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論　文

[1201] An Experimental Study on Bending Behavior of Partially Prestressed Concrete Members with Fiber Reinforced Plastic

A. M. Anisul HAQUE*1, M. TEZUKA*2, T. YOSHIOKA*2 and S. YASUMOTO*3

1. INTRODUCTION

Fiber reinforced plastic (FRP) reinforcement is one of the most promising new developments for concrete structures. Members reinforced with FRP provide not only lighter structures but also more durable structures that are free of the deterioration caused by corrosion of steel. FRP consists of synthetic or organic high strength fibers, most of which are impregnated with a resin matrix. They are available in the form of grids, rods, and ropes for reinforced and prestressed concrete members1).

Reportedly FRP can be effectively used as a prestressing tendon rather than a nonprestressed reinforcement, because its modulus of elasticity is lower than that of steel reinforcement. Fully or almost fully prestressed concrete members essentially show undesirable behavior of time dependent deflection due to creep of concrete. In order to improve this phenomenon, a part of prestressing tendons can be replaced with nonprestressed reinforcement, that is, partially prestressed concrete (PPC). When FRP is used for reinforcement, crack width is not to be limited, because FRP is free of corrosion. To satisfy the serviceability, however, deflection must be restricted.

This paper presents an experimental study on bending behavior and flexural characteristics of partially prestressed concrete members reinforced with both or either of aramid FRP (AFRP) and carbon FRP (CFRP) as prestressing tendon or nonprestressed reinforcement.

2. TEST SPECIMENS

Five partially prestressed concrete T-beams were tested. They were reinforced with prestressing tendons and nonprestressed reinforcement made of AFRP and CFRP. All the test

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*1 Graduate Student, School of Engineering, Tokai University.
*2 Chief Engineer, Research Laboratory, Oriental Construction Co., Ltd.
*3 Professor, School of Engineering, Tokai University.

specimens have the same dimension as shown in Figure 1. Each specimen has a T-section with an effective depth of 300 mm and a compressive flange width of 250 mm. Table 1 shows detail of placement of FRP tendons and reinforcement for each specimen. The specimen was symmetrically loaded at two points. The effective span and loading range were 2200 mm and 600 mm, respectively. Among them only the T-1 type has no nonprestressed reinforcement in it.

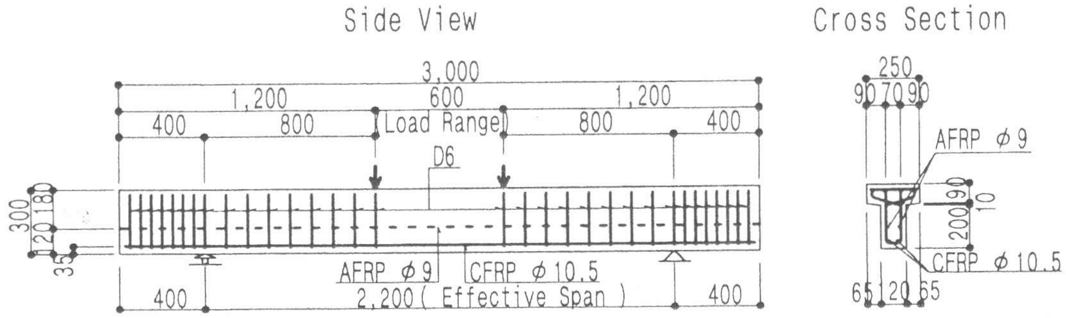
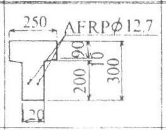
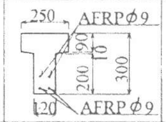
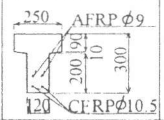
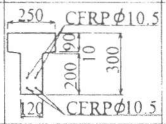
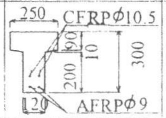


Figure 1 Test specimen

Table 1 Specimen cases

TEST SPECIMEN	TYPE OF LOAD	CROSS SECTION	PRESTRESSING FORCE (tf)	REMARK
T - 1	Static Load		21.3	AFRP Tend
T - 2	Static Load		10.6	AFRP Tend. AFRP Rein.
T - 3	Static Load		10.6	AFRP Tend. CFRP Rein.
T - 4	Static Load		12.1	CFRP Tend. CFRP Rein.
T - 5	Static Load		12.1	CFRP Tend. AFRP Rein.

The specifications of FRP for this experiment are shown in Table 2. Prestress of T-1 was determined in order that no tensile stress occurred at transfer. The other specimens were designed to have the almost same sectional area of both tendon and nonprestressed reinforcement as T-1. All tendons were tensioned with 60% of nominal tensile strength. All the specimens were reinforced with closed stirrups of steel re-bars through the specimen except the loading range to prevent shear failure (refer to Fig. 1).

Table 2 Characteristics of FRP

TYPE OF FIBER	SURFACE SHAPE	NOMINAL DIAMETER (mm)	SECTIONAL AREA (cm²)	NOMINAL TENSILE STRENGTH (kgf/cm²)	TENSILE DESIGN STRESS (kgf/cm²)	TENSILE DESIGN STRENGTH (kgf)	YOUNG MODULUS (kgf/cm²)	ELONGATION %
AFRP	Braid	12.7	1.27	17,780	8,400	10,670	700,000	2.2
AFRP	Braid	9.0	0.63	8,820	8,400	5,290	700,000	2.2
CFRP	Strand	10.5	0.56	10,080	10,800	6,050	1,400,000	1.2

3. MATERIAL PROPERTIES AND TEST METHOD

1) Concrete Mix

The concrete mix for all the test beams was designed to have a nominal 28-day compressive strength of approximately 400 kgf/cm^2. The maximum size of aggregate was 20 mm. The ages of concrete at the time of testing ranged from 45 to 60 days.

2) Measurement System

All the prestressed tendons and nonprestressed reinforcements were installed with electric resistive type strain foil gauges at critical sections. At the midspan of each specimen six polyester strain gauges were bonded to the concrete surface to measure the concrete surface strains. Five spring-type displacement transducers with a sensitivity of $500\text{X}10^{-6}/$ mm were used to measure the change in deflection due to loading. Crack widths were measured with π shaped displacement transducers. Crack spacings of all the developing cracks were recorded as well as the crack penetration of the main cracks. Position of the gauges and displacement transducers is shown in Figure 2.

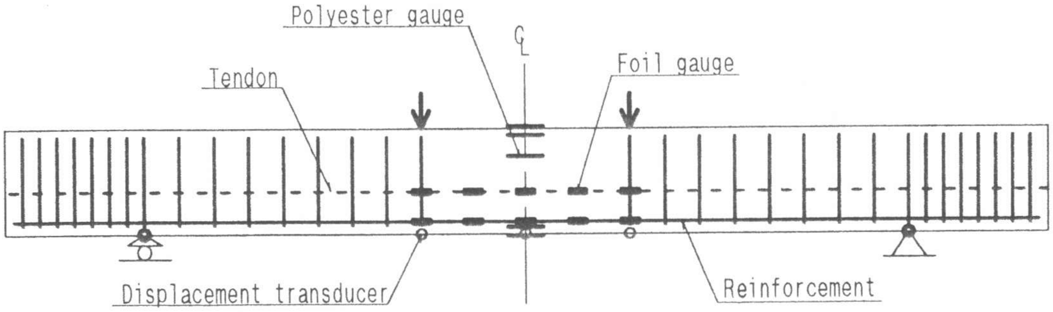


Figure 2 Position of gauges and displacement transducers

3) Loading System

Each test specimen was simply supported and tested by applying symmetric two-point loads by means of 20 tf hydraulic jack for T-1 through T-3 type and 30 tf hydraulic jack for T-4 and T-5 type. The load was statically applied in two stages. At the first stage the load was increased till the first crack developed and then reduced to zero. At the second stage the load was applied up to collapse.

4. TEST RESULTS AND DISCUSSIONS

The deflections of each specimen and the strains of FRP reinforcement and concrete were measured at every load step. Crack propagation was observed in detail. The crack widths were measured up to 2 mm at every load step. Figure 3 shows the cracking patterns of specimens at collapse.

From Figure 3 it is observed that crack patterns of specimen T-3 and T-4, which were reinforced with nonprestressed CFRP, are widely different from those of T-1 and T-2. The specimen T-1 was not reinforced with nonprestressed reinforcement and the specimen T-2 was

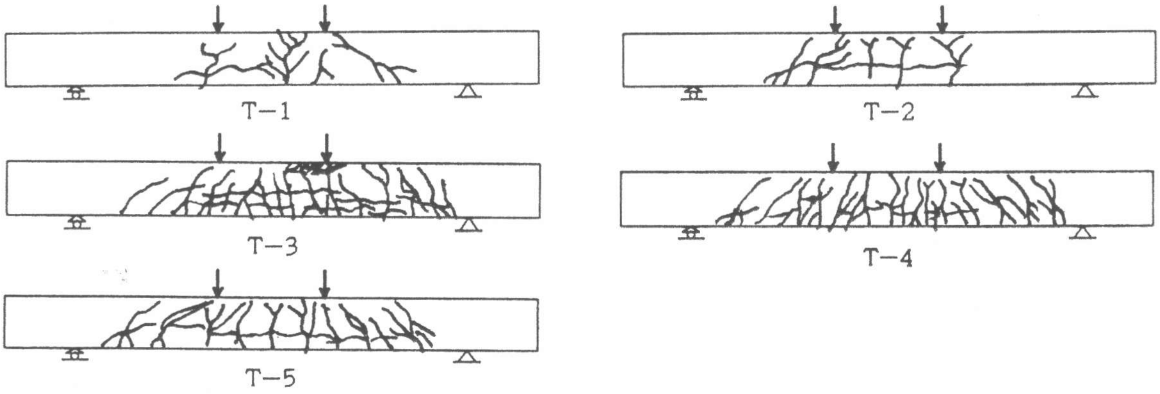


Figure 3 Cracking patterns at collapse

reinforced with nonprestressed AFRP. Crack patterns of specimen T-3 and T-4 are also somewhat different from that of T-5 which was prestressed with CFRP and reinforced with nonprestressed AFRP. From this figure it is observed that cracks of T-3 and T-4 are more finely dispersed than the others. This could be due to its bond characteristics of CFRP strand2) Therefore CFRP strand could be desirable nonprestressed reinforcement for crack control.

Figure 4 shows the relationship between the strains of nonprestressed reinforcement and crack widths measured with π - shaped displacement transducer. It is found from the figure that at the same strain level the crack widths are smaller in the specimens reinforced with nonprestressed CFRP than those reinforced with nonprestressed AFRP.

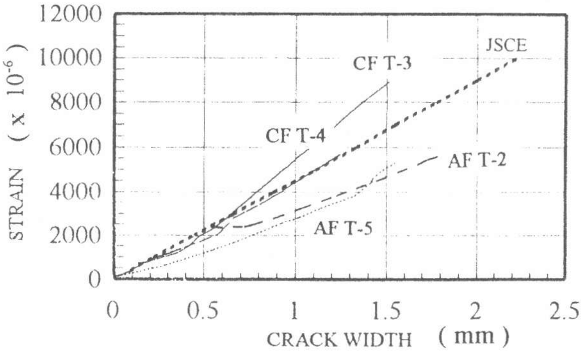


Figure 4 Strain-Crack width relationship

Crack widths were calculated by using JSCE specification's equation of crack width and also plotted in Figure 43). In this calculation the bond characteristic of value k was assumed as round bar and shrinkage effect was not taken into account. It is observed from the figure that the calculated crack widths are relatively close to the measured crack widths for the specimens reinforced with nonprestressed CFRP. This fact means that the bond characteristics of value k was suitable for CFRP strand and the value k for AFRP braid should be investigated.

Cracking and collapse loads for each specimen are summarized in Table 3 where calculated results are also shown to compare experimental results. Crack load was computed assuming that cracking starts when the tensile stress in the extreme fiber of concrete reaches its tensile strength of concrete. For crack load the tensile strength of concrete was taken as 30.5 kgf/cm^2 which was assumed from mean compressive strength of test cylinders (471 - 482 kgf/cm^2). Collapse load in accordance with JSCE specification4) was calculated with the concrete design compressive strength of 400 kgf/cm^2 and assured tensile strength of FRP which could be almost 10% less than the real strength of FRP.

Table 3 Cracking and Collapse loads and Displacements

SPEC.	CALCULATED RESULTS				EXPERIMENTAL RESULTS			
	COLLAPSE LOAD (tf)	CRACK LOAD (tf)	DISP (mm)	FAILURE MODE	COLLAPSE LOAD (tf)	CRACK LOAD (tf)	DISP (mm)	FAILURE MODE
T-1	14.1	6.83	25.5	Tend.	17.8	7.01	45.5	Conc.
T-2	14.3	4.22	27.5	Tend.	17.2	4.99	37.2	Conc.
T-3	19.1	4.22	29.5	Tend.and Rein.	23.1	4.75	47.0	Tend.and Rein.
T-4	16.1	4.58	19.4	Tend.	22.0	5.26	33.0	Tend.
T-5	12.7	4.58	16.8	Tend.	16.7	5.26	29.0	Tend.

Comparing the experimental results with the calculated results, it is found that the experimental crack and collapse loads are greater than the calculated ones. The differences between experimental and calculated results could depend on the differences between assumed and real concrete properties, prestress and tensile strength of FRP. In the specimens of T-1 and T-2 concrete failure preceded FRP failure, although FRP failure was expected before concrete failure in the calculation. This could be also caused by estimating lower tensile strength of FRP than real strength.

It is observed that conventional calculation method could be used to estimate the ultimate strength of PPC members reinforced with FRP. The measured final displacements for the specimens are also shown in Table 3 with calculated results. While the failure loads of T-3 and T-4 are almost same, the final deflection of T-3 is approximately 1.4 times that of T-4. Within the limit of this study it is expected that a member both prestressed with AFRP and reinforced with nonprestressed CFRP can give not only enough strength but also ductility. This could depend on low modulus of elasticity and large elongation of AFRP and bond characteristics of CFRP strand.

The experimental and calculated displacements for T-2 and T-3 specimens are shown in Figure 5 and 6. The calculated displacements were obtained by assuming that the total area of concrete is effective before cracking and using Branson's effective moment of inertia after cracking[4),5)].

In addition the displacements after cracking were also computed by using the moment curvature relation for prestressed concrete sections, assuming the stress-strain curves of concrete and reinforcing materials and the linear strain profile.

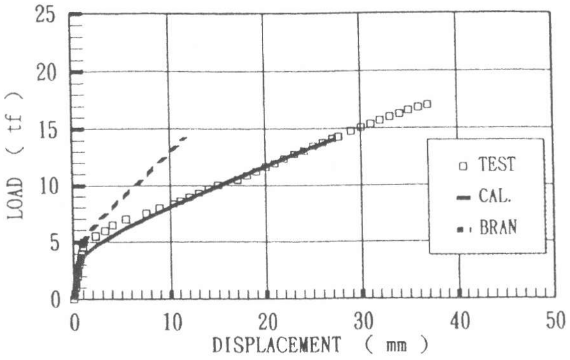


Figure 5 Load-Displacement curves T-2

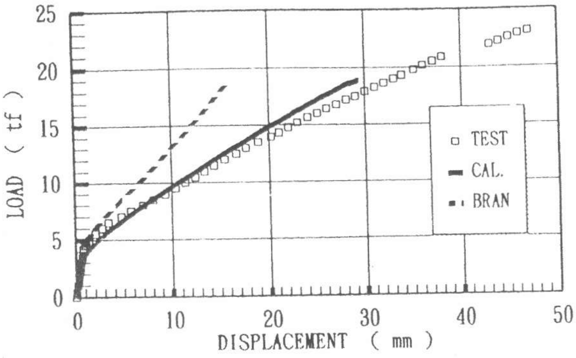


Figure 6 Load-Displacement curves T-3

From the figures it is observed that the calculated values by Branson's equation tend to become smaller than the experimental values after cracking.

However, computed values mentioned above agree well with the experimental results, although the effect of tension stiffening is not considered.

Figure 7 shows the strain distribution measured at the midspan. From the figure the linear strain profile is almost kept at any load stages.

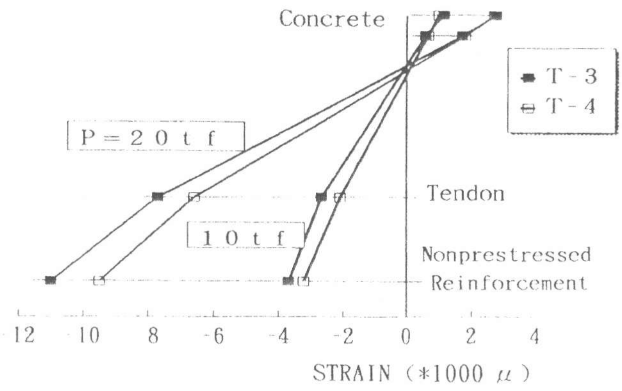


Figure 7 Strain distribution

5. CONCLUSIONS

Conclusions obtained in this research are as follows:

1) Bond characteristics of CFRP strand are desirable for crack control.
2) CFRP strand reduces crack width comparing with AFRP braid, when they are used as nonprestressed reinforcement.
3) Bond characteristics of AFRP braid should be further investigated to estimate crack width.
4) While deflection by Branson's equation does not agree with experimental results, giving too small deflection, conventionally calculated results with assumption of the moment curvature relation, the idealized stress-strain curves of materials and the linear strain profile agree with experimental results.
5) A member prestressed with AFRP tendon and reinforced with CFRP nonprestressed reinforcement showed the best bending behavior, showing enough strength and ductility.

6. REFERENCES

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