A Study on the Fatigue Strength Behavior of Reinforced Concrete Structures

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SYNOPSIS

Design methods for shear have been developed in these days. However, these are mainly based on the test results under static loading, and there are few information concerning the shear behavior of reinforced concrete beams under repeated dynamic loading.

From this point of view, this study was performed to investigate the shear behavior of four reinforced concrete beams with web reinforcement under repeated dynamic loading. From these test results, the changes in strain of stirrups and the crack propagation procedures are found as functions of the number of repeated loading cycles. These results are compared with the existing experimental formula for predicting strain of stirrups under repeated loading and also used to find the coefficients in the empirical formula using the regression technique.

1. INTRODUCTION

Lately, the study on the mechanical behavior of reinforced concrete structures have been accomplished under the various loading conditions, and the design methods for shear are revised by the active researches on the shear behavior of reinforced concrete structures. However, these researches were almost based on test results under static loading, and few tests and studies on shear behavior under dynamic loads including repeated load or moving load were performed.

Change and Kesler (Chang et al, 1958) reported that there are four modes of fatigue failure of reinforced concrete beams which are dependent on steel ratio, shear span to depth ratio, concrete strength, and magnitude of repeated load. They also reported that under low magnitude of repeated load beams are in the flexural failure mode while under high magnitude repeated load the shear failure modes are occurred. Kaar and Mattock (Kaar et al, 1963) reported that the stirrup strains increased approximately 40 percent with 1-million cycle loading at working stress level. Price and Edwards (Price et al, 1971) observed that in their prestressed concrete beams fatigue fracture of the stirrups took place at some distance from the diagonal cracks, and also reported that little changes in strains were found during 1,000 cycles of loading in spite of the considerable increase in diagonal crack widths. Hawkins (Hawkins, 1974) reported that under repeated loading the diagonal tension cracking strength should be limited to 50 percent of the static shear strength and that all stirrup fractures occurred where the bars were bent around longitudinal bars. Higai (Higai, 1978) reported that in their light weight concrete beams the shear fatigue strengths with 1-million cycles are ranged between 55 and 65 percent of the static strengths. Okamura (Okamura et al, 1981) proposed a new empirical formula for predicting stirrup strain under repeated loading.

In this investigation, four beams with web reinforcement were made in accordance with the concrete standard specifications of Korea, (The Minister of Construction in Korea, 1984) and they were subjected to repeated loading in order to investigate the crack propagation procedures and changes in strain of stirrups.

On the base of test results, the regression technique was applied to find the relationships between the stirrup strains and the number of repeated loading cycles, and these results are compared with the empirical formula which is based on the truss mechanism of Morsch. (Park et al, 1975) This study also investigated the crack growth procedure and fracture mode of reinforced concrete beams by changing the number and the size of the repeated loading

2. TEST PROGRAM

(1) MATERIAL USED

The deformed bars of D10 and D19 (specified in KSD 3504) were used in reinforcing the concrete beams. The cross-sectional areas, yield strengths and Young's moduli of the bars are shown in Table 1.

The portland cement (specified in KSL 5201) was used and the maximum size of coarse aggregate was 25mm. The design of mix proportion is shown in Table 2.

(2) TEST BEAMS

Four rectangular beams as shown in Fig. 1, were tested in this investigation and the U-type stirrups of D10 were used for shear reinforcement.

Forty cylindrical specimens of 10cm x 20cm were tested to get the compressive strength of concrete.

A vibrator was used to get good specimens and moist curing of concrete was done.

(3) TEST PROCEDURE

Waterproof strain gages were attached at the points, where diagonal cracks will be expected to occur, to measure strains on the stirrups periodically during the repeated load cycles. The crack propagation procedure was also detected by inspection using the pre-drawn grid lines of 10 by 10cm on the concrete beam surface.

Three point loading was applied, and shear span to depth ratio was 2.5. The fatigue test equipments consisted of a steel frame and a 25 ton hydraulic jack connected to a pulsator.

The tests were performed, firstly, statically up to the maximum load level to investigate the diagonal crack pattern. After obtaining the required diagonal crack, additional hundred load cycles were repeated statically ranged from the minimum to the maximum load level. Then dynamic load cycles were applied to the beams with the same magnitude at the rate of 300 cycles per minute. During this procedure, the applied load was paused periodically to measure the strains on the stirrups and the crack propagation procedure was detected at each maximum load level. The beams which were sustained up to two million cycles of loading were loaded statically again to have complete fracture modes.

3. RESULTS

Table 3 shows the applied load of beams when the diagonal crack occurred and the compressive strength of concrete.

The applied load by the fatigue test and the number of load cycles at which beams fractured are shown in Table 4.

(1) BEHAVIORS OF BEAMS UNDER FATIGUE LOADING

The general behavior of tested rectangular beams can be summarized as follows:

- 1) The main diagonal crack propagates with increasing the number of load cycles and new crack seldom appears in both end shear spans where main diagonal cracks have already been formed.
- 2) With increase of the inclined crack propagation, the strain of stirrups intersected by cracks is increased approximately in proportion to logarithm of the number of load cycles ($\log N$).
- 3) The increasing strain rates of each stirrups along the beam are not same but the increasing strain rates of stirrups where no inclined crack occurs are almost constant.
- 4) Before the appearance of the inclined cracks fatigue failure in the longitudinal bars dominates the beam failure mode but after the inclined cracks occur fatigue failure of stirrups does govern the beam collapse.

As mentioned above, each strains were closely related to diagonal crack growth. Fig. 2 and Fig. 3 show changes in stirrup strains due to the repeated loading and the crack growth procedures, respectively.

(2) COMPARISON BETWEEN THE EMPIRICAL FORMULA OF OKAMURA AND THE REGRESSION ANALYSIS FORMULA.

Okamura (Okamura et al, 1981) proposed a equation for predicting stirrup strain under repeated loading of concrete beams with web reinforcement. The empirical formula of Okamura are,

$$\begin{aligned} & \bullet \text{ when } V_{\max} \geq V_{co} & \bullet \text{ when } V_{\max} < V_{co} \\ \epsilon_w &= \frac{\beta_x \{V_{\max} - V_{co} (1 - k \log N)\}}{A_w E_s Z/S} & \epsilon_w &= \frac{\beta_x V_{co} k \log N}{A_w E_s Z/S} \end{aligned}$$

where,

- ϵ_w : strain of the stirrup
- β_x : coefficient determined by the relative positions of the stirrup to the supports or loading points, and
 - $\beta_x = x / (1.5d)$: $x < 1.5d$
 - $= 1$: $x \geq 1.5d$
- x : distance from support or loading point
- $V_{\max}$: maximum shear force in the fatigue test
- V_{co} : value of V_c at $\log N$ of 0
- V_c : shear force carried by concrete
- k : constant which indicates the rate of decrease of V_c
- A_w : area of pair of stirrups
- E_s : Young's moduli of steel
- Z : distance from centroid of compression to tensile force
- S : spacing of stirrups

According to the test results, the average strain value of stirrups is proportional to $\log N$, and the result of regression analysis by the least square method is as follow.

$$\epsilon_w = a + b \log N$$

where,

- ϵ_w : average strain value of stirrups
- a : average strain value of stirrups at the number of load cycles of 1 obtained by the regression analysis
- b : rate of increase in stirrup strain due to increase of repeated loading obtained by the regression analysis

The lines obtained by the regression analysis are shown in Fig. 4.

Although the empirical formula of Okamura agreed with the regression analysis formula in the case of member 19 F 3 and 19 F 4 as shown in Fig. 3 and Fig. 4, this empirical formula seems to be incorrect for the higher load level at which the diagonal crack occurred.

Table 5 compares the regression analysis with the empirical formula for the early strains and the increasing strain rate.

4. CONCLUSIONS

According to this investigation of stirrup strains and crack growth procedure of reinforced concrete beams under repeated loading, the followings could be obtained.

- 1) The average strain value of stirrups is proportional to $\log N$ in the shear span.
- 2) The influence of fatigue in stirrups where main diagonal crack occurs require further studies.
- 3) The new crack seldom appears in both end shear spans where main diagonal cracks have already been formed and the existing crack propagates with increasing the number of load cycles.
- 4) The crack size of the beams when the test beams are fractured were larger mainly due to static loads rather than to dynamic ones.
- 5) Before the inclined cracks occur fatigue failure in the longitudinal bars dominates the beam failure mode but after the inclined cracks occur fatigue failure of stirrups does govern the beam collapse.

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Table 1. Mechanical properties of the bars.

	ϕ mm	A mm ²	f MPa	E _s × 10 ³ MPa
Stirrup	10	71.3	366	201
longitudinal Bar	19	286.5	376	201

ϕ : diameter, A: cross-sectional area, f: yield strength
E_s: Young's moduli

Table 2. Design of mix proportion.

Specimen	S mm	W kg/m ³	C kg/m ³	W/C %	ac kg/m ³	af kg/m ³
19 F 1~2	80±20	176.7	442.0	40	1083.0	673.0
19 F 3~4	80±20	176.7	354.0	50	1083.0	673.0

S: slump value, W: water, C: cement, W/C: water-cement ratio, ac: coarse aggregate, af: fine aggregate

Table 3. Properties of specimens.

Specimen	fc' MPa	Pc KN	Pu KN
19 F1~2	22.9	176.5	264.8
19 F3~4	24.0	156.9	264.8

fc': cylinder strength
Pc: applied load of beams of which the diagonal crack occurred
Pu: static ultimate load

Table 4. Test results.

Specimen	Pmax KN	Pmin KN	Pu' KN	Nu	Fracture mode
19 F 1	132.4	39.2	210.8	—	—
19 F 2	166.7	39.2	—	1,110,400	Fatigue fracture of tension bars
19 F 3	176.5	39.2	—	955,000	Shear fracture
19 F 4	196.1	39.2	—	448,220	Shear fracture

Pu': static fracture load of beams which were sustained up two million cycles of loading

Nu: number of cycles at which fracture found

Table 5. A comparison between the regression analysis and the empirical formula.

Specimen	Regression analysis formula		Empirical formula	
	a × 10 ⁻⁶	b × 10 ⁻⁶	a × 10 ⁻⁶	b × 10 ⁻⁶
19 F1	—	—	0	134
19 F2	104	34	0	134
19 F3	271	121	229	128
19 F4	476	137	457	128

a: the early strains, b: the increasing strain rate

Fig. 1. Typical test beam and strain gauge arrangement.

Fig. 2. The crack propagation.

Fig. 3. Stirrup strains under repeated loading.

Fig. 4. The relationships between the number of repeated load cycles and the average strain value of stirrups.