論文 Influences of FRP Rod Type on Flexural Properties of Concrete Beams

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ABSTRACT: Nine types of FRP rods and a deformed steel bar were used in the laboratory testing. From the test results, it was concluded that the influences of FRP material properties on the flexural behavior were primarily characterized by modulus of elasticity and bond characteristics. The predictions of crack performance and beam deflections by some codes' equations were compared with experimental results. Calculation equations currently available need to be modified to respond to the diversity of FRP material properties.

KEYWORDS: FRP reinforcement, concrete beam, flexural property, laboratory testing

1. INTRODUCTION

Various types of FRP reinforcement have been researched for their mechanical properties in concrete members. These researches have proven that most of the calculation methods for conventional reinforced concrete members can be applied to FRP reinforced concrete members. However, some modifications must be made to respond to the diversity of FRP reinforcement[1][2]. It may be supposed that a factor to distinguish different fiber material types and another factor to reflect various geometrical shapes of FRP reinforcement are necessary.

In view of the above consideration, this study adopts a way of comparative experiments to investigate the effects of FRP material properties on the flexural behavior of beams. Twelve types of FRP rods were chosen for use in the flexural tests of beams, bond tests and bond cracking tests of the rods. Here the experimental results of nine beams reinforced by FRP rods and a beam reinforced by steel bars under short term loads are presented.

2. OBJECTIVE

The flexural behavior of reinforced concrete beams usually means the deflections, cracks, distribution of strains, and yield/ultimate moment. They are principally affected by the properties of component materials, the shape of cross section and stress condition. Among the material properties the strengths and elastic moduli of reinforcement and concrete are the most important factors. The bond characteristic of reinforcement is also significant to the crack performance and the behavior of cracked beams. Past researches showed that bond characteristic was dependent on the ratio of elastic moduli, stress level and surface shape of reinforcement. Higher stress level, lower elastic modulus and various surface shape of FRP reinforcement make its bond characteristic different from that of steel bars[3]. The aim of this research program is to comprehend the effects of the properties of typical FRP rods,

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especially the bond characteristic, on the flexural behavior of concrete beams.

In this paper, based on the experimental results of beams under short term loads, the following aspects are described and discussed: (1) Beam deflections and the influence of FRP rod type; (2) Cracking performance and its calculation.

3. EXPERIMENT SCHEME

3.1 FRP RODS

The FRP reinforcement used in beam specimens included three kinds of fiber materials: carbon, aramid and glass, and four types of surface configurations: spiral and braid patterned, deformed and strand [see Fig. 1]. Their primary properties are listed in Table 1. The rods specified with the same surface configuration were produced by the same manufacturer.

TABLE 1. FRP Rods for Beam Specimens

No	Identifi-cation	Fiber Type	Configu-ration	Elastic Modulus E(GPa)	Tensile Strength f_t (MPa)
1	GF-S_P-8	Glass	Spiral	47.0	1240
2	AF-D -8	Aramid	Deformed	75.8	1370
3	AF-S_P-8	//	Spiral	73.7	1230
4	AF-B -7	//	Braid	63.4	1940
5	CF-D -8	Carbon	Deformed	126.1	1740
6	CF-S_T-7.5	//	Strand	120.9	2210
7	CF-B -7	//	Braid	130.0	2580
8	CF-S_P-8	//	Spiral	141.5	1700
9	CF_X-S_P-8	//	//	197.3	1470
10	SD345-13	Steel	Deformed	210.0	493/699*

* Yield/ultimate stresses of reinforcing steel

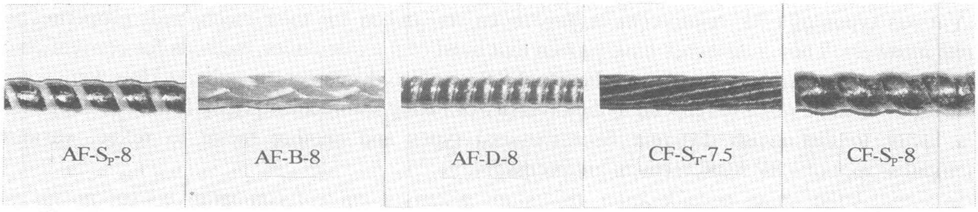

Fig. 1. Configurations of Tested FRP Rods

3.2 CONCRETE

All the concrete used in this research program was designed with an identical mix proportion. The compressive design strength is 36.0MPa. Portland cement, washed sand and gravel with a maximum size of 13mm were used. The water/cement ratio was 0.58 and the mix proportion was 1:2.24:2.34(by weight)=cement:sand:gravel.

Specimens were cast in an upright position and vibrated. After 3 hours, the exposed surfaces of specimens were smoothed with trowel and then made airtight by plastic film. After 2 weeks, the specimens were unmolded and cured in a new airtight condition until testing.

3.3 BEAM SPECIMENS

Prismatic beams with the dimension of 150mm × 250mm × 1545mm were used. The varied design factor in specimens was the type of FRP rods. Fig. 2 illustrates the details of a typical beam specimen. The individual specimen parameters are summarized in Table 2. Since this group of test specimens dealt with the flexural properties, conveniently, high strength deformed steel bars were used as stirrup. In order to maintain the ultimate moments of all beam specimens on roughly the same level, the number of reinforcement rods in each beam was altered with response to the maximum tensile force.

TABLE 2. Test Results for Beam Specimens

Beam	Rod Identification	Beam Bars*	Reinforcement Ratio p_t(%)	Concrete Strength σ_B (MPa)	Sustained Load P_s(kN)	Short Term Deflection δ_s(mm)
L1	GF-S_P-8	ϕ 8×5	0.813	37.2	45.3	7.07
L2	AF-D-8	ϕ 8×3	0.457	36.1	29.5	3.51
L3	AF-S_P-8	ϕ 8×3	0.457	36.7	29.5	3.48
L4	AF-B-7	ϕ 7×4	0.465	37.6	47.5	9.79
L5	CF-D-8	ϕ 8×2	0.305	32.0	34.3	4.52
L6	CF-S_T-7.5	ϕ 7.5×3	0.369	34.0	34.3	4.38
L7	CF-B-7	ϕ 7×3	0.349	36.8	47.5	5.13
L8	CF-S_P-8	ϕ 8×3	0.457	34.2	38.5	3.17
L9	CF_X-S_P-8	ϕ 8×3	0.457	33.9	38.5	2.50
L10	SD345-13	D13×3	1.17	35.5	45.3	1.70

* Same type and number of reinforcing bars used for top and bottom of each beam

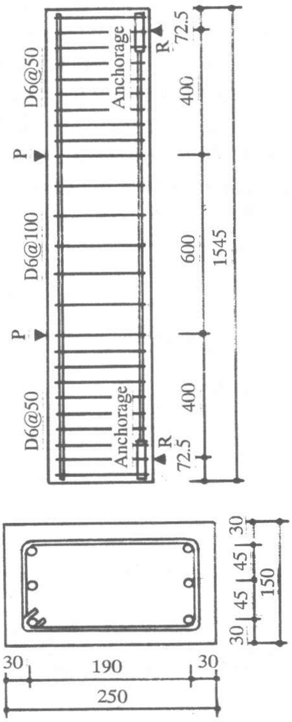

Fig. 2. The Rinforcement Details of Beams

3.4 TEST SETUP AND LOAD

Every pair of beam specimens were settled vertically in opposite direction with an end being held by a roller on a set of experimental apparatus. They were simply supported and subjected to two concentrated lateral loads. Each apparatus is a mechanical loading system, as schematically illustrated in Fig. 3. The weights, which are hanged under the end of lever arm, are magnified twenty-fold by leverage into the loads for beam specimens.

As long term testing, an important index is the stress level of longitudinal reinforcement. The specified stress level in this laboratory testing was a third of tensile strength for all the beam specimens. The sustained loads of beam specimens were shown in Table 2. During testing monotonic loads were gradually increased.

3.5 MEASUREMENT

Beam specimens were measured with displacement transducers for the deflections under midspan and load points, and with strain gages for the strains in main reinforcement. The development of cracks was observed and marked after each stage of loading. The widths of the main cracks were measured and recorded.

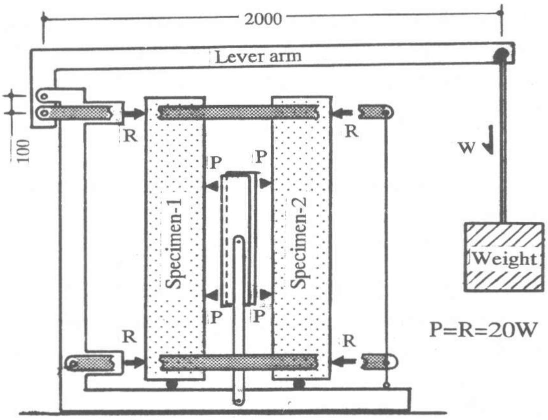

Fig. 3. Test Setup of Beams

4. PERFORMANCES OF BEAMS

The deflection responses of FRP reinforced concrete beams displayed a similar characteristic as conventional reinforced concrete beam. The load-deflection relationship could be described by a bilinear curve with a turning point when crack occurred (see Fig. 4). The instantaneous deflections of beam specimens after the application of prescribed loads listed in Table 2 indicated that the deflections of FRP reinforced concrete beams were smaller than that of the beam reinforced by steel.

The crack patterns in FRP reinforced concrete beams were similar to those in reinforced concrete beam as shown in Fig. 5. However, the crack widths in the formers were obviously greater than those in the latter, even in the beam reinforced with the FRP rods having a high elastic modulus comparable to steel bar.

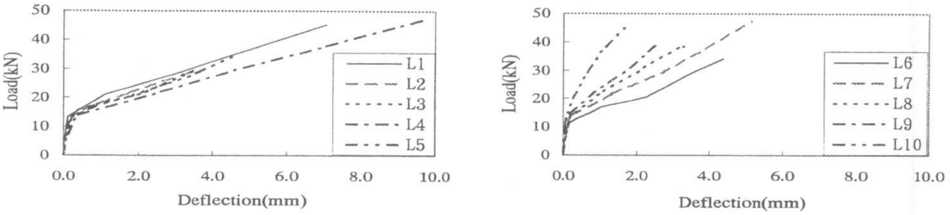

Fig. 4. Load Versus Deflection Curves

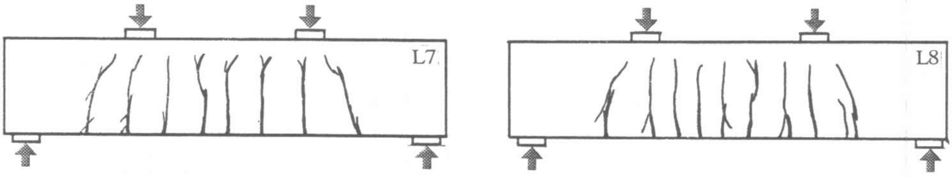

Fig. 5. Crack Patterns of Beam Specimens

5. ANALYSIS AND DISCUSSION

5.1 DEFLECTIONS

The deflections of FRP reinforced concrete beams showed strong dependence on the elastic modulus of rods as shown in Fig. 6. For the present, calculation methods for deflection of cracked concrete beams reinforced with FRP can be classified into two categories: (i)to apply the calculation equations for reinforced concrete members by replacing only the material parameters of steel bars with those of FRP rods, and (ii) to adopt the previous calculation equations including steel parameters but substitute the results with FRP parameters. The deflections predicted by the following three calculation methods are shown in Table 3.

(1) ACI code's equation

For the section of cracked concrete, the effective moment of inertia is evaluated by the following expression.

$$I_e = \beta^3 I_g + (1-\beta^3) I_{cr} \tag{1}$$

where $\beta = M_{cr} / M_s$, the ratio of predicted cracking moment to the moment of beam under sustained load, I_g is the inertia moment of equivalent section, and I_{cr} is the inertia moment of cracked section about the neutral axis by ignoring the effect of the concrete in tension.

As can be seen in Table 3, deflections predicted by Eq. (1) agreed well with the experimental results. The reason might be considered that I_{cr} reflected satisfactorily the influences of modulus of elasticity and reinforcement ratio of FRP rods. This equation identically overestimated the flexural stiffness of all the tested beams except Beam L1 with an exceptionally high reinforcement ratio.

TABLE 3 Predicted Deflections(mm)

Beam	Eq. (1)		Eq. (2)		Eq. (3)	
	δ_{cal}	$\frac{\delta_{cal}}{\delta_{exp}}$	δ_{cal}	$\frac{\delta_{cal}}{\delta_{exp}}$	δ_{cal}	$\frac{\delta_{cal}}{\delta_{exp}}$
L1	7.79	1.10	4.54	0.64	13.7	1.95
L2	1.80	0.51	3.85	1.10	8.66	2.46
L3	2.66	0.76	4.28	1.23	9.81	2.82
L4	7.30	0.75	19.8	2.02	4.82	0.50
L5	2.77	0.61	6.16	1.36	9.30	2.06
L6	3.69	0.84	6.50	1.48	10.4	2.38
L7	4.00	0.78	9.99	1.95	14.8	2.88
L8	3.06	0.97	5.74	1.81	0.66	0.21
L9	2.21	0.88	2.65	1.06	2.79	1.11
L10	1.63	0.96	1.16	0.68	1.16	0.68
Average		0.80	/	1.33	/	1.70

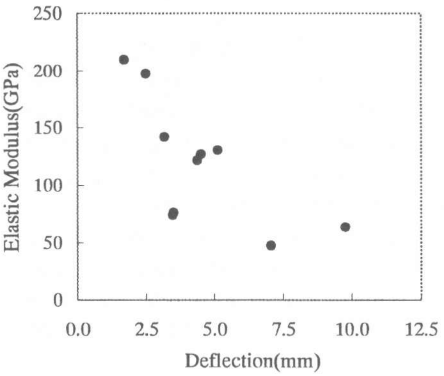

Fig. 6. Relative Deflections vs. Reinforcement Properties

The overestimation became more evident for those beams reinforced with lower modulus of elasticity of FRP rods.

(2) AIJ code's equation

In the calculation for the flexural stiffness of reinforced concrete members the following reducing coefficient is introduced.

$$\alpha_Y = (0.043 + 1.65np_t + 0.043a/D)(d/D)^2 \tag{2}$$

where $n=E_f/E_c$ for L1-L9 and $n=E_S/E_c$ for L10, the modular ratio of reinforcement to concrete, p_t is the tensile reinforcement ratio in beam section, a is the length of shear span, and D is the overall depth of section.

Since np_t represented the properties of reinforcement, it was supposed that Eq. (2) could be applied directly for FRP reinforced concrete beams provided that the parameters of FRP reinforcement were supplied[2]. The calculation results indicated that Eq. (2) overestimated the reduction of the flexural stiffness. Looking into the process of calculation, the second term in the equation, which reflected the effect of the reinforcement properties, possessed too small contribution. It may become necessary that the factor for np_t should be re-determined for FRP reinforced concrete.

(3) A modified equation[2]

Eq. (2) was induced from the experimental data of conventional reinforced concrete members, thus a suggestion for applying it in FRP reinforced concrete beams was that α_Y was calculated routinely with $n = E_S/E_C$, then the following modification was made.

$$\alpha_{FRP} = \alpha_{Y(RC)} E_f / E_S \tag{3}$$

After all, the mechanical significance of such a treatment is not clear enough to be understood easily, as the first term in Eq. (2) is a quantity that is not directly related to the properties of reinforcement. In fact, the calculation results showed that Eq. (3) could hardly evaluate the flexural stiffness of FRP reinforced concrete beams.

5.2 CRACK CHARACTERISTICS

The following equations are currently used by AIJ to evaluate the crack performance in reinforced concrete beams.

$$W_{max} = 1.5W_{av}, \qquad W_{av} = l_{av}\varepsilon_{t,av} \tag{4}$$

$$l_{av} = 2(c + s/10) + k\phi/p_e \tag{5}$$

where W_{max} is the maximum crack width(cm), W_{av} is the mean crack width(cm), l_{av} is the mean spacing of cracks(cm), ε_{tav} is the mean strain in reinforcement bars, c is the depth of concrete cover(cm), s is the distance between reinforcement bars(cm), k is a coefficient which considers the type of member, ϕ is the bar diameter(cm), and p_e is the sectional area ratio of tensile reinforcement bars to effective tensile concrete.

Table 4 shows that the above equations can give good prediction on the whole for FRP reinforced concrete beams. The predicted mean widths of cracks were fairly larger than the experimental values, thus the alternation of some factors on the basis of sufficient experimental information may be necessary.

TABLE 4 Experimental and Predicted Widths and Spacings of Cracks

Beam	$W_{av,exp}$ (mm)	$W_{av,cal}$ (mm)	$\frac{W_{av,cal}}{W_{av,exp}}$	$l_{av,exp}$ (cm)	$l_{av,cal}$ (cm)	$\frac{l_{av,cal}}{l_{av,exp}}$
L1	0.48	0.61	1.27	9.7	10.3	1.06
L2	0.36	0.44	1.22	10.1	10.9	1.08
L3	0.24	0.32	1.33	9.3	10.9	1.17
L4	0.74	0.98	1.32	10.4	12.9	1.24
L5	0.38	0.65	1.71	12.4	14.2	1.14
L6	0.33	0.44	1.33	9.5	11.2	1.18
L7	0.42	0.59	1.40	12.8	11.5	0.90
L8	0.25	0.43	1.72	10.1	10.9	1.08
L9	0.21	0.38	1.81	9.4	10.9	1.16
L10	0.10	0.081	0.81	10.0	9.2	0.92
Average (L1-L9)			1.46	/	/	1.11

6. CONCLUSIONS

(1) From the experimental results of deflections, the flexural stiffness of FRP reinforced concrete beams was much smaller than that of the beam reinforced by steel, and the reduction tended to become great with decreasing modulus of elasticity and reinforcement ratio of FRP rods. The effects of FRP reinforcement on deflection can be reduced to modulus of elasticity and reinforcement ratio.

(2) The calculation methods currently available for reinforced concrete beams could not properly evaluate the deflection of FRP reinforced beams.

(3) The patterns of the flexural cracks in FRP reinforced concrete beams were proved to be the same as those in reinforced concrete beams. However, the widths of cracks were smaller than the predicted values from the equation for conventional reinforced concrete beams

(4) It is necessary to introduce or alter a few factors in some empirical equations in order to reflect the difference among the fiber materials and configurations of FRP rods, since some of the existing equations could not evaluate the properties of FRP reinforced concrete beams acceptably.

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