Experimental Research on Fatigue Behavior of Existing Reinforced Concrete Beams

Guangzhen Qu, Pingming Huang, Guangli Zhou, and Sizhong Lv

1 School of Highway, Chang’an University, Xi’an 710064, China
2 Shandong Transportation Institute, Jinan 250012, China
3 Shandong Hi-speed Co., Ltd., Jinan 250014, China

Correspondence should be addressed to Guangli Zhou; 229993723@qq.com

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1. Introduction

In the last 40 years, most of the bridges in China have been built using reinforced concrete. Due to higher traffic load and increasing traffic volume, the fatigue damage to the bridges increased, which reduced its service life. Fatigue loading was caused by moving wheels and was characterised by a high number of load cycles which may exceed 100 million over the service life of a bridge. Long-term and frequent load action reduced the stiffness of the bridge and showed obvious cumulative damage [1]. More and more scholars were concerned about the fatigue performance and fatigue life of reinforced concrete structures [2–6]. The design code GB 50010 listed the limit values of fatigue design stress amplitude for ordinary steel bars under different fatigue stress ratios [7].

A large number of fatigue test studies on reinforced concrete beams showed that its failure characteristics were generally fatigue fracture of one or part of tensile rebars. The fracture process of rebar can be divided into crack initiation stage, stable crack growth stage and brittle fracture stage [8–11]. Chang et al. studied the relationship between crack development, midspan deflection, steel strain, and fatigue load through the fatigue performance test of 11 reinforced concrete specimens and finally obtained the S–N curve of the reinforced concrete beams [12]. Li et al. analyzed and studied the fatigue performance of flexural members through static load and constant-amplitude fatigue tests on high-strength concrete simply supported beams equipped with new grade III steel and gave calculations method for the compression zone concrete stress and longitudinal tensile steel bar stress and design value of fatigue strength of steel bars [13]. Wang et al. conducted fatigue tests of reinforced concrete beams in air, fresh water, and salt water environments and studied the deformation development process and fatigue life of the beams in three environments under repeated loads [14]. Yang et al. studied the fatigue behavior decay law of reinforced concrete beams through 150-time...
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2.1. Test Specimen. The testing beams were originally located on Jinan-Qingdao Expressway of Shandong Province, which was completed in 1993. At present, the expressway needed to be expanded to accommodate more traffic. In this process, a 24-year 8m-span RC hollow beam was dismantled from the bridge and transported back to the laboratory for fatigue test to evaluate its residual life. The demolition and storage of the test beams are shown in Figure 1.

The original design height of the test beam was 40 cm, and there was a 17 cm thick concrete leveling layer. The designed strength grade for the concrete was C25. The bottom longitudinal rebars of the beam were 25 mm in diameter with spiral ribbing, and the stirrups and top construction rebars used plain round steel with 8 mm diameter. The two outermost longitudinal steel bars were welded to the diagonal steel bars. The dimensions of the test specimens are shown in Figure 2, and the measured material parameters of concrete and rebar are shown in Tables 1 and 2, respectively.

2.2. Test Scheme. The beams were simply supported and tested under a four-point bending configuration. The clear span and shear span were 7.62 and 2.81 m, respectively. Displacement gauges were installed at the middle span, at the one-fourth span position, and at both ends of the beam. The concrete strain gauges were placed in the midspan web surface of the beam, and the bottom concrete at the reinforcement location was cut out to place the rebar strain gauges. The appearance and propagation of the cracks were observed visually, and a digital crack-width viewer was used to measure the crack widths. The vibration sensors were arranged on the top plate of the hollow beam to collect the modal information, as shown in Figure 3.

The JD1 test beam was used for static load test to determine ultimate load needed in the fatigue experiment, and the JP1 to JP3 beams were used for fatigue tests under different load levels [9, 19]. Specific experimental conditions are shown in Table 3.

2.3. Test Device and Loading Method

2.3.1. Test Device. The test was carried out using MTS electrohydraulic servo loading equipment, which can not only realize the multichannel independent test but also compile the complex fatigue load block spectrum, display, and monitor the graph of the test results in real time. It had the functions of system internal lock protection and automatic damage detection too. The MTS control system and hydraulic oil source are shown in Figure 4. The static and fatigue tests were all conducted using the fatigue testing system, and loading device for experiments is shown Figure 5.

2.3.2. Loading Method

(1) Static load test. The ultimate load \( P_u \) can be obtained by monotonic loading test. The beams should first be preloaded before the formal test. The monotonic load test was carried out through graded loading, with a load increment of 25 kN and encryption in the later stage.

(2) Fatigue load test. The beams were preloaded to check that the test instrument was working properly, and then the initial state of test beam was collected through static load to the upper limit of fatigue. Then, sine wave loading was used in fatigue test with the loading frequency of 3 Hz. When a certain number of cycles were reached, the static load test was carried out to the upper limit of fatigue. After static loading, the fatigue loading test was continued until the component was damaged. The loading program is shown in Figure 6.

3. Static Load Test

The static load test was carried out on the JD1 beam. Before loading, there were several original cracks in the constant moment region of the beam, and the original crack height was about 10 cm and the maximum width was 0.1 mm. As the load increased, the number of cracks in the test beam increased, and the crack width and height increased. Before the longitudinal tensile rebar entered the yield phase, the components showed
good elasticity and the load-deflection curve showed a linear relation; the width of the crack grew relatively slowly and remained within 0.5 mm, and the crack was essentially closed after unloading. With loading to approximately 0.9Pu, the longitudinal tensile rebar entered the yield phase, and the deflection reached approximately 1/400th of the calculated span. At this phase, the load increased gradually, whereas the midspan deflection increased rapidly. With the continuous increase of load, the number of cracks no longer increased, the crack distribution was more uniform, and the neutral axis continued moving upwards until the strain of rebar exceeded the limit strain of 0.01 [20]. Ultimately, the ultimate load was 502 kN. The failure shape and crack distribution of JD1 beam are shown in Figure 7. The load-midspan deflection curve is shown in Figure 8, and the load-rebar strain curve is shown in Figure 9.

**4. Fatigue Load Test**

4.1. *Observed Behavior.* Under cyclic loading, there was no obvious sign before the fatigue failure of the test beam. With the continuous fatigue loading, an outermost longitudinal tensile steel bar near the midspan side suddenly broke at the welding position (Figure 10). The first failure of the steel bar at the welding location was due to the existence of welding residual stress, and the fatigue fracture of the beams first occurred at the position of stress concentration [21]. After the longitudinal tensile steel bar
was broken, the beam did not collapse and still continued to bear the fatigue load. The concrete in the compression zone was not crushed, and there was no obvious abnormality.

The cracks in the constant moment region of the beam gradually developed along the original cracks slowly; when the outermost steel bar suddenly broke, the crack width increased significantly near the fracture, and the vertical crack width at the web after the steel bar broke was about 0.3 mm, and the width of some cracks at other locations had decreased. The fatigue failure shape and crack distribution of JP2 beam are shown in Figure 11.

4.2. Deflection. The load-midspan deflection curves of JP1–JP3 beams in different cycle times are shown in Figure 12. As shown in the figure, the midspan deflection changed linearly with the increase of load before and after

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Table 3: Test conditions.

| Specimen number | Loading system | Loading instructions |
|-----------------|----------------|----------------------|
| JD1             | Static loading test | Get the ultimate load, Pu |
| JP1             | Fatigue upper limit \(P_{\text{max}}\) | Fatigue lower limit \(P_{\text{min}}\) | Amplitude \(\Delta P\) | Fatigue load amplitude |
|                 | 0.5Pu | 0.1Pu | 0.4Pu | |
| JP2             | 0.6Pu | 0.1Pu | 0.5Pu | Fatigue loading to failure |
| JP3             | 0.7Pu | 0.1Pu | 0.6Pu | |

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Figure 3: Test scheme and layout of measuring points (unit: mm).

Figure 4: The MTS: (a) control system; (b) hydraulic oil source.

Figure 5: Loading device for experiments.
Figure 6: Fatigue loading program.

Figure 7: Failure shape and crack distribution of test beam: (a) failure shape; (b) crack distribution.

Figure 8: Load-midspan deflection curve.
Figure 9: Load-rebar strain curve.

Figure 10: Fatigue fracture of steel bar.

(a)

Figure 11: Continued.
Figure 11: Fatigue failure shape and crack distribution of JP2 beam: (a) failure shape; (b) crack distribution.

Figure 12: Load-midspan deflection in (a) JP1; (b) JP2; and (c) JP3.
rebar fracture. Figure 13 shows that the midspan deflection under the fatigue upper limit varied with the number of cycles. The midspan deflection of the test beams increased gradually with the increase of the number of cycles. The midspan deflection changed more obviously in the following range: (1) the first 10,000 fatigue cycles; (2) after fatigue fracture of the rebar.

After the rebar fracture, the midspan deflection of JP1, JP2, and JP3 beams increased by 1.63, 1.92, and 2.34 mm relative to the initial stage, and the increase rates were 21.2%, 18.4%, and 19.5% respectively, which indicated that the stiffness of the test beams were greatly reduced.

4.3. Strain of Material. In the process of cyclic loading, the average strain on the rebar and concrete in a section of the beam was taken as the representative of the corresponding strain in that section. The load-midspan rebar strain curves of JP1–JP3 beams in different cycle times are shown in Figure 14. It can be seen from the figure, the midspan longitudinal tensile rebar strain changed linearly with the increase of load before and after rebar fracture. Figure 15 shows that the midspan longitudinal tensile rebar strain under the fatigue upper limit varied with the number of cycles. The midspan rebar strain changed more obviously in the following range: (1) the first 10,000 fatigue cycles; (2) after fatigue fracture of the rebar. After the rebar fracture, the midspan longitudinal tensile rebar strain of JP1, JP2, and JP3 beams decreased by 40με, 55με, and 124με relative to one cycle before rebar fracture, and the reduction rates were 6.9%, 6.7%, and 12.3%, respectively.

The load-compressive strain of top edge concrete of JP1–JP3 beams in different cycle times are shown in Figure 16. During the initial loading stage, when the number of cycles was below 10,000, the strain of concrete grew rapidly. As the cracks developed, it gradually entered the stable stage. Until the rebar fracture, the strain of concrete changed very little. The strain of the concrete at the top edge compression zone of the beam and the longitudinal tensile rebar strain did not reach yield strain throughout the loading process. The mechanical behavior of the concrete beams under cyclic loading was largely determined by the presence of tensile rebar.

4.4. S–N Curve. In the fatigue test of RC beam, the tensile steel bar stress amplitude can be calculated according to the following formula:

\[
\Delta \sigma_f^s = \sigma_{s,\text{max}}^f - \sigma_{s,\text{min}}^f,
\]

\[
\sigma_{s,\text{max}}^f = \frac{\alpha_E M_{\text{max}}^f (h_0 - x_0)}{I_0^f},
\]

\[
\sigma_{s,\text{min}}^f = \frac{\alpha_E M_{\text{min}}^f (h_0 - x_0)}{I_0^f},
\]

where \(M_{\text{max}}^f\) and \(M_{\text{min}}^f\) are the bending moments produced by the upper and lower fatigue loads respectively; \(\alpha_E\) is the ratio of the elastic modulus of steel bar to that of concrete; \(x_0\) is the height of compression zone of the cross section; \(h_0\) is the effective height of the cross section; \(I_0^f\) is the moment of inertia of the converted section.

The theoretical tensile steel bar stress amplitude can be calculated by the formula above. The test and calculated values are shown in Table 4.

The failure mode of the test was mainly the fatigue fracture of steel bar, and the S–N curve with stress amplitude as parameter was usually used to deal with the fatigue life of steel bar. The standard formula is as follows [22, 23]:

\[
\log(N) = A - Blg(\Delta \sigma_f^s),
\]
where A and B are constants related to the type and connection form of steel bars; \( N \) is the number of fatigue failures; and \( \Delta \sigma \) is the steel bar stress amplitude.

Table 5 shows the information summary of the test beams. The relationship between stress amplitude of rebars and the fatigue life of the beams was established by the using double logarithmic curve. The S–N curve was obtained by linear regression simulation, as shown in Figure 17. The linear regression curve equation was as follow:

\[
\lg N = 11.41 - 2.6633 \lg \Delta \sigma_f .
\]

\( \text{(3)} \)

The correlation coefficient \( R^2 \) is 0.997. It can be seen that each point agrees well with the regression equation, and the obtained curve has high reliability.

5. Dynamic Performance in Fatigue Test

In order to further analyze the change law of the dynamic performance of the hollow slab from the initial state to the rebar fracture, the JP2 beam was subjected to modal testing under environmental excitation after a certain fatigue loading cyclic. Figure 18(a) shows the changes of the first two

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Figure 14: Load-midspan rebar strain in (a) JP1; (b) JP2; and (c) JP3.
Figure 15: Relation curve for longitudinal tensile rebar and fatigue cycles.

Figure 16: Continued.
order natural vibration frequencies of JP2 beam under different cycles. It can be seen from the figure that the natural vibration frequencies were decreasing continuously. After the fracture of longitudinal tensile reinforcement, the first- and second-order frequencies were reduced by 3.5% and 2.5%, respectively, compared with those of the initial state.

Pandey and Biswas first proposed the use of the curvature mode method to identify damage [24]. Li et al. proposed that the curvature mode $\phi_k''$ can be obtained by differential calculation of displacement mode [25]:

$$
\phi_k'' = \phi_{k+1} - 2\phi_k + \phi_{k-1} \left( l_{k-1}/l_k \right), \quad k = 1, 2, \ldots
$$

where $\phi_k$ is the vibration mode of the $k$-th measuring point and $l_{k-1}/l_k$ is the distance between two adjacent measuring points $k$ and $k-1$.

In addition, higher-order curvature modes were more sensitive to damage, and second-order curvature modes were obtained by differential calculation of second-order displacement modes of JP2 beam, as shown in Figure 18(b).
It can be seen from the figure that after the longitudinal tensile steel bar broke, the curvature near the midspan of the test beam changed greatly, which was a large damage that occurred near the midspan. The compliance matrix based on frequency and mode can achieve quantitative analysis of damage, and its formula is as follows [26]:

$$D = \sum_{i=1}^{M} \frac{\varphi_{mi} \varphi_{mi}^T}{\omega_i^2}, \quad i = 1, 2, \ldots, \quad (5)$$

where $\omega_i$ is the $i$-th measured circle frequency and $\varphi_{mi}$ is the $i$-th mass normalized mode.

The flexibility change of the JP2 beam in the middle of the span after the fatigue load cycle is shown in Figure 18(c). It can be seen from the figure that the midspan flexibility increased steadily as the number of cyclic loading increased, but after the longitudinal tensile rebar broke, the midspan flexibility increased significantly, which was 10% higher than that before fatigue cyclic loading.

6. Conclusions

A series of experiments were carried out to investigate the mechanical behavior of reinforced concrete beams in service under fatigue cyclic loading; beam failure mode, deflection, strain of concrete and rebars, and vibration mode changes were recorded during loading; also the development of fatigue damage was summarized. Based on the test results, the main conclusions were as follows:

1. The fatigue failure of the hollow beam indicated that the outermost rebar at the butt weld fractured firstly, and the crack width at the fracture position of the steel bar was about 0.3 mm, which was largest of all cracks.

2. After the rebar fracture, the midspan deflection increase rate of three beams was 18.4%–21.2% relative to the initial state, and the tensile reinforcement in the middle of the span decreased suddenly, while the concrete strain in the top compression zone remained basically unchanged.
(3) The damage developed rapidly in the following range: ① the first 10,000 fatigue cycles; ② after fatigue fracture of the rebar; and the damage development was relatively stable in the intermediate stage of the fatigue test.

(4) After the rebar fracture, the first- and second-order frequencies were reduced by 3.5% and 2.5%, respectively, and the midspan flexibility was increased 10% compared with that of the initial state.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare no conflicts of interest.

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