研 究 速 報

UDC 624.012.454 : 677.53 : 669.14

# Study on Reinforced Concrete Members Using Fiber Reinforced Concrete (6)

# 繊維補強鉄筋コンクリート構造部材に関する研究 (6)

## ——Fatigue Failure of Reinforced Concrete Beams——

Taketo UOMOTO, Tsugio NISHIMURA and Ranjan Kumarasiri WEERARATNE

魚本健人・西村次男・ランジャン K. ウィーララタナ

### Introduction

By addition of short fibers into a concrete mix, the overall strain at failure of the composite can be increased considerably. The inclusion of fibers tends to increase the strain capacity, changing the toughness or ductility of a concrete structure. Experimental evidences (1,2) are available to say such fibers can restrict the propagation of cracks by a bridging mechanism. Hence using fiber reinforced concrete (FRC) in reinforced concrete members, there is a prospect of increasing the apparent strain at failure prolonging the fatigue life when a structure is subjected to repeated loading.

Although factors which influence the fatigue behavior of plain reinforced concrete (concrete without any fibers: RC) and the manner in which they fail are well documented ( 3 ), there is very little evidence so far on the fatigue performance of FRC structural elements. T. Ito et al ( 4 ) indicate substantial improvements in fatigue life of steel fiber reinforced concrete (SFRC), when compared with ordinary plain concrete. However these conclusions were based on direct compression tests performed on standard cylinders. If fatigue cracking is going to occur in concrete structures, it is more likely to be due to repeated flexure than to direct tension or compression. A simple flexural test is probably the most useful type of test for the study of fatigue behavior of concrete structures. Results, and discussions presented in this report are therefore based on SFRC and plain RC beams subjected to repeated loading in flexure.

* Dept. of Building and Civil Engineering, Institute of Industrial Science, University of Tokyo.

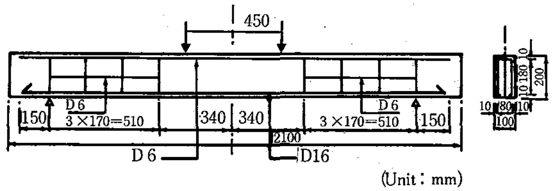


Fig. 1 Details of beams tested under fatigue loading

### 1. Outline of Experiment

Ordinary Portland cement was used in all specimens and the aggregates were well graded river sand and gravel which meet the requirements of JIS. The coarse aggregate had a maximum nominal size of 15 mm, specific weight of 2.71 and F.M. of 6.33. The fine aggregate had a specific weight of 2.62, F.M. of 2.79 and absorption of 1.56%.

The details of the beams in the study are as shown in Fig. 1. The reinforcing steel bars used were SD 30, which have a yield stress of 3655 kgf/cm$^2$. Steel fibers used were cut-wire type having a diameter of 0.5 mm and length 30 mm. The steel fiber content was 1.5% by volume and water-cement ratio of concrete was 0.5. Test specimens, cylinders and control beams remained in the forms for 24 hours and were then moist cured for a period of 4 weeks before removal to storage in normal laboratory atmosphere until tested. Fatigue tests were performed at the age of 20 weeks to 24 weeks.

All specimens were simply supported on 170 cm span and subjected to repeated loads of varying range and magnitude (Ref. Fig. 2). The central portion of the test specimen was thus subjected to pure flexure. The range of the repeated loads were varied sinosuidally throughout the investigation. The varia-

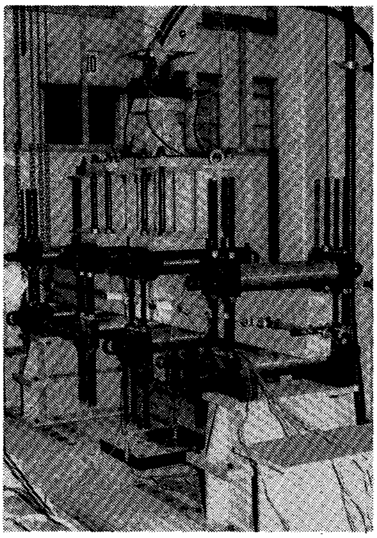

Fig. 2 Loading of beams by hydraulic loading machine

tion within each test was to maintain a constant minimum load of 1 ton. Failure of the beams or automatic stopping of the machine will occur when the deflection of the beam is increased by 5 mm or when the maximum load level becomes 5% of the applied load.

## 2. Results and Discussions

### 2.1 Failure Mode of Beams

Both SFRC and plain RC beams are provided with the same amount of steel bars. RC beams were designed so as to fail in pure flexure under static loading. The strength of beams under static loading are shown in Table 1. The calculated yield loads and maximum loads are almost equal to the tested values.

Almost all the SFRC beams tested under repeated loading failed by compression fatigue of concrete in the maximum moment region. In all cases, initially these beams developed large number of distributed tensile cracks. Crack formation was within 1000 cycles, beyond which the crack propagation was very small. Opening and closing of cracks were observed, and during fatigue loading only the widths of these cracks became large.

Although RC beams failed in pure flexure in static loading, all the plain RC beams failed in shear compression failure under fatigue. The cracks that appeared during initial loading, changed to a shear

Table 1 Results of static loading series

| Type | Yield Load | Max Load | Center Deflection (mm) | | Jack Stroke (mm) | |
|---|---|---|---|---|---|---|
| | $P_y$ (ton$f$) | $P_{max}$ (ton$f$) | at $P_y$ | at $P_{max}$ | at $P_y$ | at $P_{max}$ |
| SFRC | 8.1<br>(8.0)* | 10.10<br>(9.0)* | 6.00<br>6.00<br>5.78 | 30.00 | 1.69 | 5.75 |
| Plain | 7.4<br>(7.4)* | 8.49<br>(8.2)* | 5.78 | 20.5 | 1.64 | 4.20 |

( )* Calculated value $f_c'$(SFRC) =515 (kgf/cm$^2$)
$f_c'$(Plain) =500 (kgf/cm$^2$)

type of crack pattern with the increase in repeated loading. Finally when the beams failed by shear, it was observed that in most cases stirrups were broken and main reinforcements were bent where the stress concentration is highest.

On the contrary, SFRC beams did not show this kind of failure; all the beams failed in flexural compression. From the data obtained, it appears that addition of steel fibers have beneficial effects because of their higher endurance limit or higher fatigue strength. Also, it can be seen that the fibers have changed the mode of failure of the beams under repeated loading from rather brittle shear failure to flexural failure.

### 2.2 Effect of Load Level on Fatigue Properties of Beams

Fatigue tests of beams of both SFRC and RC were conducted with a range of load from 4.4 to 9.5 tons, and the results are presented in Figs. 3 and 4 in the forms of load vs logarithm of number of cycles and S-N curve respectively.

As shown in Fig. 3, steel fibers have not only improved the failure mode but also have extended the fatigue life of beams considerably. However, comparison of the fractured cycles of plain RC beams and SFRC beams at the same load level can not be done, as the mode of failure was different.

Two straight lines are indicated for both SFRC and plain RC beams as shown in Fig. 3 and 4. The upper line with a lower slope corresponds to maximum load level higher than the yield load of the beam. This failure might have been due to excessive deformation of steel bars which had caused larger deformations in the beams. Therefore number of cycles till failure was within $1\times10^5$. In observing the beams, it was also noted that no compression fatigue failure of concrete had occured.

When the maximum repeated load is lower than the yield value, failure of the plain RC beams was governed by shear compression failure of concrete, and the failure of SFRC by compressive fatigue of SFRC. Beams which were subjected to loads below 50% of static strength, fracture did not occur for both plain RC and SFRC beams.

**2.3 Load Deflection Curves after Fatigue Test**

In order to verify the state of beams after fatigue failure had occured, beams were again loaded statically up to failure and load deflection curves were obtained. Column (7) of Table 2 gives the maximum loads of plain RC beams and SFRC beams under static tests after fatigue failure has occured.

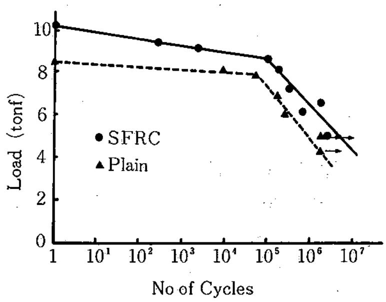


Fig. 3 Load vs number of cycles for SFRC and plain RC beams

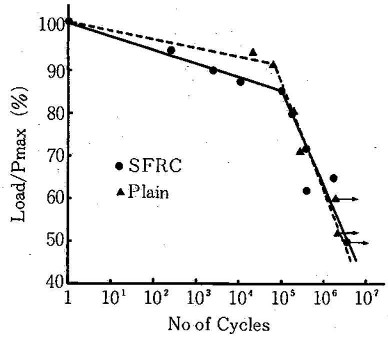


Fig. 4 Load ratio vs number of cycles for SFRC and plain RC beams

Table 2 Results of dynamic loading series

| Type | Load $P$ (ton $f$) (1) | $P/P_{max}$ (%) (2) | $f_c$ (kgf/cm²) (3) | $f_c/f_c'$ (%) (4) | $\sigma_c$ (kgf/cm²) (5) | $\sigma_c/f_c'$ (%) (6) | $P_{max}'$ (7) | $N$ (×10⁴) (8) | $\text{Log}_{10}(N)$ (9) | Failure mode (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| SFRC ($V_f$=1.5%) | 5.0 | 49.5 | 250 | 48.5 | 198 | 38.5 | 9.72 | >223.23 | 6.348 | – |
| | 6.2 | 61.4 | 301 | 58.4 | 243 | 47.2 | 5.58 | 67.2 | 5.83 | F.C |
| | 6.5 | 64.4 | 316 | 61.0 | 255 | 49.5 | 6.0 | 186.0 | 6.269 | F.C |
| | 7.2 | 71.3 | 344 | 66.0 | 281 | 54.5 | 5.9 | 37.4 | 5.57 | F.C |
| | 8.1 | 79.2 | 379 | 73.6 | 314 | 61.0 | 5.88 | 18.23 | 5.26 | F.C |
| | 8.6 | 85.2 | 400 | 77.7 | 362 | 70.0 | 5.8 | 10.35 | 5.015 | F.C |
| | 8.8 | 87.2 | 408 | 79.2 | 394 | 76.6 | 9.35 | 1.204 | 4.08 | F.C |
| | 9.1 | 90.14 | 485 | 94.0 | 462 | 89.7 | 9.6 | 0.256 | 3.4 | F.C |
| | 9.5 | 94.1 | 514 | 99.8 | 489 | 95.0 | – | 0.030 | 2.47 | F.C |
| Plain ($V_f$=0%) | 4.4 | 51.8 | 197 | 39.4 | – | – | – | 206.306 | 6.31 | S.C |
| | 5.1 | 60.0 | 226 | 45.2 | – | – | – | 220.73 | 6.34 | S.C |
| | 6.0 | 70.6 | 270 | 54.0 | – | – | – | 26.31 | 5.42 | S.C |
| | 6.8 | 80.0 | 300 | 60.0 | – | – | – | 21.43 | 5.33 | S.C |
| | 7.8 | 91.8 | 330 | 66.0 | – | – | – | 5.73 | 4.758 | S.C |
| | 8.0 | 94.2 | 347 | 69.4 | – | – | – | 18.74 | 4.273 | S.C |

$f_c'$ : Concrete maximum strength. $P_{max}$ : Max load by static loading F.C. : Flexural Compression
$\sigma_c$ : Effective concrete stress $P_{max}'$ : Max. load after fatigue. S.C. : Shear Compression

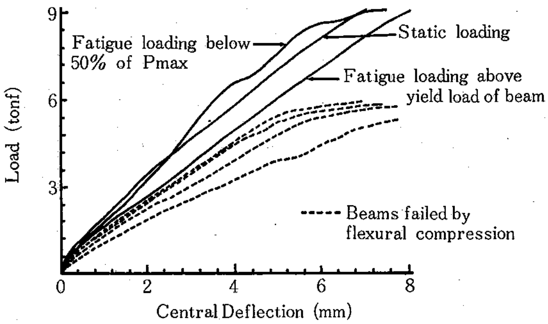


Fig. 5 Load deflection curves of SFRC beams after fatigue loading

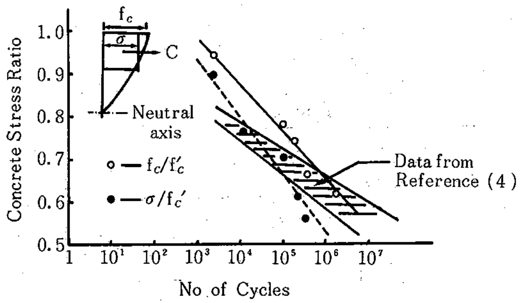


Fig. 6 Stress ratio of SFRC vs number of cycles

SFRC beams, which were loaded to maximum repeated from 6.2 to 8.6 tons, gave almost an equal maximum load of 6 tons. This is because as explained in the earlier section that these beams failed by compressive fatigue of concrete, and all the beams seems to be in the same state after failure. In fact, load deflection curves of all the 5 beams were almost the same (Ref. Fig. 5). SFRC beams which were loaded from 8.8 to 9.5 tons gave a maximum load of around 9.5 tons; showing only a very small reduction in ultimate strength of beams. This is because concrete in the compression zone has not failed due to fatigue, and failure was governed by excessive steel deformation. Therefore maximum strength after fatigue failure did not reduce much. In the case of the beam which was loaded to 5 tons, load deflection curve is almost the same as initial curve. In this case, stiffness of the beam was higher than that of the original beam.

Plain RC beams did not show this kind of behavour. After the beams failed under fatigue, they could not be loaded again. This means that in the case of SFRC beams though the progressive cracking has occured due to fatigue, they can withstand farely high load when they are subjected to static loading.

**2.4 Comparison of Fatigue Life of SFRC Beams with Direct Compression Fatigue Results**

Fig. 6 was obtained by plotting the concrete stress ratio, obtained from the maximum operating stress in the compression region to static strength, with the logarithm of number of cycles. The data obtained by Ito et al (4) for direct compression fatigue tests on cylinders were also plotted in the same figure. The difference in results may be due to the inaccuracy of the compressive stress assumed. In actual situation, a strain gradient exists across the depth of the beam and this situation does not arise when obtaining the fatigue data from cylindrical concrete specimens. In order to compare the results, consideration must be given to the strain gradient of beams.

Such analysis was performed for all SFRC beam data based on an effective stress in compression zone of the beam. This stress, denoted by ● in Fig. 6, was calculated considering equilibrium conditions. When this stress is used in plotting, the line obtained seems to fall closer to the cylindrical specimen data. Difference in results may be due to the following reasons. Firstly, although beams were assumed to have failed, the state of crushing of concrete in the compression zone may be not the same as actual crushing that had occured in obtaining the data for cylindrical specimens. Secondly, the data available is limited. Therefore conclusions cannot be drawn from the figure. It should be mentioned that further data, where the beams actually failed by crushing of concrete in the compression zone is needed to clarify the method of predition of fatigue life of SFRC beams from cylindrical specimen data.

(Maunscript received, September 25, 1984)

**References**

1) D. J. Hannant: Fiber Cements and Fiber Concrete, A Wiley Interscience Publication, 1978.
2) Kitisak Visalvanich and Antonie E. Naaman: Fracture Model for Fiber Reinforced Concrete, ACI Journal, Technical paper, Title No. 80-14
3) Genne M. Nordby: Fatigue of Concrete -A review of Research-, A Symposium Sponsored by ACI committee 215, Title No. 55-11
4) T. Ito, K. Kobayashi and T. Nishimura: Compressive Fatigue Tests on SFRC, Annual Meeting of JSCE, Oct., 1976.