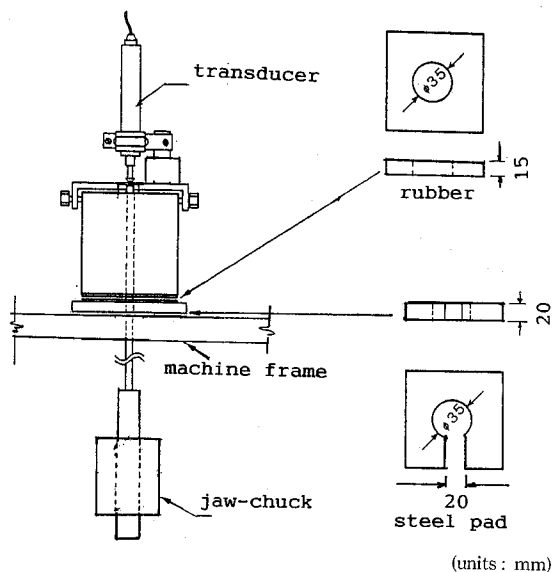
Fig. 2.2   Test assembly

Table 2-3   Bond stress at slippage

Symbol	Bond stress at slip (kgf/cm^2)			Max.
	0.05mm	0.1mm	0.25mm	
L-C1	41.9	58.1	88.7	156.4
L-C2	79.2	90.4	97.9	123.1
T-C1	41.2	43.7	43.8	44.7
T-C2	50.5	52.6	53.6	54.4
T-C3	84.2	88.2	87.1	94.2
K-C1	55.6	60.6	65.3	136.7
K-C2	73.4	79.9	84.8	142.2
S-A2	61.8	80.2	92.5	118.0
M-A1	22.5	32.8	51.2	78.0
M-A2	67.0	79.1	99.8	128.9
M-A3	13.7	20.3	37.2	87.2
KR-V2	85.4	89.3	92.3	93.4

(3)   Results and discussion

The bond stress "τ" is calculated according to the *Test Method for Bond Strength of Reinforcing Steel and Concrete by Pull-Out Test (Draft) JSCE.* The bond stress is calculated using the following relationship ;

$$\tau = \frac{P}{\pi \phi L} \cdot \alpha \qquad (1)$$

where
  P=load
  τ=bond stress
  ϕ=diameter
  L=bonded length
 $\alpha = \dfrac{300}{f'_{ck}}$
  f'_{ck}=concrete compressive strength

The average compressive strength of concrete at pull-out test are shown in **Table 2-2**. The typical bond stress versus slippage relationship of FRP rods are shown in **Figs. 2.3**(a)～(f). Three specimens are tested for every FRP rod. The average bond stresses are shown in **Table 2-3**. From the bond stress versus slip graphs, the bond-slip relationships are categorized in three groups. The first group (MA&LC) has gradual increasing nature of bond stress against slip. The second group (TC, SA, KRV) shows a sudden change of slippage at 70～90% of the maximum bond stress

levels, and after that only small increment of bond stress with large slippage follows. The third group (KC) type, shows an intermediate nature between the first and the second.

### a)   First group (LC, MA types)

The LC type FRP rods in this group have the surface deformation with large spirals and wide pitch of spiral but MA type is braided. Comparatively, the pitch of the spirals of the LC type is about five times that of the other types of FRP rods (KRV, SA, KC). Here, it is considered that the initial stage of slipping is due to the wide pitch of large spirals. At the maximum level, the large spirals caused wedge action and consequently fractured the surrounding concrete. As for the braided type (MA), the braiding are normally milder, therefore, the initial stage of slipping is steady. However, at the maximum level, cracking of concrete is observed. This is cleared at the open-cut observations. Some abrasion is observed on the surface of FRP rod and also some traces of fibers at the interface of concrete. This is considered to be the wedge action. From further observations, the surface roughness of MA type FRP rods change with the diameter.
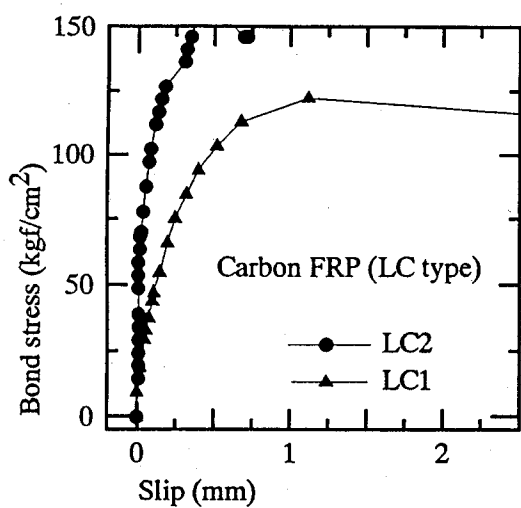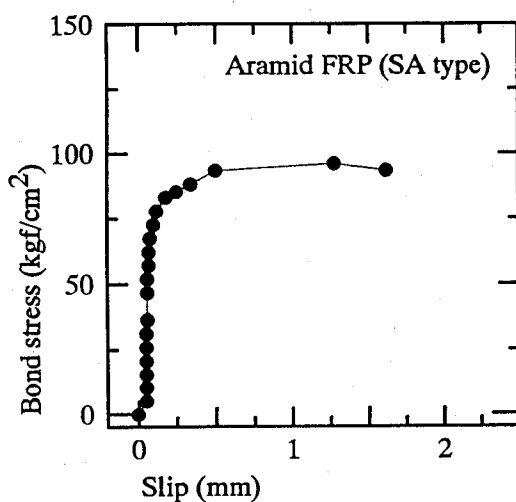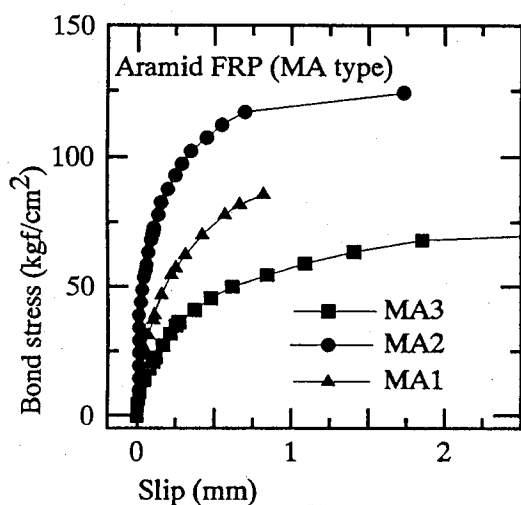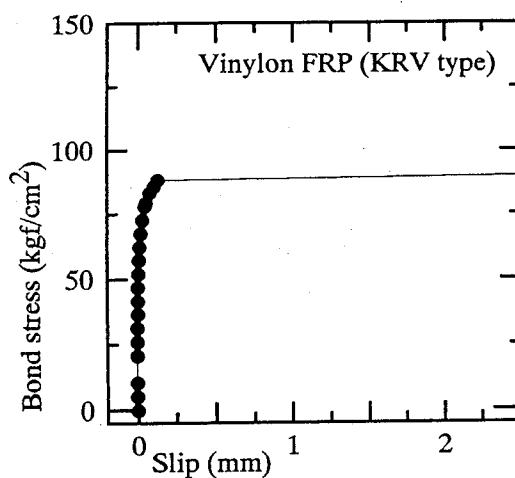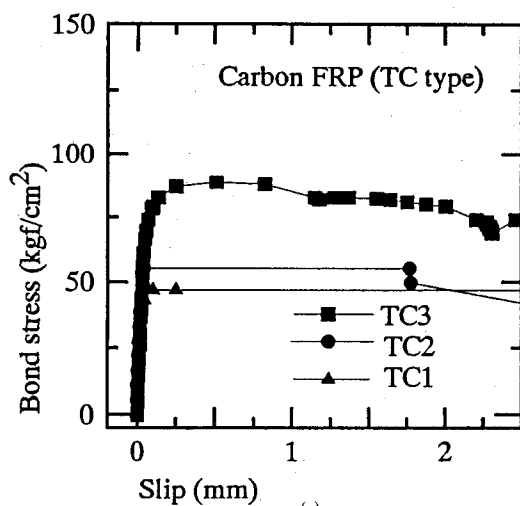
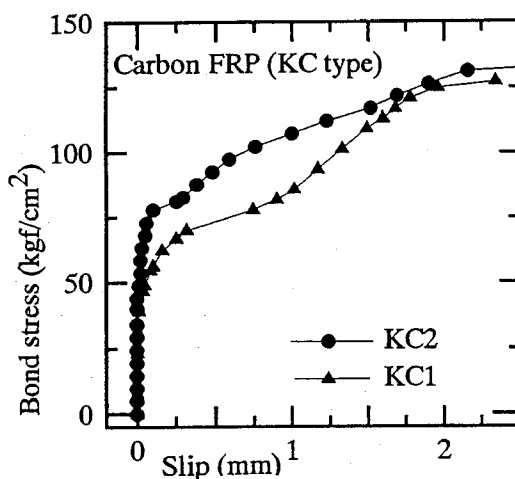**Fig. 2.3** Bond stress vs. slip of FRP rods

b) Second group (TC, SA, KRV types)

In this group, the initial bond stress was increasing with little or no slippage. However, at a certain level of bond stress, the FRP rods slipped and failed. No cracks were found on the specimens and the slipping of the free end into the concrete can be clearly seen.

In the case of TC (strand) type, clear grooves indented by the strands are found at the open-cut observations. This showed that the TC strands slid along its grooves at the maximum load. Here also the surface roughness of the TC rods increased with the diameter. Therefore, the bond stress of TC type FRP rods depend on the adhesion of the rod to the concrete.

As for the SA and KRV types, the rods slipped through the concrete regardless of the mechanical friction of the spirals. The further investigations in the open-cut observations showed spirals peeled off from the rod and broken. Therefore, the rods slipped through the spirals at the maximum load. The bond stresses in this case can be considered upon the strength of spirals and the adhesion of spirals to the rods.

c) Third group (KC type)

The third group consists of only KC (spiral) type. At the initial stage, the bond-slip curve was similar to the second group, but when the bond stress level reached around 50% of the maximum level, the curves turned similar to those of the first type. In the open-cut observations the spirals peeled off from the rod. Therefore, it is considered that the bond characteristics at the initial stage depends on the adhesion of the spirals to the rods. After the adhesion is broken, the bond strength is maintained by the interlocking effect between the rod and the peeled spirals. This type of FRP rod is made by winding the spirals tightly to the rod. Therefore, the maximum bond strength depends on the fiber strength and adhesion of spirals to the rod.

(4) Summary and conclusion

In general, the bond strength of re-bars in concrete depend on the compressive strength. This may also be applied to the FRP rods. Apart from the concrete's strength, the bond strength of FRP rod in the cement concrete also depends on the surface condition, the adhesion of spiral to rod and the fiber strength.

The bond~slip character of FRP rods in this study can be categorized in three groups. They are; gradual increasing bond-slip relationship, sudden slip at a level and the one having both characters.

Although the spirals produce some resistance against slippage, these spirals cannot be compared to the deformations of the steel bars, because they are monolithic. On the other hand, for the FRP rods, the
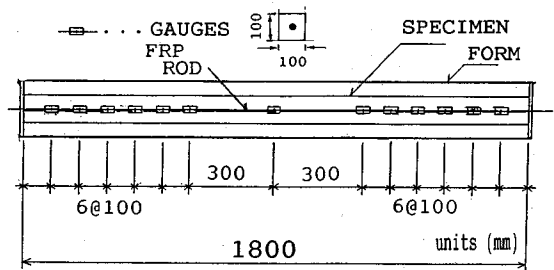

Fig. 3.1 Outline of specimen

spiral windings of FRP rods are made on the longitudinal rod only afterward, therefore, this cannot be taken as monolithic body.

3. TRANSFER LENGTH OF VARIOUS TYPE OF FRP RODS

(1) Introduction

The FRP rods having high tensile strength and low modulus of elasticity have attracted the attention of engineers and designers as an excellent candidate material. When these FRP rods are to be used in pretensioned type prestressed concrete structures the transfer length plays an important role. To clarify the transfer bond behavior, the authors have carried out an experimental study on transfer length. Fourteen types of FRP rods are used for this experiment and are shown in **Table 1-1** and marked in the remarks column as "T". These FRP rods are made from carbon, aramid, glass and vinylon. A comparative study for consecutive two years produces some consistent results.

(2) Outline of experiment

The outline of specimen is shown in **Fig. 3.1**. A pretensioning bench and steel forms are used to fabricate the specimens. The tension applied to the FRP rods are 50%, 60% and 70% of tensile strength specified by the maker. The concreting was made after the FRP rods were tensioned. The prestress was introduced to the specimen after six days of curing of concrete in the atmosphere. The strain gauges were fixed axially on the concrete surface of the specimen and measured the amount of strain induced and hence the stress was calculated.

The position of strain gauges are also shown in **Fig. 3.1**. The strains were monitored for two weeks continuously. After that the specimen were kept for two months and the static bending test was conducted.

(3) Experimental results and discussion

a) Estimation of transfer length
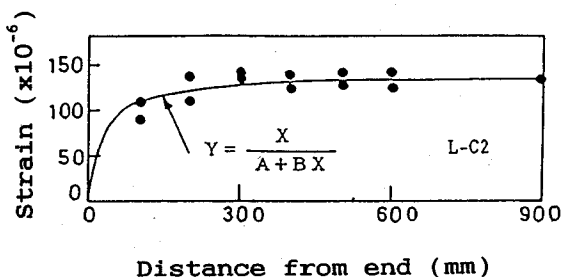
To estimate the transfer length of FRP rods with
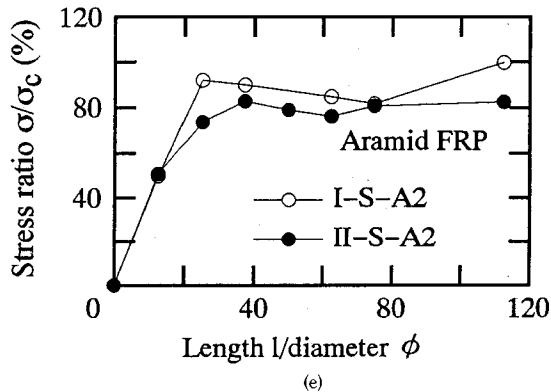
Fig. 3.2 Typical strain distribution on the specimen
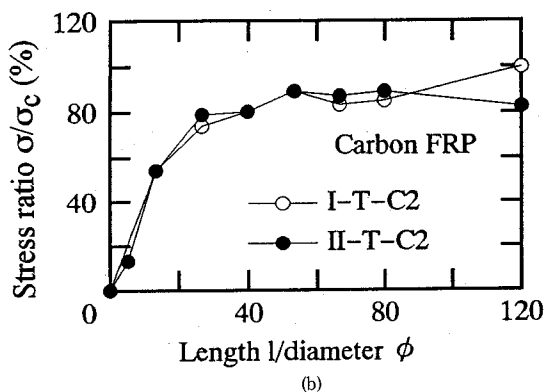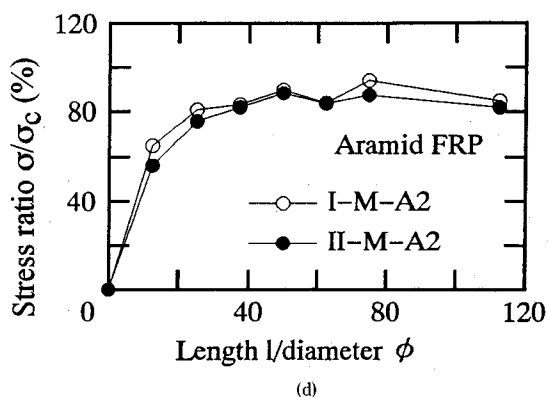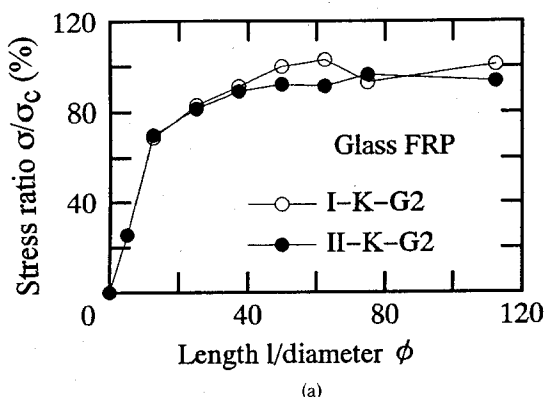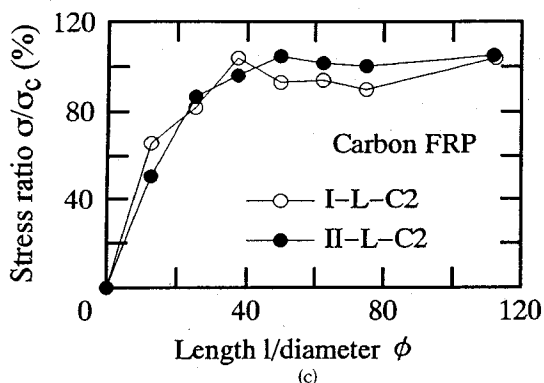

(c)

(a)

(d)

(b)

(e)

Fig. 3.3 Stress ratio vs. length/diameter ratio

respect to the type of fibers and not by the diameter, the following assumptions were made.

(a) the strain at the center of each specimen was estimated from the calculated strain curve (**Fig. 3.2**).

(b) the (σ/σ_c) versus ($1/\phi$) was plotted, here(σ/σ_c) is proportional to ($\varepsilon/\varepsilon_c$)

(c) from the above non-dimensional curve, the transfer length was determined when the prestress level becomes relatively constant.

The following steps were also made to reduce the data ;

(a) the ratio of the measured strain from one end (ε) to the calculated strain at the center (ε_c) as non -dimensional figure.

(b) the ratio of ($1/\phi$) was determined by the distance of the position of strain gauges (1) and the diameter of FRP rod (ϕ).

b) Transfer length immediately after prestressing

Figs. 3.3(a)~(e) show the stress ratio versus length (l)/diameter(ϕ) curves of FRP rods. The "l" and "ϕ" are the position of strain gauges from pre-stressing end and the diameter of FRP rods respectively. **Fig. 3.**

Table 3-1 Transfer length of FRP rods immediately after prestressing

Symbol	Trans.length / φ
K-C1	50
K-C2	37.5
L-C1	50
L-C2	50
T-C1	60
T-C2	53.3
K-CP	37.5
M-A1	66.7
M-A2	53.3
S-A1	50
S-A2	62.5
K-G1	66.7
K-G2	62.5
KR-V1	100

(a)

(b)

Fig. 3.4 Transfer length at different prestressing levels

3(a) is on glass FRP rod, **Fig. 3.3**(b) & (c) show carbon FRP rods and **Fig. 3.3**(d) & (e) show aramid FRP rods. The open circle and solid circle are the two consecutive year's data.

The transfer length of the FRP rods immediately after prestresssing are shown in **Table 3-1**.

c) **Transfer length at different prestressing levels**

Figs. 3.4(a) and (b) show prestress ratio versus distance/diameter ratio curves of braided aramid (MA type) and strand carbon (TC type) FRP rods. The level of prestressing were 50%, 60% and 70% of the makers tensile strength. The nature of the curves showed similarity. The experimental results showed that the levels of prestressing have minimum influence on the transfer length.

d) **Transfer length at cutting-off**

Figs. 3.5(a)∼(c) show the strain distribution axially on the concrete surface of the specimen after cutting -off at the center. They are grouped in carbon, glass and aramid. From these figures the positive strain of glass FRP rods might be due to the end slippage. The other strain gauge points show stable and with no changes, showing sufficient bonding. The overall performances of the FRP rods at cutting-off showed encouraging results.

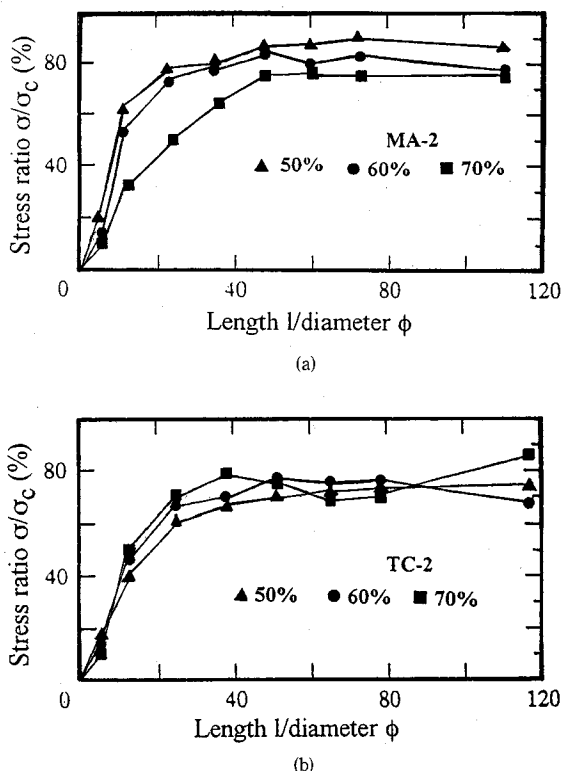The transfer length after cutting-off were found to be 18∼30 φ for carbon FRP, 23 φ for glass FRP and 25∼32 φ for aramid FRP. Therefore, it can be recommended that transfer length at cutting-off will be sufficient taking 300 mm.
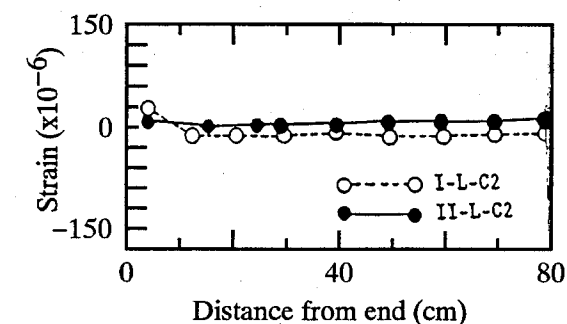
e) **Effective prestress evaluation**

The effective prestress on the specimen was evaluated from the static bending test, two months after prestressing was introduced to the specimen. The measured effective prestress were obtained by measuring the readings of strain gauges on the specimen. The measured and calculated values are shown in **Table 3-2**. From the table ; around 75%∼90% of the introduced prestress is retained by carbon FRP, 79%∼88% by aramid FRP and 78%∼87% by glass FRP. In general, the mean effective prestress retained by FRP rods are around 80%.

(4) Summary and conclusion

The transfer length of FRP rods can be determined experimentally using strain gauges, fixed on the concrete surface of the specimen at the time of introducing prestress.

The experimental results showed that the level of prestressing have minimal influence on the transfer length.
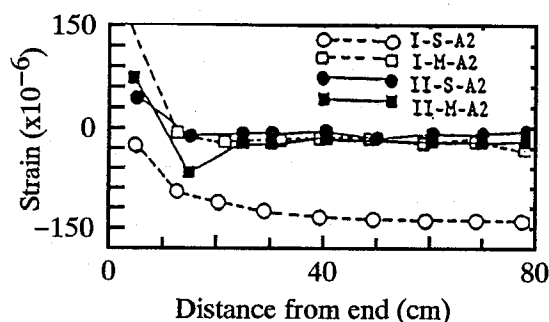
The transfer length after cutting-off will be sufficient taking 300 mm.

(a)
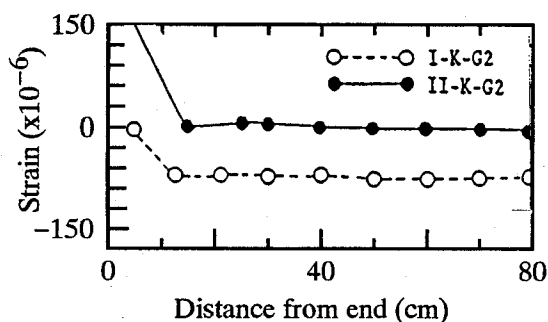
(b)

(c)

Fig. 3.5 Strain vs. distance from end at cutting off

Table 3-2 Effective prestress of FRP rods

Symbol	Stress level x Pu	Prestressed (kgf/cm²)		Ratio (%)
		Measured	Calculated	
K-C2	0.6	47	54.5	86
L-C2	0.6	33.4	41.8	80
T-C2	0.5	27	33.5	80
T-C2	0.6	28.3	36.6	77
T-C2	0.7	37.1	45.8	81
K-CP	0.6	44.1	48.8	90
S-A2	0.6	43.4	51.5	84
M-A2	0.5	26.9	36.1	75
M-A2	0.6	32.2	39.5	81
M-A2	0.7	42.9	52.3	82
K-G2	0.5	27.1	30.8	87
K-G2	0.6	31.1	37.4	83

The effective prestress retained in the specimen using FRP rods was around 80% of the initial prestress.

4. ANALYTICAL APPROACH ON TRANSFER LENGTH

(1) Introduction

The analytical approach on the transfer length is a complex issue. The factors influencing the transfer length are; strength of fiber, strength of concrete, dimension of FRP, frictional coefficient, prestressing force and poisson's ratio of FRP. Many researchers in the past have proven and established the transfer length of steel tendons in pretensioned prestressed concrete structures. As for the FRP rods, which are made recently, no standard test exists to establish the transfer length. When the outstanding properties of FRP rods were found, many researchers and engineers considered that these materials are possible to substitute conventional steel in construction. From the practical point of view, the authors have conducted experimental work on the transfer length of FRP rods in prestressed concrete structures. To interpret the experimental results and to estimate the transfer length, an analytical approach have been made.

(2) Prestress transfer bond in pretensioned concrete structures

When tendons are pretensioned, their stress is often transferred to the concrete solely by bond between the two materials. Therefore, the transfer length at each of the tendon is to perform the function of anchorage when mechanical anchorage are not provided. The stress in the tendon varies from zero at the exposed end to the full prestressed at some distance inside the concrete. That distance is known as "Transfer Length" and such bond stress is termed as prestress transfer bond. The analysis using elastic theory had been carried out by A. Watanabe[2] in 1964.

The Watanabe's equation for initial transfer length for steel tendon in pretension type prestressed con-

crete is expressed as follows:

$$\lambda_0 = \frac{r_1}{2\mu\psi} \ln \frac{1}{1-0.95\mu\psi\sigma_{se}/(\tau_0+\mu\phi)} \quad (2)$$

$$\phi = \frac{\nu_s\sigma_{se}}{nr_1^2[(1-\nu_c)+(1+\nu_c)r_2^2/r_1^2]/(r_2^2-r_1^2)+(1-\nu_s)} \quad (3)$$

$$\psi = \frac{\nu_s+n\nu_c k}{nr_1^2[(1-\nu_c)+(1+\nu_c)r_2^2/r_1^2]/(r_2^2-r_1^2)+(1-\nu_s)} \quad (4)$$

where

λ_0 = initial transfer length
r_1 = radius of steel tendon
r_2 = radius of concrete
σ_{se} = initial tensile stress of tendon
τ_0 = initial bond stress
μ = frictional coefficient
$k = r_1^2/(r_2^2-r_1^2)$
ν_c = poisson's ratio of concrete
ν_s = poisson's ratio of steel
n = modular ratio

(3) Analytical approach

When the equation (2) is used to determine the initial transfer length of FRP rods, the unknown parameters are; initial bond stress τ_0, coefficient of friction μ and the poisson's ratio ν of FRP rod. The initial bond stress τ_0 is calculated from the pull-out test data and using the exponential equation(5)[3].

$$\tau_0 = aX^b \quad (5)$$

where

τ_0 = initial bond stress
X = slip at (0.002ϕ)
ϕ = diameter
a, b = constants.

The constants a and b can be determined from the bond stress versus slip curve by the method of least squares.

The bond stress versus slip of T-C 1 and M-A 1 are shown in **Figs. 4.1**(a) & (b). **Figs. 4.2**(a) & (b) show the family of curves plotted with varying coefficient of friction μ on a graph of poisson's ratio ν against transfer length.

These family of curves show that the transfer length is inversely proportional to the poisson's ratio. The transfer lengths are calculated by equation (2) varying the coefficient of friction μ and poisson's ratio ν. This graphical estimation is used due to the lack of coefficient of friction and poisson's ratio of FRP rods. On the other hand, the experimental studies on the transfer length of FRP rods have been made and reported[4],[5]. To determine the possible range of coefficient of friction and poisson's ratio, the experimental data are used (**Table 3-1**). From the experimental data the transfer lengths of T-C1 and M-A1 are 300 and 400 mm respectively. If an imaginary line is drawn at a point of 300 mm in X-axis against the ordinate, this line will cut the family of curves and
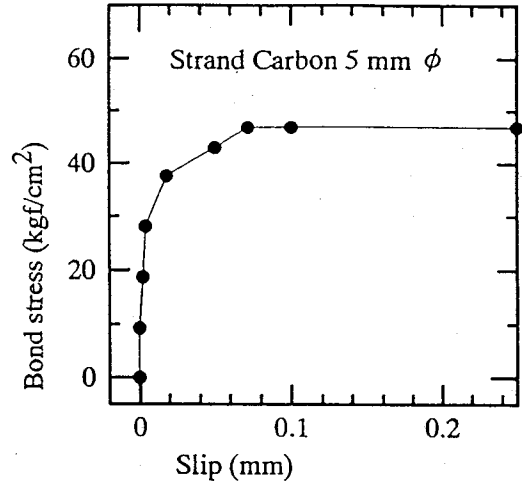

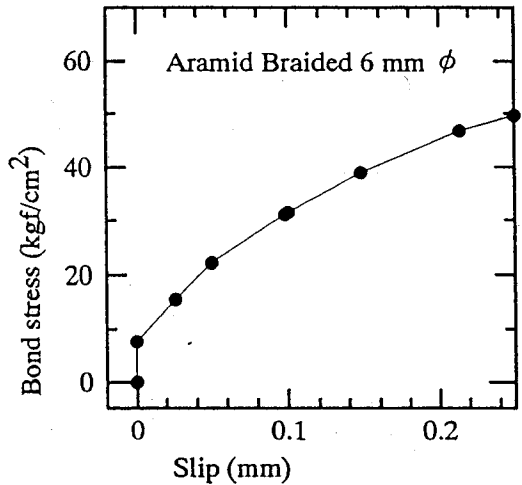**Fig. 4.1** (a) Bond stress vs. slip of T-C1

Fig. 4.1 (b) Bond stress vs. slip of M-A1

sets of poisson's ratio and coefficient of friction will be obtained. These are the possible sets of μ and ν for a transfer length of 300mm. Using these possible sets of data and substituting in equation (2), the transfer length are calculated again.

Table 4-1 shows the transfer length of T-C2 with calculated to measured ratios in percentages, using these sets of coefficient of friction μ and poisson's ratio ν and equation (2). Judging from the results in the table, it is found that any set of data of μ and ν gives the transfer length which is very close to the measured ones. Here, the authors have chosen the most probable set of data as 0.4 for coefficient of friction μ and 0.125 for poisson's ratio ν. This choice have been made with regards to the experimental results of Sano et al[6] which gave the poisson's ratio
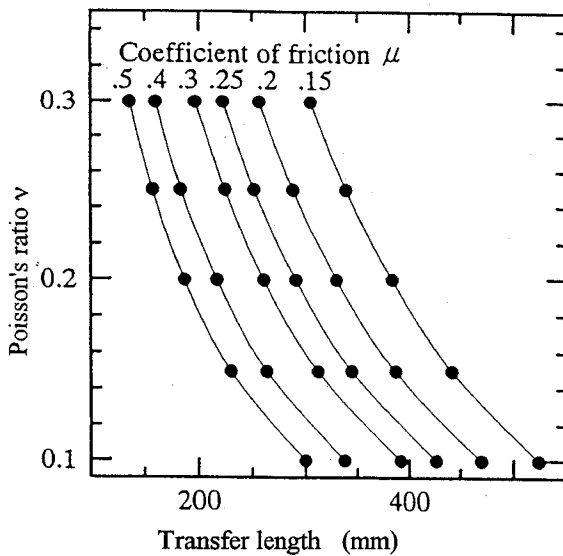
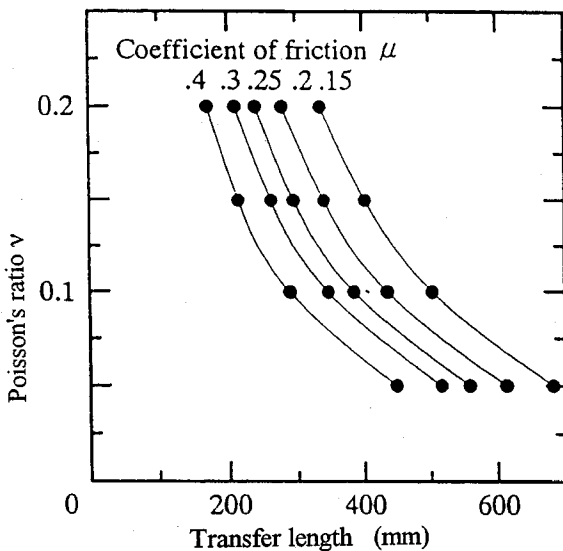**Fig. 4.2** (a) Poisson's ratio vs. transfer length of T-C1

Fig. 4.2 (b) Poisson's ratio vs. transfer length of M-A1

Table 4-1 Transfer length of T-C2

Set No.	μ	ν	Tl(mm)*	(%)#
A	0.5	0.1	386	96
B	0.4	0.125	401	100.25
C	0.3	0.16	403	100.75
D	0.25	0.19	401	100.25
E	0.2	0.235	399	99.75
F	0.15	0.32	389	97.25

Note:* calculated transfer length
  # ratio of calculated to measured

Table 4-2 Transfer length of M-A2

Set No.	μ	ν	Tl(mm)*	(%)#
A	0.4	0.068	378	94.5
B	0.3	0.086	383	95.75
C	0.25	0.096	393	98.25
D	0.2	0.114	399	99.96
E	0.15	0.146	403	100.85
F	0.1	0.225	392	98

Note:* calculated transfer length
  # ratio of calculated to measured

(4) Summary and conclusion

An analytical approach is made on the transfer length of FRP rods in pretension type prestressed concrete structures. The Watanabe's equation (2) is used to determine the transfer length. The coefficient of friction and the poisson's ratio of the FRP rod is assumed first. From the graph in **Figs. 4.2**(a) & (b), several possible combinations of the poisson's ratio and the frictional coefficient can be determined when the measured transfer length is plotted in the same graph. The magnitude of transfer length can be further refined by using the values of poisson's ratio obtained from experimental study[6].

From this analysis, the coefficient of friction μ and the poisson's ratio ν of strand type carbon FRP rod T-C1 are 0.4 and 0.125 respectively. When the T-C1 type FRP rod's μ and ν are used on T-C2, it is found that the calculated value is almost the same as the measured one. The same procedure is applied to the braided aramid FRP rod M-A1, using the μ and ν as 0.2 and 0.144, and calculating that of M-A2, it was found that the calculated value is almost the same as the measured one.

of T-C1 as 0.08~0.12.

Furthermore, when the poisson's ratio of T-C2 is taken as 0.235, the ratio of calculated to experimental data is 99.75%. This also agreed with the Sano et al[6] value of T-C2 as 0.14~0.27.

Table 4-2 shows the calculated values of transfer length of M-A2 using the estimated values of μ and ν of M-A1 on equation (2). From the table, the set No. D is considered to be the probable set. Here also the experimental results of Sano et al gave the poisson's ratio of M-A1 type as 0.05~0.09 and 0.13~0.23 for M-A2.

From the above results on strand type carbon and braided type aramid it is possible to estimate the transfer length analytically by the equation (2), when the coefficient of friction μ and poisson ratio ν are determined graphically.

5. CONCLUSIONS

This research is a result of four consecutive years of experiments and analyses on FRP rods. Fourteen type of FRP rods are used for studying the transfer length and twelve types for bond properties.

The bond properties of FRP rods are grouped and discussed. All the FRP rods in this study showed sufficient bond to concrete. Also from the bond~slip relationship, the initial bond stress of FRP rods are determined.

According to the Watanabe's equation (2) for transfer length, there are many influencing factors. Since the friction coefficient μ and the poisson's ratio ν of FRP rods are not established yet, the authors used graphical estimation. With these values of μ and ν the transfer length can be calculated by the equation (2).

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プレテンション PC 部材における各種 FRP ロッドの
付着挙動に関する基礎的研究

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本研究では，コンクリート中の連続繊維補強材の付着性能およびプレテンション方式のプレストレストコンクリート構造物の伝達長に関して実験的研究の結果について論じたものである．その結果，さまざまな摩擦率 μ に対する伝達長とポアソン比 ν の関係を把握し，その関係を用いることにより径の異なったタイプの伝達長が推定できる．