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Flexural Fatigue Behavior of Concrete Beam with FRP Reinforcement

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Reprinted from

Transactions of the Japan Concrete Institute 1987

FLEXURAL FATIGUE BEHAVIOR OF CONCRETE BEAM WITH FRP REINFORCEMENT

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ABSTRACT

The FRP reinforcement has recently been developed to resist corrosion and chemical attack, where longitudinal bars and stirrups were formed in one body. In this study, concrete beams with this FRP reinforcement were tested to clarify the effect of FRP reinforcement on their flexural fatigue behavior . According to the test, stirrups provided bond and anchorage to concrete for longitudinal bars and the fatigue strength of FRP reinforcement was equal or superior to that of the equivalent deformed steel bar which has the same static tensile capacity.

1. INTRODUCTION

Recently, reinforced concrete structures have been seriously deteriorated by corrosion of reinforcing steel bars. As a basic solution of this problem, FRP(Fiber Reinforced Plastics) reinforcement, which has a good resistance against corrosion and chemical attack, has been developed for concrete structures in place of steel bars(1,2).

This FRP reinforcement has characteristics as follows; (a) requested strength, Young's modulus and elongation at failure can be obtained with combination of different properties of continuous fibers and (b) the bond strength of monolithic bar is small, while the cross points of grids are sufficiently anchored to concrete.

And some report(3) showed that the fatigue property of FRP was different from that of a homogeneous material such as metal. Then, the fatigue behavior of concrete beams with FRP reinforcement as well as the static behavior should be clarified especially in case of being subjected to repeated loading such as a traffic load.

In this study, FRP reinforcement where longitudinal bars and stirrups were formed in one body was applied for concrete beams. Then static and fatigue tests of the concrete beams were carried out and the effect of the property of FRP reinforcement on their static and fatigue behavior was discussed.

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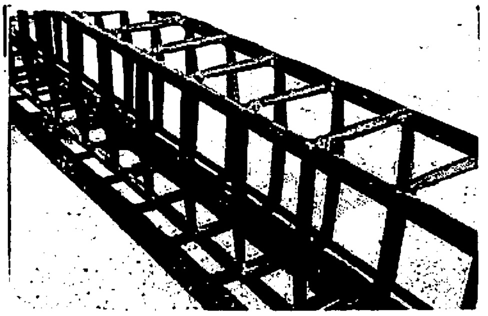

Fig.1 FRP reinforcement

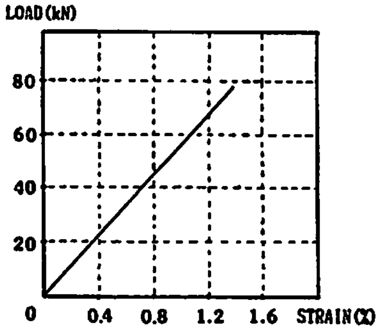

Fig.2 Load-strain relation of longitudinal bar

Table 1 Property of FRP reinforcement

	NF		VF	Af	Tfu	ε fu	Ef
	glass R2220	carbon HTA-7-12000	(%)	(cm²)	(kN)	(%)	(GPa)
longitudinal bar	48	24	25.5	2.071	78.6	1.36	27.1
stirrup	26	13	25.5	1.122	(42.6)	(1.36)	(27.1)

NF: number of fibers
VF: fiber content
Af: cross sectional area
Tfu : ultimate tensile capacity
ε fu: ultimate strain
Ef : Young's modulus
note) Mechanical property of stirrup was assumed according to the tension test result of longitudinal bar.

2. OUTLINE OF EXPERIMENT

2.1 MATERIALS AND SPECIMENS

FRP reinforcement consists of continuous glass and carbon fibers impregnated with resin and is formed in one body by the filament winding method (see Fig.1). Its strength at the cross point of grids is secured enough so that stirrups sufficiently provide bond and anchorage to concrete for longitudinal bars.

The property of FRP reinforcement used is listed in Table 1 and the load-strain relation of longitudinal bar is shown in Fig.2.

Ten specimens were tested; two of them were statically loaded and the other eight were for fatigue loading. The detail of specimen is shown in Fig.3. Concrete was placed with the use of high early strength portland cement and the maximum size of aggregate was 25mm. The compressive strength of concrete cylinder was 39.4MPa and the modulus of elasticity was 30.4GPa.

2.2 TESTING PROCEDURE AND MEASUREMENTS

As shown in Fig.3, test specimens were loaded with 120cm of span. In static test, load was increased gradually to failure with the measurement of deflection and strain of longitudinal bar and concrete together with the observation of crack propagation. In fatigue test, load was applied statically duringfirst two cycles and then repeated loadihg was performed using a pulsator with a frequency of 200 cycles per minute . Repeated loading was sometimes stopped and static loading was carried out so as to check the flexural rigidity of the beam and measure crack width with a contact gage or a π gage. Crack width was defined as an elongation of 10cm of concrete at the location of the bottom longitudinal bar.

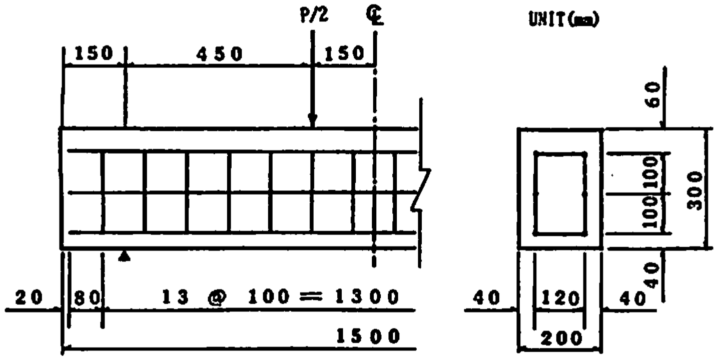

Fig.3 Specimen and loading system

3. RESULTS OF STATIC TEST AND DISCUSSION

Test results and observed cracks are shown in Table 2 and Fig.4 respectively.

3.1 CRACK PROPAGATION AND FAILURE MODE

Most flexural cracks propagated along stirrups and the maximum spacing of cracks was about 20cm, which was equivalent to the double spacing of stirrups. And cracks extended upward more than that of concrete beams with steel bars.

In specimen NS-1, two bottom longitudinal bars failed at the cross point with the stirrup near the crack in the constant moment region and the concrete in the compression zone was crushed at the same time. The failure load agrees with the calculation, 226kN, on the assumption that tensile stress in concrete is ignored and that the beam ruptures when the strain of the bottom longitudinal bars reaches the ultimate strain while the top and middle ones remain elastic.

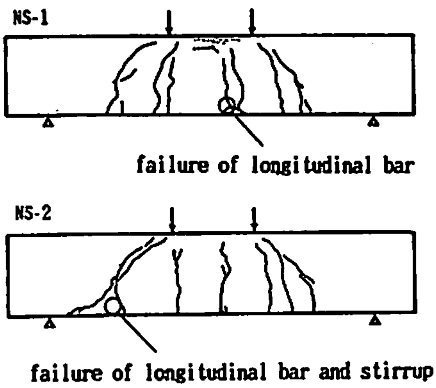

Fig.4 Observed crack after static test

Table 2 Results of static test

SPECIMEN	load at flexural cracking (kN)	load at diagonal cracking (kN)	ultimate load Pu (kN)	failure mode
NS-1	34.3	88.3	234	failure of longitudinal bar in the constant moment region
NS-2	29.4	98.1	225	failure of longitudinal bar and stirrup in the shear span

On the other hand, in specimen NS-2, shear failure occurred due to failure of the stirrup and the bottom longitudinal bar at the same cross section near the diagonal crack in the shear span. The shear capacity calculated on the assumption of truss analogy (according to Reference 4) is about 470kN, which is twice greater than the experimental result.

Thereason is considered as follows; the shear capacity by concrete in the compression zone reduced due to high position of neutral axis, the shear capacity by aggregate interlock decreased due to wide diagonal crack and the shear capacity by dowel action of longitudinal bar was lessened due toits smallstiffness. Then,the calculated shear capacity assumedto be carried only by stirrups is about 382kN, which is still larger than the measured ultimate shear capacity. This is because stirrups are bent at a right angle at the cross points with longitudinal bars and local bending stress occurs at the corner of stirrups. Then it leads to the reduction of the ultimate tensile capacity of stirrups.

3.2 LOAD-STRAIN RELATION

The relations between load and strain of the bottom longitudinal bar and the concrete of the edge of compression zone in the constant moment region are shown in Fig.5. They agree with the calculations by the elastic theory assuming effective cross sectional area before appearance of a flexural crack and neglecting tensile stress in concrete after that.

It indicates that FRP reinforcement is sufficiently anchored to concrete at the cross points of grids. The flexural theory can be, therefore, applied to this type of concrete beams as well as steel reinforced concrete beams.

Compared with a steel reinforced concrete beam, the lower stiffness of FRP reinforcement leads to higher location of neutral axis, lower flexural rigidity of the beam and larger stress of the bottom longitudinal bar after initial flexural cracking.

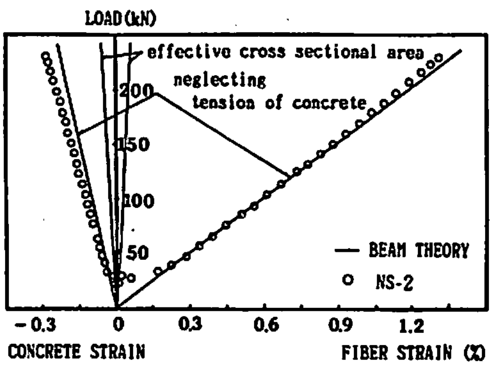

Fig.5 Load-strain of longitudinal bar and concrete relation

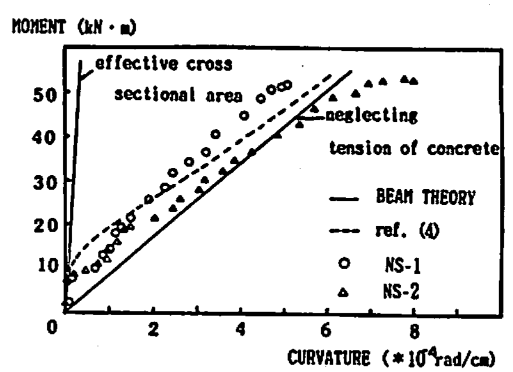

Fig.6 Bending moment-curvature relation

3.3 BENDING MOMENT-CURVATURE RELATION

The bending moment-curvature relation which was computed with the displacements at the center of span and two loading points is shown in Fig.6. Since the curvature varied with the number of cracks in the measured range, there is some difference of the results between two specimens, NS-1 and NS-2. It can be seen that the measured curvature in specimen NS-2 is followed by the calculation on the assumption that total cross sectional area is effective before flexural cracking and that tensile stress in concrete is ignored after cracking. The dotted line in Fig.6 shows the calculation according to Reference 4.

3.4 LOAD-DEFLECTION RELATION

Fig.7 shows the load-deflection relation at the center of span. It can be noted that the experimental results agree with the calculation by the elastic theory in which total cross sectional area is effective before flexural cracking and approach the calculation by the beam theory in which tensile stress in concrete is ignored after cracking. After appearance of diagonal crack, however, the measured deflection becomes larger than the calculated one because of the assumption that shear deformation of the beam is neglected.

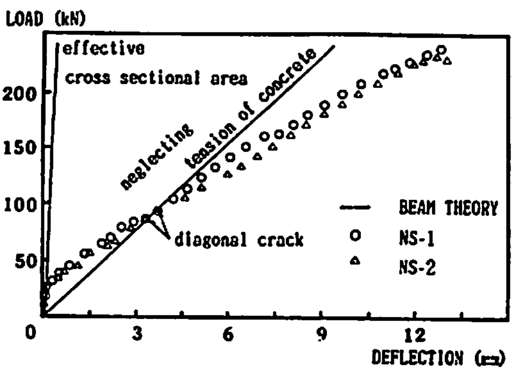

Fig.7 Load-deflection relation

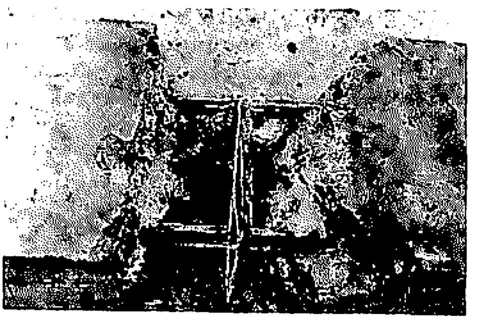

Fig.8
Fatigue failure of longitudinal bar (NC-1)

4. RESULTS OF FATIGUE TEST AND DISCUSSION

The main results of fatigue test are listed in Table 3. Though they varied, the failure of all specimens was caused by fatigue failure of the bottom longitudinal bars in the constant moment region (see Fig.8) or that of the longitudinal bars and stirrups in the shear span. The rupture of FRP reinforcement occurred at the cross points of longitudinal bar and stirrup near cracks.

Table 3 Results of fatigue test

SPECIMEN	maximum load P_{max} (kN)	$\frac{P_{max}}{P_u}$	$\frac{T_{fmax}}{T_{fu}}$	cycles to failure N (cycles)	failure position of FRP reinforcement (*)
NC-1	122	0.519	0.517	$1.43*10^6$	bottom longitudinal bar (M)
NC-2	147	0.627	0.620	$8.53*10^4$	bottom longitudinal bar (M)
NC-3	134	0.573	0.569	$>2.81*10^6$	not failed
NC-4	141	0.602	0.594	$4.50*10^4$	longitudinal bar and stirrup (S)
NC-5	141	0.602	0.594	$1.30*10^5$	bottom longitudinal bar (M)
NC-6	129	0.547	0.543	$1.78*10^6$	bottom & middle longitudinal bar (S)
NC-7	129	0.547	0.543	$1.68*10^5$	longitudinal bar and stirrup (S)
NC-8	122	0.519	0.517	$7.53*10^5$	bottom longitudinal bar (M)

Pu: ultimate flexural capacity (= 234kN)
Tfmax: tensile force of bottom longitudinal bar at the maximum load
Tfu: tensile capacity of bottom longitudinal bar (= 78.6kN)
Pmin (minimum load) = 18.1kN
Tfmin (tensile force of bottom longitudinal bar at the minimum load) = 8.53kN
*) M: in the constant moment region, S: in the shear span

4.1 CRACK WIDTH

Most flexural cracks propagated along stirrups and few between stirrups. Fig.9 shows that the width of crack between stirrups corresponds to the elongation of the bottom longitudinal bar between two stirrups (10cm) and the width of crack along a stirrup corresponds to that between the double spacing of stirrups (20cm). This behavior proves that FRP reinforcement is sufficiently anchored to concrete at the cross points of grids.

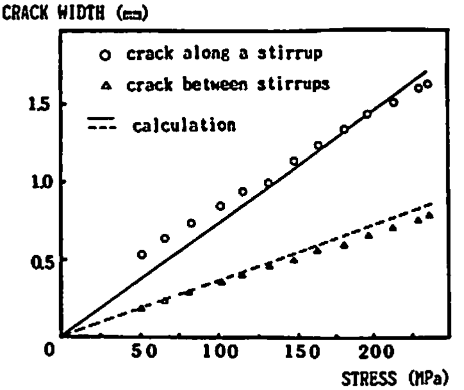

Fig.9 Crack width-stress of bottom longitudinal bar relation

The hysteresis curves of crack width during loading and unloading in the constant moment region and shear span are shown in Fig. 10 (a) and (b) respectively.

It can be seen that the hysteresis curve of crack width in the shear span encloses larger area than that in the constant moment region. The area becomes small with the increase of loading cycle.

This is considered to be caused by shear displacement along the crack in the shear span. Therefore, the crack in the shear span is more difficult to be closed in unloading than that in the constant moment region, and also the crack surface is heavier to be damaged during repeated loading, which results in the gradual increase of crack width in the shear span (see Fig.11).

4.2 FATIGUE STRENGTH OF FRP REINFORCEMENT

Fig.12 shows the relation between tensile force of the bottom longitudinal bar at the maximum load and cycles to failure of the beam. Since quantity of resin has a small effect on the tensile load-strain relation of FRP reinforcement, the cross sectional area including resin is not effective on the calculation of the stress of FRP reinforcement. It is, therefore, better to represent the fatigue property of FRP reinforcement with tensile force or strain than with stress.

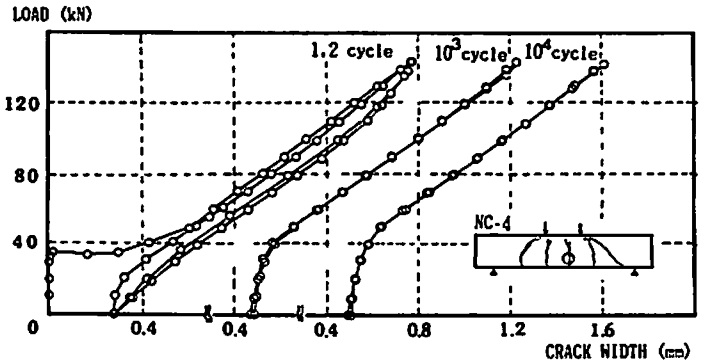

Fig.10(a) Load-crack width relation
(in the constant moment region)

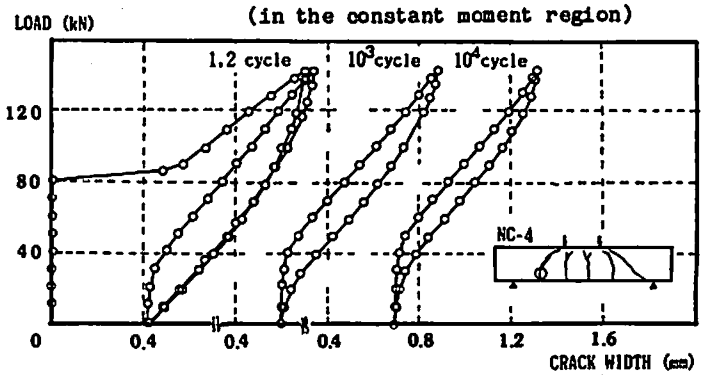

Fig.10(b) Load-crack width relation
(in the shear span)

In this study, the equivalent steel bar which has the same ultimate tensile capacity as longitudinal FRP bar is considered in order to compare the fatigue strength of FRP reinforcement with that of deformed steel bar. Its diameter is calculated to be about 15.1mm for SD30 type and about 14.3mm for SD35 type. The fatigue strength of those bars computed according to Reference 4 are given by solid and dotted lines in Fig.12. It can be seen that FRP reinforcement has a little greater fatigue strength than deformed steel bars.

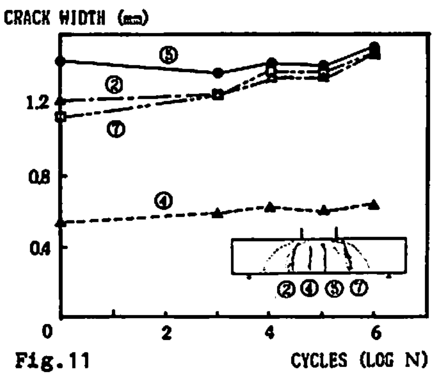

Fig.11
Crack width at the maximum load -cycles relation

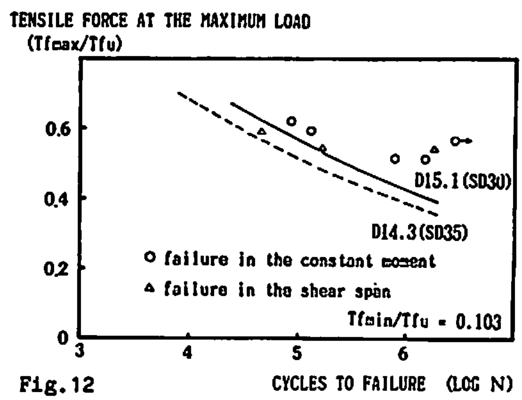

Fig.12
Fatigue strength of FRP reinforcement

The fatigue failure of longitudinal FRP bar occurred at the cross point with stirrup due to stress concentration caused by rapid change of reinforcement sectional area. Therefore, the fatigue property of FRP reinforcement will change if stirrup spacing or the shape of the cross point with stirrup varies.

FRP reinforcement is made of composite material which consists of glass fiber, carbon fiber and resin having various Young's modulus and tensile strength. Therefore, its fatigue mechanism will be complicated. It is necessary to accumulate further data with various parameters such as stirrup spacing and combination of glass and carbon fibers.

5. CONCLUDING REMARKS

Experimental study on the flexural fatigue behavior of concrete beam with FRP reinforcement was carried out and the following conclusions were derived .

(1) Though the bond strength of monolithic bar is small, FRP reinforcement is sufficiently anchored at the cross points of longitudinal bar and stirrup. Therefore, the flexural beam theory can be applied as well as to steel reinforced concrete beams.

(2) Most flexural cracks propagated along stirrups and the crack width at the location of the bottom longitudinal bar corresponded to the elongation of the bar between double spacing of stirrups. The crack showed larger width than that of steel reinforced concrete beams because of lower Young's modulus of FRP reinforcement.

(3) The failure of FRP reinforcement occurred at the cross point of grids near cracks in static and fatigue loading. It is considered to be caused by stress concentration due to rapid change of cross sectional area of FRP bar.

(4) The fatigue strength of FRP reinforcement was shown to be greater than that of the equivalent deformed steel bar which has the same ultimate tensile capacity. And further accumulation of data with such parameters as stirrup spacing and combination of glass and carbon fibers should be carried out in future.

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