論文 Flexural Failure Mode and Ultimate Moment of FRP Reinforced Concrete Beams after Sustained Loading

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ABSTRACT: The flexural behavior of FRP (Fiber Reinforced Plastic) reinforced concrete beams after sustained loading was investigated. Test results were compared with the non-loaded beams. No significant difference was found in flexural failure performance between two groups of beams. The tests also assured that conventional reinforcement factor could be applied to estimate the flexural failure mode of FRP reinforced beams.

KEYWORDS: FRP reinforcement, beam, deflection, crack, ultimate moment, flexural failure mode, sustained loading history

1 INTRODUCTION

The use of FRP materials in civil and architectural construction is booming in two fields of tensile reinforcement for new reinforced concrete members and repair or strengthening materials for existing structural members. To establish a reasonable design criterion, all the strength, ductility and durability of FRP reinforced members are research subjects.

It has been shown by experimental research that the flexural behavior of beams reinforced with FRP rods is similar in general to conventional beams reinforced with steel bars [1], [2]. However, the mechanical properties of FRP reinforcement are different from steel bars. The quantitative effects of these properties on ultimate moment as well as stiffness of beams need to be examined.

For example, FRP rods have various types of fiber materials and different surface configurations. Their module of elasticity do not keep constant but vary in a wide range. To estimate the stiffness of FRP reinforced members after cracking is one of problems.

Moreover, even in non-seismic area, designers also definitely avoid the brittle failure of structural members. FRP materials usually fail as brittle rupture without yielding in tension and have different performance between compression and tension. In the design of conventional reinforced beams, a ***reinforcement factor q*** is defined, as follow [3]:

$$q = p_t f_y / \sigma_B \tag{1}$$

where p_t: tensile reinforcement ratio,
f_y: yield strength of tensile reinforcement,
σ_B: compressive strength of concrete.

From the assumption of linear strain distribution and the equilibrium conditions of stress at the limit state, a critical reinforcement factor can be determined and used to design a suitable section to satisfy the requirements in both strength and ductility. But, a critical reinforcement

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factor for an FRP reinforced beam is not established yet. In particular, the difference between FRP reinforced members with and without sustained loading history is unknown. For answering these questions, sufficient experimental efforts are necessary.

This study aims to clarify the long-term flexural behavior of FRP reinforced beams and the primary influences on it. Here the experimental results of the beams with and without sustained loading history are presented. The load-deflection response, flexural failure mode and ultimate moment of the beams are discussed.

2 EXPERIMENTAL PROGRAM

2.1 TEST SPECIMEN DETAILS

The laboratory tests of 15 FRP reinforced beams and of two conventional reinforced beams have been carried out. The main parameters of these test specimens are listed in Table 1. All the tested beams except S02 were prepared in pairs. The specimens labeled by L experienced sustained loading for 43 weeks for L1, L4 and L7-L10 and for 41 weeks for L5 and L6. After unloaded, these beams were still laid in the laboratory for over seven weeks until destructive tests. Each of pair beams with the same rod number was separately classified as L-group or S-group. They were simultaneously manufactured with the same batch of concrete. The S-group beams were kept free from load in the same laboratory during the sustained loading of L-group beams.

The test beams were designed with the same length of 1545mm, having a rectangular cross section of 250mm overall depth and of 150mm width. The same type and the same number of bars were used as reinforcement at the top and bottom for each beam. High strength deformed steel bars were used as stirrup. Typical cross-sections of the beams are shown in Fig. 1.

2.2 MATERIAL PROPERTIES

The reinforcing bars in test beams included glass FRP rods (denoted as GF in Table 1), aramid FRP rods (denoted as AF), carbon FRP rods (denoted as CF) and deformed steel bars (denoted as SD). Those FRP rods had four types of surface configuration: spirally-wound

Table 1 The parameters of test specimens

Test specimen	Reinforcement				Rein-forcement ratio p_t(%)	Concrete			Reinforce-ment Factor q(%)
	Identifica-tion	Elastic modulus E(GPa)	Tensile strength f_t (MPa)	Diameter (mm) × number		Elastic modulus E_c(GPa)	Compres-sive strength σ_B(MPa)	Tensile strength f_{ct}(MPa)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
L1, S1	GF-S_P-8.9	46.7	1240	8×5	0.793	26.2	38.8	3.00	25.3
S02	AF-D-8	75.3	1360	8×2	0.305	33.1	22.8	2.61	18.2
L4, S4	AF-B-7.3	58.1	1775	7.3×4	0.532	25.6	41.8	2.60	22.6
L5, S5	CF-D-8	125.3	1730	8×2	0.305	23.4	36.8	2.59	14.3
L6, S6	CF-S_T-7.5	121.3	2210	7.5×3	0.276	24.2	36.0	2.67	16.9
L7, S7	CF-B-7.3	119.2	2360	7.3×3	0.381	27.2	41.8	2.86	21.5
L8, S8	CF-S_P-8.9	140.7	1690	8×3	0.458	24.1	36.3	2.52	21.3
L9, S9	CF_X-S_P-8.9	196.1	1460	8×3	0.458	24.2	36.5	2.72	18.3
L10, S10	SD345-13	196.3	699/493*	D13×3	1.17	25.6	37.1	2.74	15.6

* Yield strength of steel reinforcement

(denoted as S_P), braided (denoted as B), deformed (denoted as D) and strand (denoted as S_T).

The compressive strength of concrete was designed as 36.0MPa with mix proportion of Portland cement: river sand: crushed stone (13mm maximum size)=1: 2.24: 2.34 in weight. The water-cement ratio was 0.58. The beams of L-group were loaded at the age of about 4 weeks.

2.3 TEST SETUP AND INSTRUMENTATION

The loading and support configuration of most beam specimens in destructive tests is shown in Fig. 1, which is the same as that of sustained loading tests. A steel spreader was used to apply a concentrated load to the test specimen. Loading or support points consisted of two 200mm(length)×100mm(width)×19mm(thickness) steel plates and a steel roller of 40mm diameter between the two plates. As an alternative, in the tests of S7, S8, and S9 beams, one-point centrally loading was adopted to investigate the potential effect of loading condition.

Load was applied by a test machine of 750kN capacity with an overhead actuator, using the stroke-control mode. The deflections at midspan and loading points were measured on one side of the beam by displacement transducers. Strain gauges were attached to reinforcing rods to monitor the strain during the test. All the results were recorded automatically.

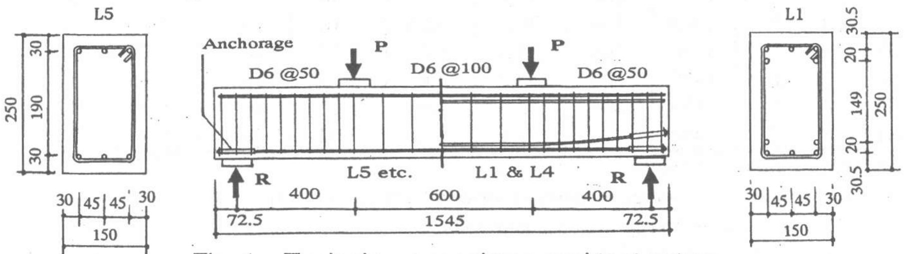


Fig. 1 Typical test specimen and test setup

2.4 LOADING SEQUENCE

A unidirectional cyclic loading was employed in the experiment. As shown in Fig. 2, the peaks of cycles were decided from load or midspan deflection, such as: (1) P_s, the experienced maximum load for L-group beams, or P_{cr}, the actual cracking load for S-group beams, (2) $P_{1/3}$, a third of calculated ultimate load $P_{u,cal}$, (3) $P_{2/3}$, two third of $P_{u,cal}$, (4) 2 $\delta_{2/3}$, two times of the midspan deflection at $P_{2/3}$, (5) 4 $\delta_{2/3}$ or final failure.

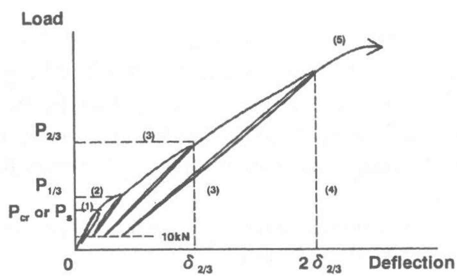


Fig. 2 Load cycles in test

3 FLEXURAL BEHAVIOR OF BEAMS

Experimental results are listed in Table 2, where the Columns (5) and (6) give the calculated results of tested beams by using the conventional beam theory. $M_{u,cal}$ is the ultimate moment calculated and $\sigma_{u,cal}$ is the stress of reinforcing bars under $M_{u,cal}$. In the calculation, an exponential expression proposed by Umemura was used for the stress-strain relationship of concrete, and a linear relationship was used for FRP rods.

Table 2 Experimental results of beams

Test specimen	Number of loading points	Overall span (mm)	Shear span (mm)	Calculated $M_{u,cal}$ (kN-m)	Calculated $\frac{\sigma_{u,cal}}{f_t}$	Experimental $M_{cr,exp}$ (kN-m)	Experimental $M_{u,exp}$ (kN-m)	$\frac{M_{u,cal}}{M_{u,exp}}$	Failure mode
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
L1	2	1400	400	37.7	0.67	5.32	46.6	0.81	CR
L4	2	1400	400	35.7	0.66	5.44	39.0	0.92	CR
L5	2	1400	400	35.4	1.0	5.96	35.5	1.00	R
L6	2	1400	400	38.6	0.95	5.16	40.7	0.95	R
L7	2	1400	400	48.3	0.81	5.44	50.7	0.95	CR
L8	2	1400	400	50.2	1.0	5.56	55.4	0.91	R
L9	2	1400	400	43.6	1.0	5.56	55.5	0.79	R
L10	2	1400	400	37.5	1.0	5.32	39.0	0.96	R_Y
S1	2	1400	400	37.7	0.67	5.90	46.2	0.82	CR
S02	2	1400	400	28.1	1.0	3.04	27.6	1.02	R
S4	2	1400	400	35.7	0.66	6.46	38.7	0.92	CR
S5	2	1400	400	35.4	1.0	4.30	36.8	0.96	R
S6	2	1400	400	38.6	0.95	4.16	38.0	1.02	R
S7	1	1400	700	48.3	0.81	6.72	46.4	1.04	CSR
S8	1	1400	700	50.2	1.0	5.39	58.5	0.86	R
S9	1	800	400	43.6	1.0	5.00	56.7	0.77	SR
S10	2	1400	400	37.5	1.0	3.02	38.0	0.99	R_Y

Note for Failure modes:

1 CR: failure in concrete crushing followed by rupture of rods
2 R: failure due to rupture of tensile rods
3 R_Y: yielding of steel bars
4 CSR: failure in concrete crushing and shear followed by rupture of rods
5 SR: failure in shear followed by rupture of rods

3.1 CRACK DEVELOPMENT

All the tested beams exhibited a similar crack pattern and crack development process, as shown in Fig. 3. Initially one or two cracks always occurred in the central flexural span during P=15-32kN or M=3.0-6.5MPa. Then, other flexural cracks up to 6-8 in total number developed in the flexural span. Approximately same number of cracks occurred in the central part under one-point loading. The average spacing between flexural cracks appeared to be about 100mm in all the beams.

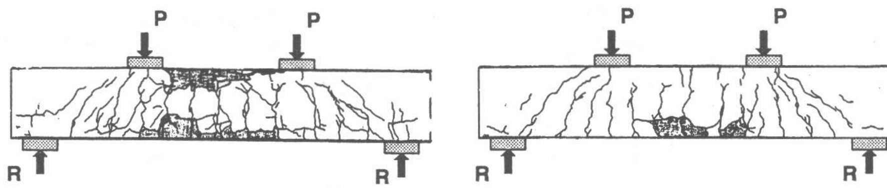
No difference was observed between L-group and S-group on characteristics of cracks under loading beyond P_{cr} or P_s in Fig. 2.

3.2 FAILURE MECHANISM

Two failure modes were mainly observed in the tests of FRP reinforced beams. One was rupture of tensile reinforcing rods, which could be observed in the right case of Fig. 3 and named R-mode, and the other was crushing of concrete followed by the rupture of rods, which was showed in the left case of Fig. 3 and named CR-mode.

R-mode was brittle failure without warning. The rupture of tensile rods started from one or two rods. If load was kept on, all the other rods would rupture in a short moment. The beam broke in two parts, which were only linked by the rod and concrete in the compressive zone.

CR-mode was slightly mild failure. It began with the breaking of concrete cover in the compressive zone and went into crushing in a wide area, although load could still be maintained.



(a) Beam L4, failed in CR-mode (b) Beam L9, failed in R-mode

Fig. 3 Crack patterns and failure zones of tested beams

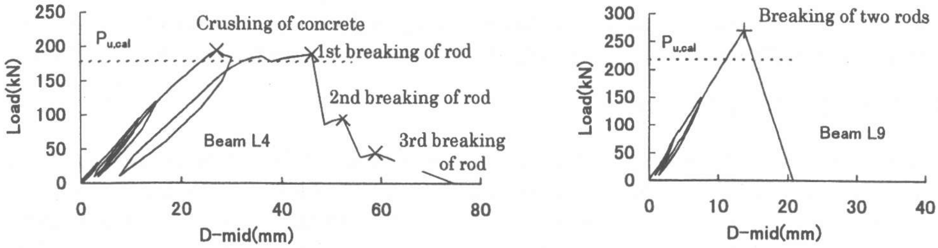


Fig. 4 Load-versus-deflection responses

The crushing of outer layer concrete caused the neutral axis to move so down that the stresses of tensile rods increased. Finally, it leaded to the rupture of the rods.

In the tests of S7 and S9 beams under one-point loading, the propagation of shear cracks was clearly observed when the beams approached final failure.

3.3 LOAD-DEFLECTION RESPONSE

Two typical load-deflection curves of FRP reinforced beams are shown in Fig. 4, which demonstrate the difference of the flexural responses between the beams failed in CR-mode and R-mode. Due to the non-plastic behavior of FRP reinforcement, the beams reinforced with FRP are apt to fail in a brittle way. However, like the case of L4, considerable ductile deformation can develop during concrete crushing prior to the rupture of rods.

4 DISCUSSION OF TEST RESULTS

4.1 FLEXURAL FAILURE MODE

The beams of L1, S1, L4, S4, L7 and S7 failed in CR-mode. It is found from Table 1 that the reinforcement factors q of eq.(1), substituting the tensile strength f_t of FRP rods for f_y, are more than 21.5%, while those of all the other beams failed in R-mode are smaller than 18.5% except for L8 and S8. In fact, concrete crushing had been substantially occurred in L8 beam prior to rupture of rods. It can be seen that the reinforcement factor q is an important indicator to estimate the failure mode of FRP reinforced beams.

According to Table 2, the stress-intensity calculation of tested beams could provide successful prediction on the failure mode of FRP reinforced beams. That is, in the column (6) of Table 2, the calculated stresses of tensile reinforcement at the ultimate moment of the beams failed in CR-mode were far smaller in than their tensile strength.

4.2 ULTIMATE MOMENTS OF BEAMS

Experimental results of all pair beams showed that the FRP reinforced beams experienced sustained loading had approximately same ultimate moments as those freshly loaded beams.

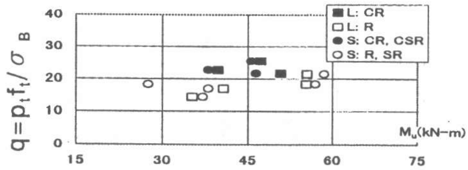


Fig. 5 Ultimate moment versus Reinforcement factor

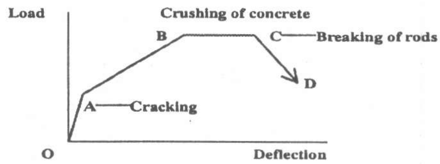


Fig. 6 A load-deflection relationship model

Also, the calculated ultimate moment of tested beams agreed well with the experimental results. The average ratio of the calculated to the experimental moment of all the beams was 0.905.

4.3 DEFLECTION OF BEAMS

The load-deflection relationship of concrete beams reinforced FRP rods can be simulated by a poly-linear curve (Fig. 6). It was clear from experimental results that sustained loading had no effect on the ultimate deflection of beams. The load-deflection path of the freshly-loaded beam took the route of O-A-B-C-D, while that of the beam with sustained loaded history tended to go through O-B-C-D. It should be noted that the both types of curves include the line B-C, which means properly-designed FRP reinforced beams have certainly moderate deformation before its final failure.

5. CONCLUSIONS

The following summaries are obtained from the experimental results of this study:

(1) Sustained loading history had no significant effect on the flexural failure behavior of FRP reinforced concrete beams.

(2) All the FRP reinforced beams ultimately failed in the sudden rupture of tensile reinforcing rods. However, in the case that failure was CR-mode, the beam could behave ductile, following the crushing of concrete.

(3) Conventional reinforcement factor $q=p_tf_t/\sigma_B$ could be applied to estimate the failure mode of FRP reinforced beams. Further, conventional flexural calculation of the beam could give a good prediction about the flexural behavior of these beams.

(4) The load-deflection relationship of FRP reinforced beams could be described by a poly-linear curve.

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