Retraction

Retraction: Fatigue characteristic and life test of reinforced concrete T girders under cyclic loading (IOP Conf. Ser.: Earth Environ. Sci. 358 052041)

Published 29 March 2022

This article has been retracted by the authors following discovery of errors in the work. The authors description of the errors follows: "As the strain acquisition/loading instrument used in the experiment was found working abnormal in recent maintenance check, the measured data validity is not guaranteed and the paper leads to the inappropriate result."

IOP Publishing cannot verify this information as accurate, however in the interest of transparency and reproducibility, IOP Publishing agrees to retract this article.

Retraction published: 29 March 2022
Fatigue characteristic and life test of reinforced concrete T girders under cyclic loading

Jinquan Zhang¹, Bing Bai¹, Shangchuan Zhao¹, Xindai Zuo¹

¹ Bridge and Tunnel Research Center, Research Institute of Ministry of Transport, Beijing, 100088, China

Abstract: Aiming at the issue of reinforced concrete girder fatigue, a typical T shaped scale model girder form is selected as the test specimen based on the real structure drawings. On the basis of designing test program reasonably, 7 same batch test girders are loaded with different constant cyclic loading amplitude. Thus according to the test data, girder failure mode, fatigue life, mechanical property evolution law as well as rebar S-N curve is discussed systematically. The result indicate that the longitudinal rod fracture is the domain failure mode of girders, which can finally induces whole specimen rupture brittlely. The mode is clear and definite in the observation. On account of all observation, the longitudinal rod stress range is more regular and stable, which seems suitable for life evaluation. Using the data obtained above, the rod S-N curve equation is calculated by linear fitting method. Result shows the data fit well and all the data lie within the normal range of deviation, which may reveal the law between cyclic load and girder fatigue life.

1. Foreword
Reinforced concrete girder bridges with wide application at present are one of the main bridge forms, which occupies an important position in China's traffic network. With the rapid development of economic construction in recent years, the traffic volume continues to increase, and the fatigue problem of bridge bearing vehicle-borne functions repeatedly becomes more and more prominent, which leads to the short service life of the structure and needs to be paid attention to. Highway engineering technical standard (JTG B01-2014) [1] issued in 2014 had clearly proposed that the design of bridge life should be considered.

However, the above status and regulations are not commensurate with the current specifications and standards in China, which lack verification methods or theories aimed the fatigue behavior and life of reinforced concrete girder bridges, so the provisions and analysis of life design are virtually insignificant.

Aiming at this problem, the scholars from the different countries have carried out a series of fruitful researches. Reinforced concrete girder bridge fatigue problem is not significant in traditional view, but this view has been challenged increasingly. In the 1970s, the United States began to analyze the fatigue problem of concrete structures [2][3], and obtained rich results. In recent years, some foreign scholars have conducted more in-depth discussions on its existence and the leading mode of destruction by experiment and research. Barnes and Mays[4] carried out a fatigue test study on 5 groups of reinforced concrete girder, and the results show that the fatigue fracture of longitudinal tensile rebars is the dominant failure mode of the structure, and the fatigue life of concrete is relatively similar as long as the stress range of rebars is the same regardless of reinforcement. Heffernan and Erki [5] studied 12 pieces of 3m and 3 pieces of 5m span reinforced concrete girder respectively, and
divided the load amplitude of 3m span test girders into three grades. The results showed that all test girders were still damaged by fatigue fracture of tensile rebars, and only reinforcement with carbon fiber plate (CFRP) improved the service life because it reduced the stress range of rebars. In order to explore the failure modes of larger specimens, Charalambidi et al. [6] reported the fatigue test results of 7 large-sized 3m T girders and found that although the load amplitude was relatively larger, but it did not change the failure mode of the structure. Based on this, the strengthening parameters of carbon fiber plates were analyzed. In 2017, Mirzazadeh et al. [7] studied the fatigue characteristics of reinforced concrete girders at different temperatures, and discussed the structural failure mode and stiffness changes. The results showed that low temperature may have a beneficial impact on their fatigue life. In China, different scholars [8]–[10] have also carried out similar test analysis, and deeply discussed the related characteristics of the fatigue behavior of reinforced concrete girders, which has important reference value for further study of the problem. However, due to the complexity of the problem and the size of the test, parametric test is still relatively lacking in the same batch. At the same time, the reinforcement and structural design in the early tests abroad may not be consistent with the current situation in China, and there is still a lack of definite analysis on the fatigue failure mode mechanism of domestic reinforced concrete girders and the evolution law of related structural parameters. In view of this, it is helpful to reveal the external characteristics and internal mechanism of the fatigue behavior of reinforced concrete girders by systematically and scientifically carrying out the experimental research on the fatigue performance of structures under different load ranges.

Due to the difficulty and complexity of the problem, the fatigue performance of reinforced concrete girders is generally carried out by means of experimental research and theoretical analysis. The constant-amplitude fatigue behavior of seven test girders with the same batch under different load amplitudes is tested. The failure characteristics of the specimens and the corresponding structural parameters and the evolution law of their life are systematically discussed, which provides relevant reference for the fatigue life design of reinforced concrete structures and has positive significance for improving the long-term service performance of such bridges.

2. Design and test scheme of test girder

2.1 Design of Test girder

Reinforced concrete T girder is the main structural form of medium and small span bridge in highway traffic in China and is of universal significance to be taken as the object of study. For the specific construction of the test girder, in order to ensure a wider reference and applicability of the results, referring to the standard diagram of the 20m simply supported T girder in the road bridge and culvert design drawing-assembled reinforced concrete T-girder (JT/GQS 025-84) Design, the test girder was designed according to 1:4 scale. There were 9 test girders of the same structure, of which 2 were used for static load destructive test and the other 7 were used for equal amplitude fatigue test.

![Figure 1. General sketches of the test girders (unit: mm).](a) Façade sketch (b) Cross section reinforcing

The total length of the test girder is 5m, and the calculated span is 4.5m. It adopts a T-shaped cross section. The girder height is 0.37m, the wing width is 0.5m, and the rib thickness is 0.12m. The...
concrete grades used are all C40, the longitudinal tensile main reinforcement is HRB335 B12 rebar with yield stress of 442MPa, the vertical reinforcement bars and stirrups are R235 A8 bars with yield stress of 335MPa, the stirrups spacing is 200mm. Its specific structure is shown in figure 1. By the reinforcement check calculation of design structure, the designed test girder is balanced-reinforced girder ($\rho=0.66\%$). When the blanking is made, each material is made of the same batch of the same manufacturer and is poured once.

2.2 Test loading and testing program

There are 9 test girders in total, 2 of which are used to determine the static ultimate bearing capacity of the girder, and the upper and lower limits of the load amplitude are determined for the subsequent fatigue tests, and 7 of which are used to carry out the constant amplitude fatigue test of the structure to explore the fatigue behavior characteristics of reinforced concrete girders.

In terms of the fatigue problem of reinforced concrete girders, it is mainly caused by the repeated action of the vehicle. For medium and small span girder bridges, the single wheel load (axial load) has relatively more significant functions. Therefore, the direct single-point bending loading method is more realistic and widely used [11][12]. According to this feature, all test girders are loaded in the form of mid-span single point bending. The loading instrument is PMW-2000 electro-hydraulic pulsating fatigue test machine with the maximum loading capacity of 1000kN and precision of 1kN, which can meet the loading requirements of this test. The loading diagram of the test girder is shown in figure 2.

![loading diagram](loading_diagram.png)  
(a) Loading diagram

![photo of loading layout](loading_layout.png)  
(b) Photo of Loading layout

Figure 2. Sketch of the test loading.

According to the test plan and specific conditions of the test girders, the static ultimate bearing capacity of T girders is obtained firstly, then the equivalent amplitude fatigue test of the 7 T girders is carried out according to the corresponding values (the fatigue load amplitude of each girder is different). The specific loading parameters of each test girder are shown in table 1.

After the test girders fail due to load, the cycle times and corresponding phenomena of girder physical mechanics are recorded, then the failure modes are checked and observed to determine the internal failure modes.

Table 1. Loading parameters of test.

| Test identifier | Loading form                | Load range (kN) | Valley value (kN) | Peak value (kN) | Loading frequency (Hz) |
|-----------------|-----------------------------|-----------------|-------------------|-----------------|------------------------|
| S-1             | Static bearing capacity     | -               | -                 | $P_{ul}=77$     | -                      |
| S-2             | Static bearing capacity     | -               | -                 | $P_{ul}=63$     | -                      |
| F-1             | Equal amplitude fatigue     | 30              | 5                 | $35 / 0.5P_a$   | -                      |
| F-2             | Equal amplitude fatigue     | 23              | 5                 | $28 / 0.4P_a$   | 3~4                    |
| F-3             | Equal amplitude fatigue     | 16              | 5                 | $21 / 0.3P_a$   | -                      |
We are concerned about the fatigue characteristics of the test girders in this research. The strain, displacement (deflection) and crack observation methods are used to test girders, and the measuring points are arranged in the key positions of the girder. Four test sections (1, 2-1, 2-2, and 3) are set for concrete strain, and a total of 13 gauges with length of 5 cm are laid from wing plate to floor plate for each section. The reinforcement strain is tested by selecting the bottom two longitudinal rebar with gauge length of 5 mm arranged in 1/4 span and mid-span sections to test the reinforcement stress. In addition, 5 cable displacement sensors (LVDT) are set to test the deflection changes near the support, 1/4 span and mid-span respectively to obtain the macroscopic structural deformation law. A typical measuring point arrangement is shown in figure 3.

3. Test Results

The fatigue life and main failure modes of each test girder are shown in table 2. Among them, the test girder F-3 showed a run out phenomenon. In order to carry out supplementary research on the working condition test, the fatigue tests of the test girders F-6 and F-7 are carried out, and the two test girders are both destroyed after a certain cycles, and no run out occurred.

| Girder identifier | Loading frequency (Hz) | Load range (kN) | Rebar average stress range (MPa) | Actual cycles to failure (10^3) | Failure mode |
|-------------------|------------------------|-----------------|---------------------------------|--------------------------------|--------------|
| S-1               | -                      | -               | -                               | -                              | -            |
| S-2               | -                      | -               | -                               | -                              | -            |
| F-1               | 3                      | 5–35            | 305                             | 384                            | Longitudinal rebar yielding |
|                   |                        |                 |                                 |                                | 3 rebar fracture, 1 main crack ran through the full cross-section, the maximum crack width is 20 mm |
| F-2               | 3                      | 5–28            | 230                             | 555                            | Longitudinal rebar yielding |
|                   |                        |                 |                                 |                                | 3 rebar fracture, and 3 main cracks occurred and penetrated the web at 2.3–2.4 m from the support, the maximum crack width is 17 mm |
| F-3               | 3.5                    | 5–21            | 126                             | >900,0                         | Ran out, the static load capacity after 9 million cycles is 64 kN |
|                   |                        |                 |                                 |                                | 3 rebar fracture, and 1 main crack occurred and penetrated the web at 2.4 m from the support, the maximum crack width is 7 mm |
| F-4               | 4                      | 5–17.5          | 116                             | 3,401                          | -            |
|                   |                        |                 |                                 |                                | -            |
As can be seen from the above fatigue test results, except for the F-3 girder run out, the fatigue life of the remaining test girders is basically negatively correlated with the load width/longitudinal rebar stress range, and the load amplitude/longitudinal rebar stress range is larger, corresponding fatigue the lifespan is smaller. The fatigue life variation range is between 38.4~376.4 million times (corresponding to the rebar stress range 305MPa~116MPa), and basically covers the range of common fatigue test results in the laboratory. However, determined by the microscopic mechanism of material fatigue [13], the overall life rule of the test girder presents considerable dispersion. The F-6 and F-7 girder fatigue load inputs are relatively close, but their fatigue life is quite different. Combined with the final failure mode, it is mainly caused by micro-metallurgical defects or surface condition differences of the rebars. This phenomenon has also appeared in the results of other experiments [14].

For the main characteristics of structural fatigue failure, the previous researches are not very unified. By observing the test results of various girders, it can be found that the leading failure mode is the fatigue fracture of the longitudinal tensile main reinforcement at the ultra-wide crack, which causes the members to lose their bearing capacity, and concrete failure is not the main cause of structural failure. In terms of its specific process, when T girder is close to failure, only 1~3 main cracks continue to expand near the middle span, while the other crack gradually close. At this time, the width of main cracks generally exceeds 0.2mm. After that, the cracks and deflections of the girder increased further and expanded at a speed that could be observed by the naked eye. In the end, the main bars of T girder suffered fatigue fracture near the main crack in the middle span (2.4~2.6m from the girder end), and the number of fractures was 2~3. As a result, cracks and deflections of the test girder developed rapidly, and the girder lost its bearing capacity. In the tests of various working conditions, concrete crushing phenomenon occurred in the compression zone of the wing plate of F-1 girder without loading limit device, while this phenomenon was not observed in the other working conditions (with limit device). The concrete in the compression zone remained relatively intact, which confirmed the findings of Song Yupu et al. [15]. Under the normal reinforcement condition, the concrete in the compression zone will not be fatigue failure before the longitudinal tension main reinforcement. Failure modes of typical test girders (F-1 and F-2 girders) are shown in figure 4, and the rest of the girders are similar to them, which will not be given here.

![ Typical fatigue failure characteristic of the test girders.](image-url)
After the test, the fracture rebar is taken out to observe the morphology of the fracture. As can be seen from the fracture, compared with the ductile failure (yield and necking, as shown in figure 5 (a) of rebars in the static load test, the fatigue failure of rebars in T-girder is relatively less, and there is no significant deformation or symptom before the failure. The rebar fracture (as shown in figure 5 (b) is smooth without necking, and obvious crack growth zone can be observed, which conforms to the characteristics of metal fatigue fracture [13][16]. For the initial location of fracture, all of them originate at the surface rib root of the span, and this area is exactly the stress concentration area of the reinforcement, which is consistent with the description of related theories such as fracture mechanics.

![Rebar failure modes](image)

(a) rebar yield failure  (b) rebar fatigue failure

Figure 5. Fracture morphology comparison between different rebar failure mode.

4. Discussion on the S-N Curve Rule of Reinforcement

For the fatigue life analysis and prediction of concrete girders, the preliminary experimental research shows that the fatigue fracture of longitudinal reinforcement is the leading cause of the subsequent failure of the test girder. The S-N curve equation for constructing the longitudinal reinforcement is a suitable method for life analysis.

According to the test results, the scatter of the longitudinal rebar S-N result of each girder is shown in figure 6. Due to the run out of F-3 girder, there are only 6 sets of data points available, which may leave the curve fitting (just based on the above 6 sets of data) in doubt about statistical significance and wide applicability. Therefore, it is necessary to include more fatigue life data.

In order to study the applicability of the fitted curve equation, we collect other research results [8][14][17]. The results show that the test life sample points obtained by each test have large differences, and the 6 points fitting curves may only be applicable to the respective test data. In view of this situation, it is difficult to use only one set of test results to reflect the global characteristics. A feasible solution is to merge all the collected data for global regression analysis. Based on this idea, using the 24 sets of data points collected above for linear fitting, the S-N curve equation can be obtained as:

\[
\lg N = -2.3577 \lg \Delta \sigma + 11.1809
\]

The curve is the median curve obtained by fitting, and the correlation coefficient is \( r = 0.779 \). In general, the more data points the regression fits in, the lower the correlation coefficient. However, at this moment, \( r \) is still larger than the threshold value \( r_{\text{min}} = 0.404 \) [18], and the regression test can pass the significance test. The comparison of the fitting results with the data is shown in figure 6.
For the specific structure fatigue life evaluation, a certain guarantee rate should be considered based on the S-N median curve. Referring to the relevant standard practices, 2 standard deviations are taken downward to get the actual calibration curve equation as:

\[ \log N = -2.3577 \log \Delta \sigma + 10.6309 \]  

Observing the corresponding curve of the equation in figure 6, it can be seen that all data points are above the curve, and the guarantee rate can meet the calibration evaluation requirements.

5. Conclusion
Aiming at the fatigue problem of reinforced concrete girders, the fatigue test analysis of 7 T-girders under different load amplitudes was carried out, and the experimental results were discussed theoretically. The main findings are as follows:

1) The failure modes of the tested test girders are relatively consistent. Except for 1 girder run out, all the other girders are fatigue fracture of longitudinal rebars and it causes structural fracture failure. The fracture of rebars conforms to the typical fatigue failure characteristics, and the structural failure mode is clear;

2) The S-N curve equation of the longitudinal reinforcement is obtained by the test results and the regression of other test data. The equation fitting effect is good, and the analysis and research of more tests based on the existing data is one of the important contents of the next step.

Acknowledgements
This study was funded by the Science and Technology Innovation Foundation of Research Institute of Ministry of Transport [grant No. 2018-A0004] and the Fundamental Research Foundation of Central-level Public Welfare Research Institute [grant No. 2017-9035].

References
[1] JTG B01-2014. (2014) Technical standard of highway engineering. China Communications Press, Beijing.
[2] ACI Committee 215. (1974) Considerations for design of concrete structure subjected to fatigue loading. ACI Proceedings, 71(3): 97-121.
[3] Holmen, J.O. (1979) Fatigue of concrete by constant and variable amplitude loading. ACI Special Publication, 75: 71-110.
[4] Barnes, R., Mays, G. (1999) Fatigue performance of concrete beams strengthened with CFRP plates. Journal of Composite for Construction, 3(4): 63-72.
[5] Heffernan, P.J., Erki, M.A. (2004) Fatigue behavior of reinforced concrete beams strengthened with carbon fiber reinforced plastic laminates. Journal of Composite for Construction, 8(2): 132-140.
[6] Charalambidi, B.G., Rousakis, T.C., Karabinis, A.I. (2016) Fatigue behavior of large-scale reinforced concrete beams strengthened in flexure with fiber-reinforced polymer laminates. Journal of Composite for Construction, 20(5): 04016035.

[7] Mirzazadeh, M.M., Noel, M., Green, M.F. (2017) Fatigue behavior of reinforced concrete beams with temperature differentials at room and low temperature. Journal of Structural Engineering, 143(7): 04017056.

[8] Zhu, H.B. (2011) Method and experiment research on highway reinforced concrete simply-supported girder bridge's fatigue residual service life forecast. Central South University, Changsha.

[9] Ma, Y.F., Su, X.C., Guo, Z.Z., Wang, L., Zhang, J.R. (2017) Experimental study on fatigue behavior of reinforced concrete beams with corrosion-induced cracking. Journal of Natural Disasters, 26(6): 61-68.

[10] Li, X.F., Wu, P.G., Zhao, G.Y. (1997) Experimental research on bending fatigue behavior of high-strength concrete beams. China Civil Engineering Journal, 30(5): 37-42.

[11] Soltani, A., Harries, K.A., Shahrooz, B.M., et al. (2012) Fatigue performance of high-strength reinforcing steel. Journal of Bridge Engineering, 17(3): 454-461.

[12] Gao, D.Y., Zhang, M., Zhu H.T. (2013) Fatigue test and stiffness calculation of steel fiber reinforced high-strength concrete beams with reinforcements. Journal of Building Structures, 34(8): 142-149.

[13] Schijve, J. (2014) Fatigue of structures and materials (second edition). Aviation Industry Press, Beijing.

[14] Li, X.F., Wu, P.G., Zhao, G.Y. (1997) Experimental study on fatigue properties of deformed bars. Engineering Mechanics, (sup1): 349-356.

[15] Song, Y.P. (2006) Fatigue behavior and design principle of concrete structures. China Machine Press, Beijing.

[16] Suresh, S. (1999) Fatigue of materials (second edition). National Defense Industry Press, Beijing.

[17] Zhong, M., Wang, H.L., Liu, Z.B., Meng, J.W. (2005) Experimental research of high-strength concrete beams reinforced by high-strength bars under static loading and fatigue loading. Journal of Building Structures, 26(2): 94-100.

[18] TB/T 2349-2016. (2016) Fatigue test method for connection of railway steel bridge. China Railway Press, Beijing.