An experimental study on bearing capacity of simply supported T-beam bridge strengthened with steel plates

Hui-lin Chen

1Rear service support office of Wuhan University of Technology, Wuhan 430070, P.R. China

*Corresponding author’s e-mail: Chenuilin@whut.edu.cn

Abstract. Due to the increasing traffic load, existed bridges suffer from various diseases such as aging, cracking, excessive deflection, etc., which lead to the decrease of structural bearing capacity and a series of safety accidents. In this paper, various diseases of a 5 × 20m simply supported T-beam bridge are identified by routine bridge detection, and then the mechanism of diseases are also analyzed. According to the characteristics of the diseases, the reinforcement method with bonded steel plates is proposed. Finally, the static load test of bearing capacity to evaluate the strengthening effect of the bridge is carried out. The results show that the deformation law and strain state of the strengthened bridge structure are normal, the bearing capacity and rigidity of the structure meet the requirements of the design load standard, so the problem of insufficient shear and bending capacity of the simply supported T-beam bridge can be effectively improved by sticking steel plate. The research results have important engineering application value for improving the structural performance of existed bridges, promoting the sustainable development of existed bridges and saving economic costs.

1. Introduction

Due to the increasing traffic load and vehicle carrying capacity, long-serving bridges are subject to structural diseases such as aging, cracking, and excessive deflection, which may lead to a decrease in bearing capacity as well as resultant safety accidents [1-2]. At present, extensive research has been carried out regarding the maintenance and performance testing of bridges. Specifically, The paper [3] proposed a calculation formula for the pre-stress loss of reinforced concrete beams strengthened with prestressed carbon fiber plate. Li Linguostudied the rules of the influence of parameters including the number of layers, length, thickness, and reinforcement ratio of sticking steel plate on the flexural performance of steel-reinforced RC beams[4]. Zhang Linhuainvestigated the bearing capacity, structural deformation, and seismic performance of a prestressed concrete continuous beam bridge and examined whether they conformed to the standards using static load tests [5]. Liu Jujiu verified the reliability of the Guangzhou Haizhu Bridge's finite element model using static and dynamic load tests and based on the result of finite element analysis, determined the key locations of safety monitoring as well as stress and deformation warning values[6]. Reinforcing measures such as increasing the section and applying fiber-reinforced polymers or steel plates promise to effectively solve bridge diseases. Whether or not the bearing capacity of a bridge after reinforcement meets traffic requirements can be verified by tests and safety assessment.

With a 5×20 m simply supported T-beam old bridge as an example, this study aims to investigate the pathogenic mechanism and disease severity of the bridge using conventional bridge inspection
methods and develop bonded steel plate reinforcement measures according to its disease characteristics. In the end, the reinforcement effect is verified by static load tests.

2. Project Overview

2.1. Bridge overview
The simply supported T-beam bridge, completed and opened to traffic in 1986, is a two-lane, two-way bridge with 1.75m sidewalks on both sides. The bridge has a span of 5×20 m and a width of 12.5 m. The cross section is shown in Fig. 1. There are a total of 7 beams in the transverse direction, and 5 cross beams that are located at the two ends, L/4, 2L/4, and 3L/4. A single-piece T beam is 131 cm high, 158 cm wide, and the web plate is 18 cm thick. The cross-sectional dimensions are shown in figure 1.

![Figure 1. The cross-sectional dimensions (cm)](image)

2.2. Bridge diseases
The bridge has been in service for more than 30 years. Due to the low load grade originally designed, it has no longer met the increasing traffic demand. A comprehensive examination showed that the bridge, subject to heavy traffic load, had developed the following diseases:

1. Serious exposure of reinforcing steel bars in the concrete main beam;
2. Water seepage in wet joints and crossbeams, local exposure of steel bars due to concrete peeling-off;
3. Several oblique cracks near the main beam and the supports;
4. Longitudinal cracks at the mid-span of the main beam bottom and multiple vertical cracks in the web plate;
5. Aging and damaged rubber bearing and rusty expanded steel plates.

These diseases are primarily attributed to the insufficient shear capacity of the main beam near the support and the poor ultimate flexural capacity of the main beam near the mid-span under the joint action of the low concrete strength and increasing traffic load, consequently causing the concrete to crack. Due to the poor durability and the failure of the drainage system, the penetration of water into the concrete results in the rusting and expansion of the steel bars, and local peeling-off of the beam bottom.

3. Reinforcement design
According to the disease characteristics, the bridge was reinforced by ponding steel plates at bottom of the T beam, and the steel plates ponded were 8 mm thick and 18 cm wide. Starting from the end cross beam, 13 U-shaped steel plates were bonded on the web plate of the T beam, with each steel plate having a thickness of 8 mm and a width of 25 cm. The distance between steel plates was 10 cm. On the web plate of the L/4 span transverse beam near the midspan direction, a U-shaped steel plate was bonded. The geometric dimensions of the steel plate layout are shown in figure 2.
The specific construction techniques adopted are as below:

① Chiselling away the concrete in the damaged area of the beam. In the process, efforts are made to keep the concrete in the undamaged area intact as much as possible. After the chiselling, the steel bars are cleaned up and high-strength concrete is used for mending.

② The surface of concrete on which the plates are to be bounded shall be roughened and flattened, so as to make sure that the bounding surface is smooth and clean.

③ After the sheets of steel are cut into plates, the surface of the plates produced shall be treated with rust removal and polishing until metallic luster appears. The bounding surface of the steel plates after polishing shall be cleaned, positioning lines thereon shall be drawn, and installation holes are drilled with an electric drill at the designed places.

④ The steel plate is mounted on the installation holes drilled by bolts. After the installation, the nuts are tightened and planting-bar anchorage glue is injected into the bolt holes from the side.

⑤ The periphery of the steel plates is sealed. Edge banding glue is applied evenly with a spatula to the corners between the side of the steel plate and the concrete surface, and an appropriate pressing force is exerted to make the edge banding glue tightly bonded with the concrete and the side of the steel plate.

⑥ The edge banding glue shall be injected from one end of the steel plate to the other end under pressure that must be controlled within the range of 0.2-0.4 MPa. During the injection, the steel plate should be continuously knocked with a rubber hammer to improve the fluidity of the glue.

4. Load test

The strain and deflection in key control sections of the bridge structure were measured using static load tests, to provide technical support for the evaluation of the bridge in terms of safety and reliability. For the static and dynamic load testing, one of the spans in a 5×20m T beam was selected.

4.1. Finite element modeling

A simply supported T-beam bridge finite element model whose spans are 20 m long was built, as shown in figure 3, using the finite element software MIDAS. With the finite element model built, the parameters of static load testing were calculated, in an attempt to determine the number and location of the loaded vehicles and develop the ultimate scheme of the test.

Vehicle load: HS20 vehicle, crowd load: 3.5kN/m2. 330kN loading vehicles were used for static load testing, as shown in figure 4.
4.2. Static load test scheme

4.2.1. Test conditions
Since reinforcement with bonding steel plates was made for the 0-L/4 sections of the main girder to improve their shear resistance, so did the midspan section of the main girder to its bending resistance. Tests were carried out under the following five conditions:

| No. | Description |
|-----|-------------|
| I   | The MPBM of the mid-span section symmetrically distributed in a transverse direction |
| II  | The MPBM of the mid-span section distributed eccentrically on the left side in a transverse direction |
| III | The MPBM of the mid-span section distributed eccentrically on the right side in a transverse direction |
| IV  | The MSR of the near-the-support section distributed eccentrically on the left side in a transverse direction |
| IV  | The MSR of the near-the-support section distributed eccentrically on the right side in a transverse direction. |

Note: MPBM is short for the maximum positive bending moment; MSR is short for the maximum shear force.

4.2.2. Sections tested
Strain and deflection tests were conducted for the section near the support and the sections at the L/4, 2L/4, and 3L/4 spans, as shown in figure 5.

![Figure 5. Test section (cm)](image)

4.2.3. Layout of measuring points
Strain and deflection measuring points were laid out on each test section. Specifically, on all 7 main beams at the L/4, 2L/4, and 3L/4 span sections, measuring points were placed, with each section having 21 strain measuring points and 7 deflection measuring points. On the 1#, 2#, 6# and 7# T beams of the section near the support, shear stress measuring points were laid out. In addition, 5 deflection measuring points (supporting point, L/4, L/2, 3L/4, support point) were placed on both sides of the carriageway, as shown in figure 6.

(a) Strain measuring points of L/4, L/2, 3L/4
4.2.4. Positions of loading vehicles

As stipulated in Specification for Inspection and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2001), the efficiency of load tests for existing bridges shall be in the range of 0.95-1.05. According to the results of finite element calculation, 2330kN loading vehicles were placed to meet the requirements of load efficiency. The positions of the loading vehicles under each test condition are shown in figure 7.
4.3. Static load test results
Given that the volume of the test data was large, only the vital data of some typical test conditions were set out for analysis.

4.3.1. Condition I
Under the action of the MPBM of the mid-span section symmetrically distributed in the transverse direction of the bridge, the theoretical and measured strain values of each measuring point are shown in Table 2 and Figure 8.

Table 2. The theoretical and measured strain values of measuring point under the load of Condition I

| No. | Residual strain(με) | Elastic strain (με) | theoretical strain(με) | Strain calibration coefficients | maximum relative residual strain(%) |
|-----|---------------------|---------------------|-------------------------|-------------------------------|------------------------------------|
| 3   | 1                   | 10                  | 20                      | 0.50                          | 9.1                                |
| 6   | 1                   | 11                  | 24                      | 0.46                          | 8.3                                |
| 9   | 0                   | 13                  | 28                      | 0.46                          | /                                  |
| 12  | 2                   | 16                  | 30                      | 0.53                          | 11.1                               |
| 15  | 0                   | 14                  | 28                      | 0.50                          | /                                  |
| 18  | 1                   | 10                  | 24                      | 0.42                          | 9.1                                |
| 21  | 0                   | 9                   | 20                      | 0.45                          | /                                  |
As illustrated, under the load of Condition I, the strain calibration coefficients are between 0.46 and 0.53, all less than 1.0, and the maximum relative residual displacement is 11.1%, less than 20%.

Table 3. The theoretical and measured displacement of measuring point under the load of Condition I

| No. | Residual displacement (με) | Elastic displacement (με) | theoretical value(με) | Displacement calibration coefficients | maximum relative residual displacement(%) |
|-----|---------------------------|---------------------------|-----------------------|---------------------------------------|------------------------------------------|
| 6   | 0.1                       | 2.4                       | 5.4                   | 0.44                                  | 4.0                                      |
| 7   | 0.3                       | 3.8                       | 7.9                   | 0.48                                  | 7.3                                      |
| 8   | 0.2                       | 2.5                       | 5.6                   | 0.45                                  | 7.4                                      |
| 2   | 0.2                       | 2.2                       | 5.4                   | 0.41                                  | 8.3                                      |
| 3   | 0.4                       | 3.9                       | 7.9                   | 0.49                                  | 9.3                                      |
| 4   | 0.1                       | 2.6                       | 5.6                   | 0.46                                  | 3.7                                      |

As illustrated, under the load of Condition I, the strain calibration coefficients are between 0.41 and 0.49, all less than 1.0, and the maximum relative residual displacement is 9.3%, less than 20%.

4.3.2. Condition III

Under the action of the MPBM of the mid-span section distributed eccentrically on the right side in the transverse direction of the bridge, the theoretical and measured strain values of each measuring point are shown in table 4 and figure 10.
Table 4. The theoretical and measured strain of measuring point under the load of Condition III

| No. | Residual strain (με) | Elastic strain (με) | theoretical strain (με) | Strain calibration coefficients | the maximum relative residual displacement(%) |
|-----|---------------------|---------------------|-------------------------|-------------------------------|---------------------------------------------|
| 3   | 3                   | 28                  | 50                      | 0.56                          | 9.7                                         |
| 6   | 2                   | 23                  | 46                      | 0.50                          | 8.0                                         |
| 9   | 2                   | 22                  | 41                      | 0.54                          | 8.3                                         |
| 12  | 1                   | 15                  | 32                      | 0.47                          | 6.3                                         |
| 15  | 1                   | 12                  | 28                      | 0.43                          | 7.7                                         |
| 18  | 1                   | 8                   | 19                      | 0.42                          | 11.1                                        |
| 21  | 0                   | 5                   | 10                      | 0.50                          | 0.0                                         |

Figure 10. Theoretical and measured strain of Condition III

As illustrated, under the load of Condition III, the strain calibration coefficients are between 0.43 and 0.56, all less than 1.0, and the maximum relative residual displacement is 11.1%, less than 20%.

Under the action of the MPBM of the mid-span section distributed eccentrically on the right side in the transverse direction of the bridge, the theoretical and measured deflection values of each measuring point are shown in Table 5 and figure11.

Table 5. The theoretical and measured strain of measuring point under the load of Condition III

| No. | Residual strain (με) | Elastic strain (με) | theoretical strain (με) | Strain calibration coefficients | the maximum relative residual displacement(%) |
|-----|---------------------|---------------------|-------------------------|-------------------------------|---------------------------------------------|
| 6   | 0.2                 | 3.4                 | 7.0                     | 0.49                          | 5.6                                         |
| 7   | 0.4                 | 5.2                 | 10.4                    | 0.50                          | 7.1                                         |
| 8   | 0.2                 | 3.7                 | 7.4                     | 0.50                          | 5.1                                         |
| 2   | 0.1                 | 0.7                 | 1.8                     | 0.39                          | 12.5                                        |
| 3   | 0.1                 | 1.1                 | 2.7                     | 0.41                          | 8.3                                         |
| 4   | 0.1                 | 0.8                 | 1.9                     | 0.42                          | 11.1                                        |
As illustrated, under the load of Condition III, the strain calibration coefficients are between 0.39 and 0.50, all less than 1.0, and the maximum relative residual displacement is 12.5%, less than 20%.

4.3.3. Condition V

Under the action of the MSR of the near-the-support section distributed eccentrically on the right side in a transverse direction, the theoretical and measured strain values of each measuring point are shown in Table 6. The values of strain in the three directions were calculated according to formula (1), and the maximum shear strain value was worked out.

\[
\gamma = \sqrt{(\varepsilon_{\phi} - \varepsilon_{\phi0})^2 + (2\varepsilon_{\phi} - \varepsilon_{\phi0} - \varepsilon_{\theta0})^2}
\]

As illustrated in Table 6, under the load of Condition III, the strain calibration coefficients are between 0.56 and 0.58, all less than 1.0, and the maximum relative residual displacement is 10.0%, less than 20%.

5. Conclusion

This study reinforced a 5×20m simple-supported T-beam bridge using bonded steel plates according to its disease characteristics and verified the reinforcement effect through static load tests.

1) Under the static load test conditions, both the strain and deflection calibration coefficients of the structure of the bridge reinforced with steel plates were less than 0.1, and both the maximum relative residual displacement and the maximum relative residual strain were less than 20%, suggesting that the bridge after reinforced with bonded steel plates meets the requirements of design load standards for bearing capacity and rigidity.

2) The reinforcement with bonded steel plates can effectively address the problem of diagonal cracking in the web of T beam bridges near the support caused by insufficient shear resistance, and the problem of vertical cracking in the web of T beam bridges near the midspan resulting from the insufficient bending resistance.

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