Scientific Research

Study on the Dynamic Performance of a Bridge Reinforced with CFRP Plates

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Abstract: Using carbon fiber reinforced polymer (CFRP) plates is currently an effective technique for bridge reinforcement. This study fully introduces a dynamic performance test of a bridge reinforced with prestressed CFRP plates, including a structural modal test, moving vehicle test, braking test, and bumping test. The dynamic displacement, dynamic strain, and related impact effects of the structure were monitored, which demonstrated the high effectiveness of prestressed CFRP plates in reinforcing bridges. Relevant findings and data provide a reference for the dynamic testing of similar bridges.

Keywords: CFRP plate; prestress; bridge reinforcement; dynamic test

1 Introduction

Since the late 1980s, China has been developing carbon fiber-reinforced polymer (CFRP) reinforcement technology and applying it in the repair of civil structures. In the 1990s, it had been used to reinforce and repair bridges, tunnels, water conservancy projects and other special structures in addition to industrial and civil buildings [1]. With the development of technology and the increase of social needs, CFRP materials began to be used for the seismic reinforcement of bridge structures, marine and port engineering, etc. They have been considered one of the most promising reinforcement methods [2].

Traditional concrete structure reinforcement technology using CFRP attaches CFRP sheets to the structure but does not apply prestress. As a result, the high-strength properties of CFRP materials fail to come into play. The greater strength of CFRP materials can only be utilized when the structure undergoes a large deformation. For a cracked structure, further deformation may reduce the structural performance. When CFRP and steel bars work together, the steel bars fully exert their strength, while only less than 20% of the strength of the CFRP material comes into play. Thus, the structure cannot fully utilize the strength of the CFRP within the load [3-5]. To prevent structural deformation and crack propagation, a large amount of CFRP materials is required, which mitigates its high-strength advantages and economic benefits. This restricts the further application of CFRP-reinforced composites in reinforcement.

The prestressed CFRP plate anchoring system solves this problem by applying prestress to the CFRP-reinforced composites [3, 6]. After the prestress is applied to the CFRP, the component has exerted high strength before bearing the load, which not only effectively utilizes the high-strength characteristics of the CFRP but also controls the deformation and crack propagation of the component. Having solved the problem of the large ratio of CFRP strength to elastic modulus, this approach effectively improves the cracking load, flexural rigidity and other properties of the flexural members. The utilization of CFRP strength far exceeds a situation without prestressing, which produces great economic and social benefits [1, 2, 7].

Citation: Li, Y. Study on the Dynamic Performance of a Bridge Reinforced with CFRP Plates. *Prestress Technology* **2023**, 2, 38-50. https://doi.org/10.59238/j.pt.2023.02.004

Received: 05/03/2023
Accepted: 17/05/2023
Published: 25/06/2023

2 Engineering Background

A highway bridge is considered with a total length of 452.53 m, a bridge width combination of 0.5+10.25+0.75 m, and an intersection angle of 90°. It was completed and opened to traffic in November 1994. The upper structure is built with continuous hollow prestressed concrete slab girders: the first, second and third parts are 5×25.0 m; the fourth part is 15.5+2×22.0+15.5 m. The design load is automobile: 20 t and trailer: 120 t. The seismic grade is grade VII. For a photo of the bridge before reinforcement, see Figure 1.

Figure 1 Bridge bottom before reinforcement

The CFRP plate and anchoring system used in this reinforcement project are provided by the Liuzhou OVM Machinery Co., Ltd. The anchoring system has an anchoring efficiency of ≥ 95% for CFRP materials and a total strain of ≥ 1.2%, which enables the properties of CFRP materials to be fully utilized. Figure 2 shows the CFRP after reinforcement.

Figure 2 Bridge bottom after reinforcement

Since the study objective is the difference in the mechanical properties of bridges before and after reinforcement, we focus on comparing the changes of performance before and after reinforcement. On the basis of testing whether the actual force condition of the bridge structure meets the requirements of the design and specifications after it is reinforced with prestressed CFRP plates, an overall evaluation is made on the reinforcement effect of the bridge structure through an on-site loading test and a comprehensive analysis of the test observation data and test phenomena. Additionally, the actual working status of existing bridges is tested to provide basic data for a comprehensive evaluation of the bridge reinforcement effect [8, 9].

3 Dynamic Test Scheme

According to the purpose of this load test and the reinforcement scheme, since the fourth part (15.5+2×22.0+15.5m) only reinforces the third hole on the right side (i.e. the 18th hole of the whole bridge), this hole is selected as the test span. The bridge reinforcement position and test span are shown in Figure 3. The reinforced cross-section of the bridge is shown in Figure 4.

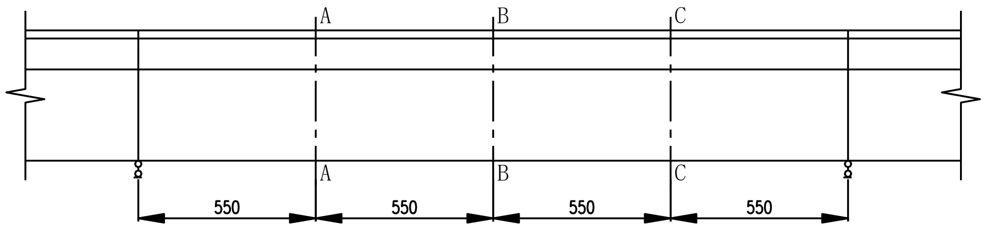

Figure 3 Longitudinal arrangement of test sections (Unit: cm)

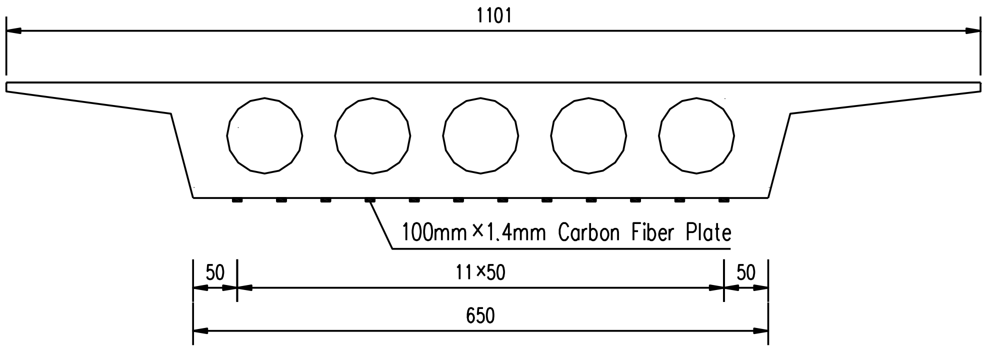

Figure 4 Reinforced cross-section of the bridge (Unit: cm)

Limited by the length of this article, the dynamic performances of the bridge before and after reinforcement are introduced here. In this dynamic test, combined with relevant design documents, completion data, previous inspections, and maintenance and reinforcement data, it is loaded by standard highway – grade I for the design load of the bridge, with the equivalent automobile load. The load standard and loading method are used for relevant load tests in accordance with the General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015), Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018), Specification for Inspection and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2011), and Load Test Methods for Highway Bridge (JTG/T J21-01-2015).

3.1 Test Scheme

3.1.1 Overall Plan

According to the structural characteristics of the third bridge span, three sections A-A, B-B and C-C are selected as the test sections. The longitudinal arrangement plan of the test sections is shown in Figure 3.

In the test, four carbon plates are used for the FBG coupling test. Their layout is shown in Figure 5. In particular, #1 and #3 are stretched as per the design stress, while #2 and #4 are not stretched.

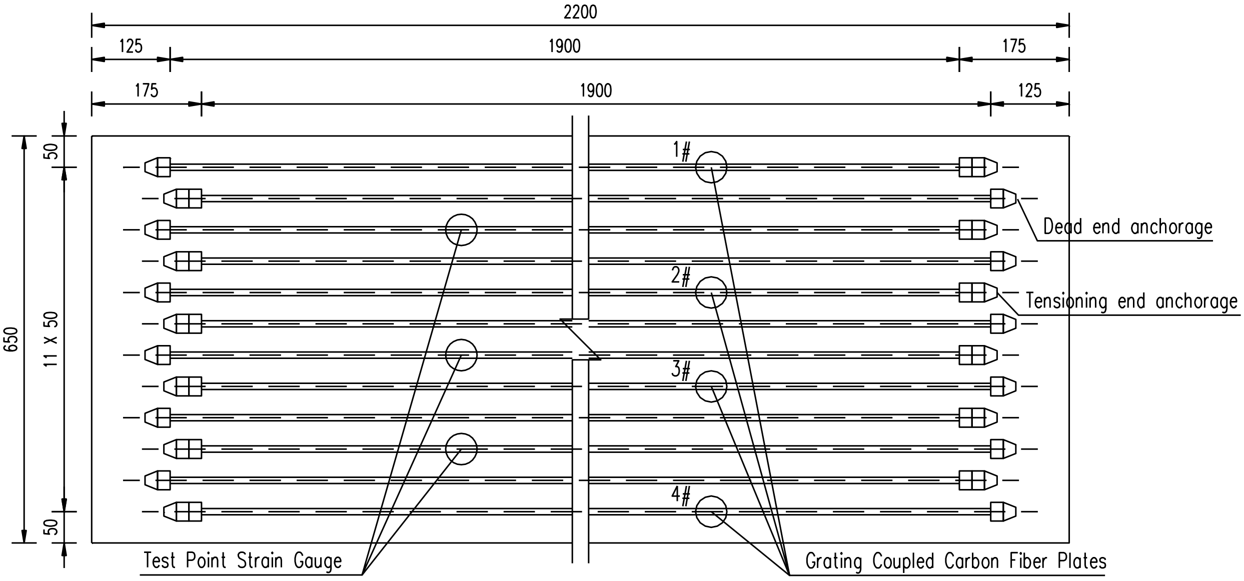

Figure 5 Layout of carbon plates for grating coupling test (Unit: cm)

3.1.2 Arrangement of Measuring Points

(1) Speed measuring points: A vertical acceleration sensor is arranged at the upstream and downstream sides of the B-B section at the mid-span, and a horizontal acceleration sensor is provided at the upstream side. Figure 6 shows the layout of horizontal acceleration sensor.

(2) Dynamic strain measuring points: Two dynamic strain measuring points are arranged at the bottom of the B-B section beam at the mid-span. See Figure 6 for the horizontal arrangement plan of dynamic strain.

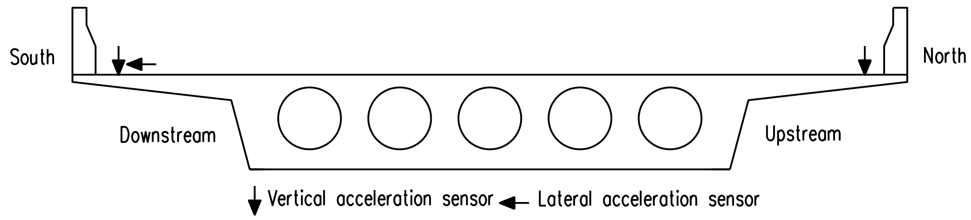

Figure 6 Arrangement of measuring points at the cross section for acceleration sensor

3.2 Test Loading Conditions

(1) Moving vehicle condition: A vehicle of 350 kN travels over the bridge at 20 km/h, 30 km/h, and 40 km/h to test the dynamic stress and forced vibration frequency of the B-B section.

(2) Braking condition: A vehicle of 350 kN travels over the bridge at 30 km/h to measure the dynamic stress and vibration performance of the B-B section.

(3) Bumping condition: A vehicle of 350 kN passes over a 15-cm triangular wood plank and then brakes to test the vibration performance of the bridge.

4 Dynamic Load Test and Comparative Analysis

From a test and analysis before reinforcement, we have the following comparison results: changes of natural frequency and damping ratio obtained through a structural mode analysis before and after reinforcement; a comparison of the maximum dynamic displacement at the mid-span, the maximum dynamic strain of the concrete, the maximum dynamic strain of the CFRP plate, and the impact coefficient through the moving vehicle test at different speeds; a comparison of the maximum dynamic displacement at the mid-span, the maximum dynamic strain of the concrete, and the maximum dynamic strain of the CFRP plate through the braking test at 30 km/h; and a comparison of the impact coefficient and damping ratio through the bumping test.

4.1 Modal Analysis

Channels 1-1, 1-4, and 1-3 correspond to the velocity vibration pickups at the bridge deck of the A-A section, B-B section, and C-C section, respectively. The time histories before and after reinforcement are shown in Figures 7 and 8.

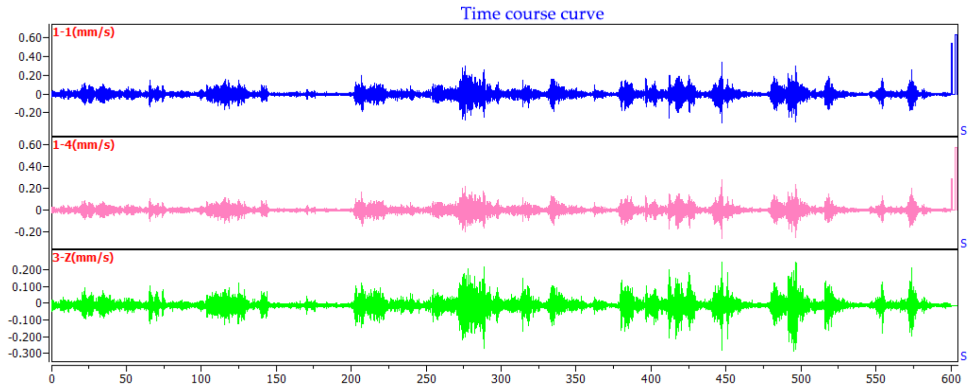

Figure 7 Time histories before reinforcement

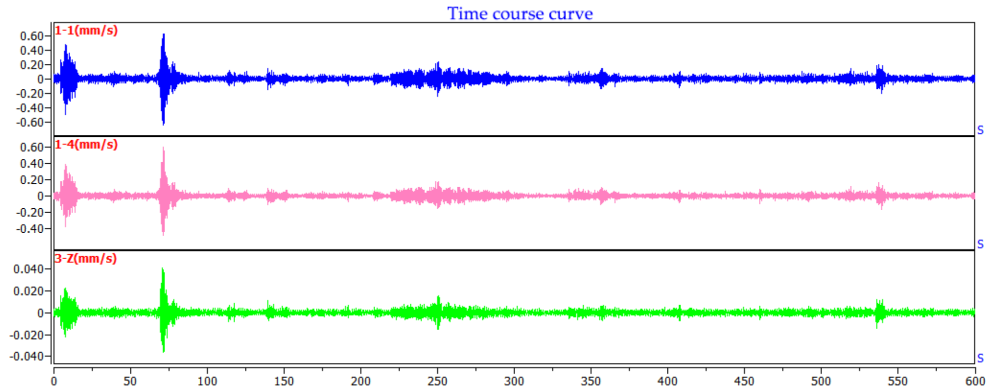

Figure 8 Time histories after reinforcement

The time history and spectrum curves before and after reinforcement are shown in Figures 9 and 10.

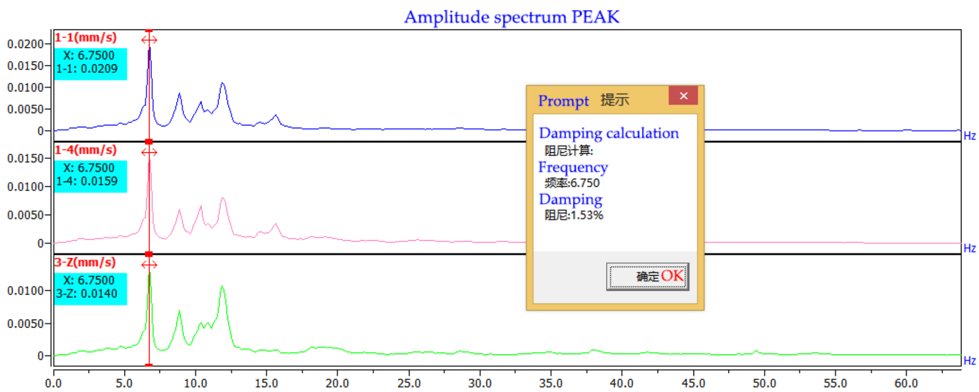

Figure 9 Spectra before reinforcement

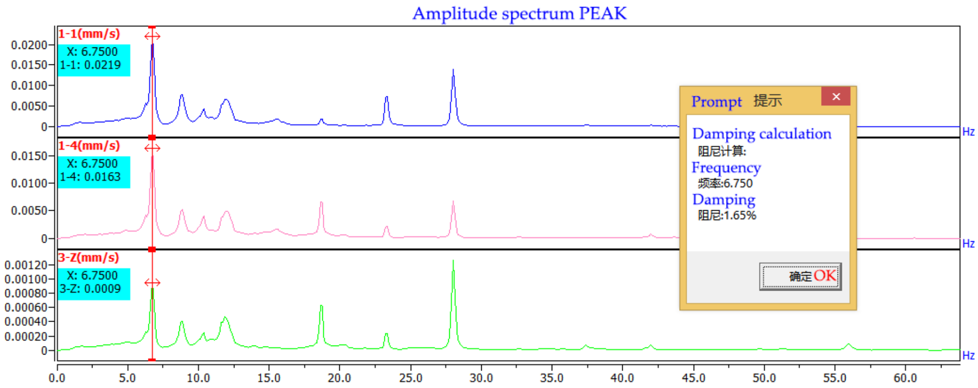

Figure 10 Spectra after reinforcement

It can be seen in the analysis of the time histories that the natural frequency and damping ratio of the bridge are 6.750 Hz and 1.53%, respectively.

A comparison between the modal analysis results of the load test before and after reinforcement is shown in Table 1 below.

Table 1 Comparison between the modal analysis results of the load test before and after reinforcement

Items	Before Reinforcement	After Reinforcement	Improvement Rate
Natural frequency	6.750 Hz	6.750 Hz	0%
Damping ratio	1.53%	1.53%	0%

It can be seen in Table 1 that the change rates of natural frequency and damping ratio before and after reinforcement are both 0. In summation, the free vibration system of the main structure of the bridge has a high vibration frequency in the first order, and the stiffness of the bridge is large. Thus, reinforcement almost has no impact on the natural frequency and damping ratio of the bridge.

4.2 *Moving Vehicle Test*

Channel 1-1 corresponds to the No. 3 strain measuring point of B-B section, channels 1-2 and 1-3 to the No. 1 and No. 2 displacement measuring points of B-B section, channel 1-4 to the strain measuring point on the CFRP plate in the middle of B-B section, and channel 3-Z to the velocity vibration pickup at the bridge deck of the B-B section.

For example, when the moving vehicle speed is 20 km/h, the maximum dynamic dis-placement at the mid-span is 0.8232 mm, such as in channel 1-3; the maximum dynamic strain on the mid-span concrete is 8.6495 $\mu\varepsilon$, as shown in channel 1-1 of the line diagram; the maximum dynamic strain on the mid-span CFRP plate is 21.0724 $\mu\varepsilon$, such as in channel 1-4. The comparison results are shown in Table 2. For relevant time histories, see Figures 11–14.

Table 2 Results of load tests after reinforcement under moving vehicle conditions

No.	Velocity (km/h)	Maximum Dynamic Displacement (mm)	Maximum Dynamic Strain of Concrete ($\mu\varepsilon$)	CFRP Plate Dynamic Strain of Concrete ($\mu\varepsilon$)	Impact Coefficient
1	20	0.8232	8.6495	21.0724	1.12
2	30	0.7748	8.6495	21.0724	1.21
3	40	0.6873	7.2369	18.4162	1.28

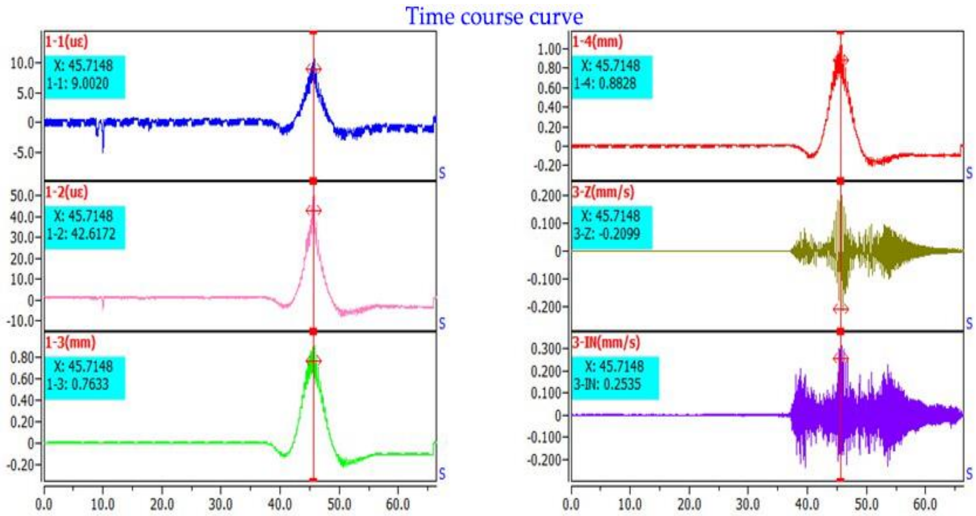

Figure 11 Time histories before reinforcement under moving vehicle conditions

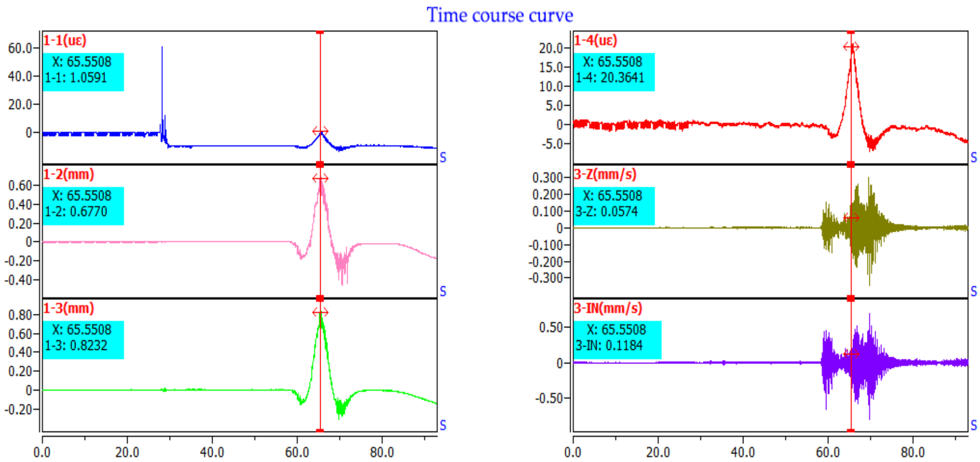

Figure 12 Time histories after reinforcement under moving vehicle conditions

When the vehicle moves at 20 km/h, the time history curve is analyzed. The impact coefficients before and after reinforcement are 1.24 and 1.12, respectively.

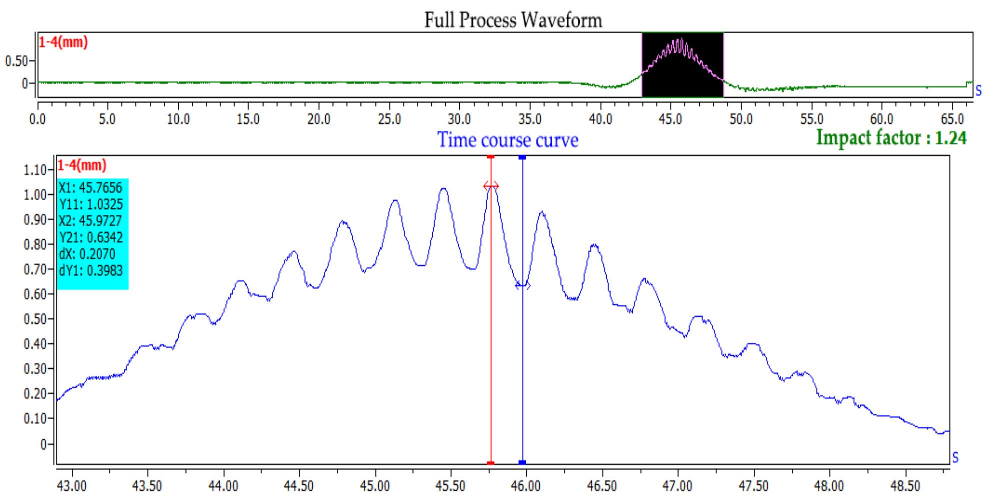

Figure 13 Displacement time history segment before reinforcement under moving vehicle conditions

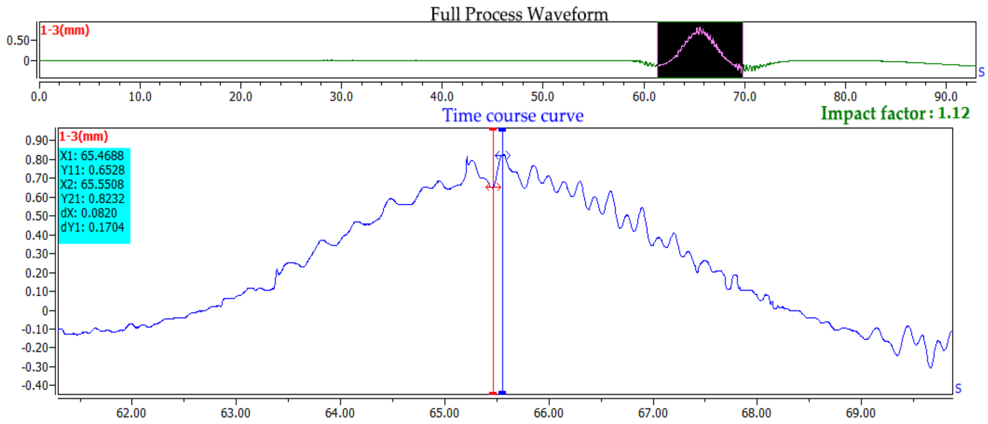

Figure 14 Displacement time history segment after reinforcement under moving vehicle conditions

The comparison between maximum dynamic displacements at mid-span is shown in Table 3.

Table 3 Comparison between maximum dynamic displacement (mm) at mid-span

No.	Moving vehicle Condition (km/h)	Before Reinforcement	After Reinforcement	Change Rate (%)
1	20	0.8828	0.8232	-6.75
2	30	0.9807	0.7748	-21.00
3	40	0.9254	0.6873	-25.73

According to the comparison between maximum dynamic displacements at mid-span, the following conclusions can be drawn:

(1) At different moving vehicle speeds, the maximum dynamic displacement at mid-span after reinforcement is smaller than that before reinforcement, decreasing up to 25.73%;

(2) With the increase in moving vehicle speed, the change rate of the mid-span dynamic displacement before and after reinforcement gradually rises;

(3) Reinforcing with prestressed CFRP plate can effectively improve the dynamic response of the bridge (maximum dynamic displacement of mid-span).

The comparison between the mid-span maximum dynamic strains of concrete is shown in Table 4.

Table 4 Comparison between mid-span maximum dynamic strain ($\mu\varepsilon$) of concrete

No.	Moving Vehicle Condition (km/h)	Before Reinforcement	After Reinforcement	Change Rate (%)
1	20	9.0020	8.6495	-3.92
2	30	9.7081	8.6495	-10.90
3	40	8.8255	7.2369	-18.00

According to the comparison between maximum dynamic strains at mid-span, the following conclusions can be drawn:

(1) At different moving vehicle speeds, the maximum dynamic strain at mid-span after reinforcement is smaller than that before reinforcement, decreasing up to 18.00%;

(2) With the increase in moving vehicle speed, the change rate of the mid-span dynamic displacement before and after reinforcement gradually rises;

(3) Reinforcing with prestressed CFRP plate can effectively improve the dynamic response of the bridge (maximum dynamic strain of mid-span).

The comparison between maximum dynamic strains at mid-span for the CFRP plates is shown in Table 5.

Table 5 Comparison between maximum dynamic strain ($\mu\varepsilon$) of mid-span CFRP plate

No.	Moving vehicle Condition (km/h)	After Reinforcement
1	20	21.0724
2	30	21.0724
3	40	18.4162

According to the table above, with the increase in moving vehicle speed, the change rate of the maximum dynamic strain at mid-span for the CFRP plate decreases after reinforcement.

Table 6 shows a comparative analysis of impact coefficient.

Table 6 Comparative analysis of impact coefficient

No.	Moving vehicle Condition (km/h)	Before Reinforcement	After Reinforcement	Change Rate (%)
1	20	1.24	1.12	-9.68
2	30	1.22	1.21	-0.82
3	40	1.12	1.28	14.29

It can be seen from the impact coefficients under different moving vehicle conditions before and after reinforcement that after reinforcement, the vertical dynamic force produced by the bridge structure increases, the coefficient decreases, and the dynamic characteristics of the bridge are improved when the automobile travels across the bridge. It is recommended to control the construction quality and ensure the flatness of the bridge deck to reduce the impact effect of the bridge when repaving the bridge deck.

4.3 Braking test 30 km/h

Under braking conditions, the maximum dynamic displacement at mid-span is 0.8047 mm, such as in channel 1-3; the maximum dynamic strain on the mid-span concrete is 10.4141 $\mu\varepsilon$; the maximum dynamic strain at mid-span CFRP plate is 21.4265 $\mu\varepsilon$, such as in channel 1-4. For relevant mileage curves, see Figures 15–18.

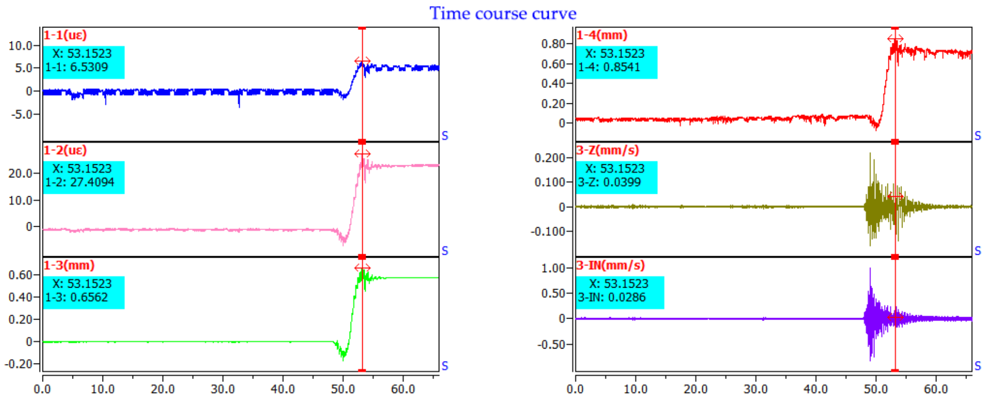

Figure 15 Time histories before reinforcement when braking

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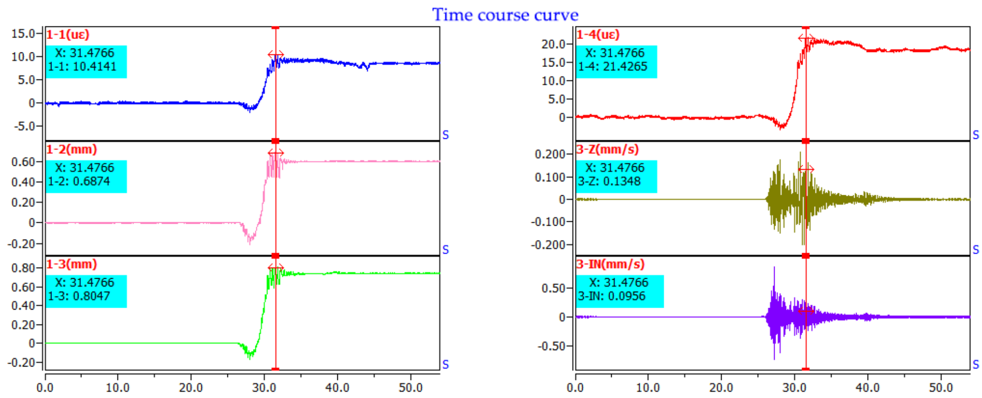

Figure 16 Time histories after reinforcement when braking

Under the braking condition of 30 km/h, the time histories are analyzed. It can be seen that the impact coefficient is 1.10, and 1.15 after reinforcement, with the change rate being 4.5%. The impact coefficient increases compared to a normal moving vehicle test at the same speed.

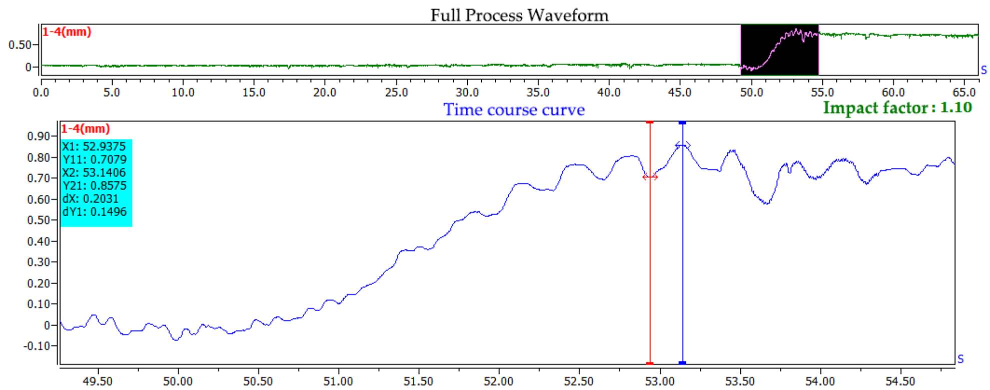

Figure 17 Time history segment analysis before reinforcement when braking

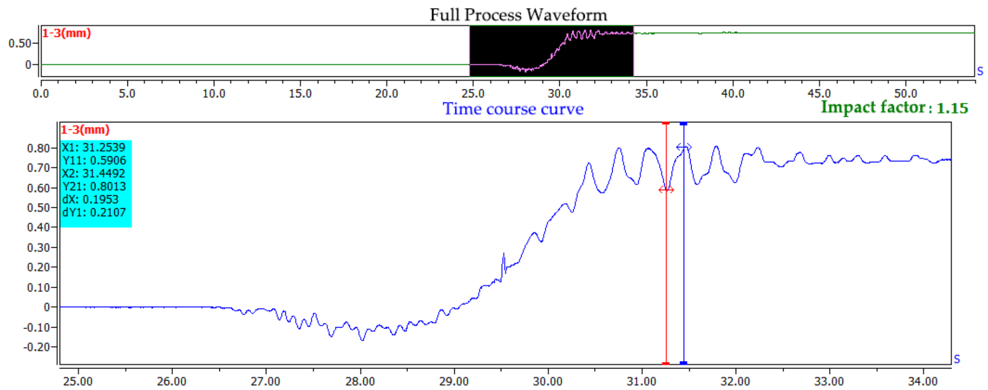

Figure 18 Time history segment analysis after reinforcement when braking

A comparison of mid-span related results is shown in Table 7 under the braking condition of 30 km/h before and after reinforcement.

Table 7 Comparison of results before and after reinforcement under the braking condition of 30 km/h

No.	Test Item	Before Reinforcement	After Reinforcement	Change Rate (%)
1	Maximum Dynamic Displacement (mm)	0.8541	0.8047	-5.78

No.	Test Item	Before Reinforcement	After Reinforcement	Change Rate (%)
2	Maximum Dynamic Strain of Concrete ($\mu\varepsilon$)	6.5309	10.4141	59.46
3	Dynamic Strain of CFRP Plate ($\mu\varepsilon$)	/	21.4265	/

It can be seen in the comparison of the results before and after reinforcement under the braking condition of 30 km/h that after reinforcement, the maximum dynamic displacement at mid-span decreases, while the maximum dynamic strain at mid-span concrete increases by nearly 60%.

4.4 Bumping test

Before reinforcement: Under bumping conditions, the time history curve is analyzed. The impact coefficient is 1.40. By analyzing the speed measuring point 3-Z, we know the damping ratio is 2.93%.

After reinforcement: Under bumping conditions, the time history curve is analyzed. The impact coefficient is 1.37. By analyzing the speed measuring point 3-Z, we know the damping ratio is 1.65%.

For relevant time histories, see Figures 19–24.

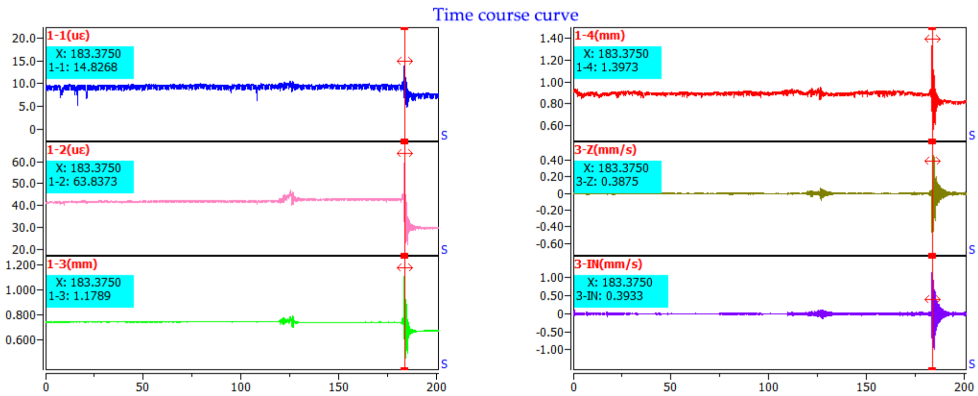

Figure 19 Time history curve analysis before reinforcement when bumping

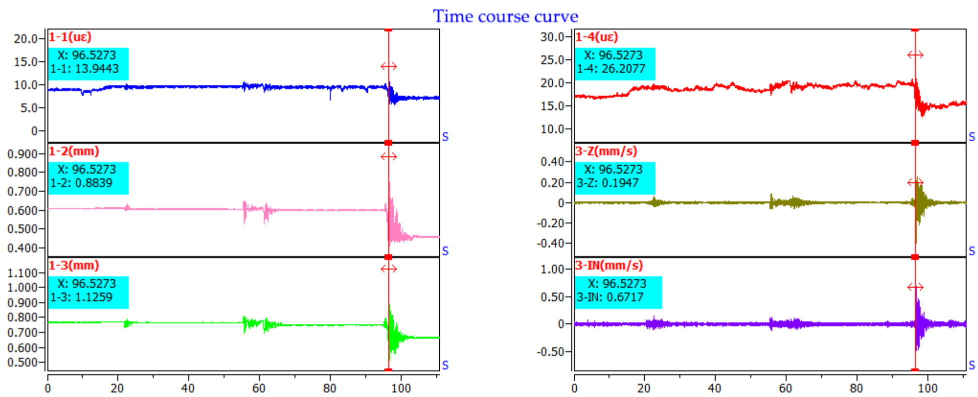

Figure 20 Time histories after reinforcement when bumping

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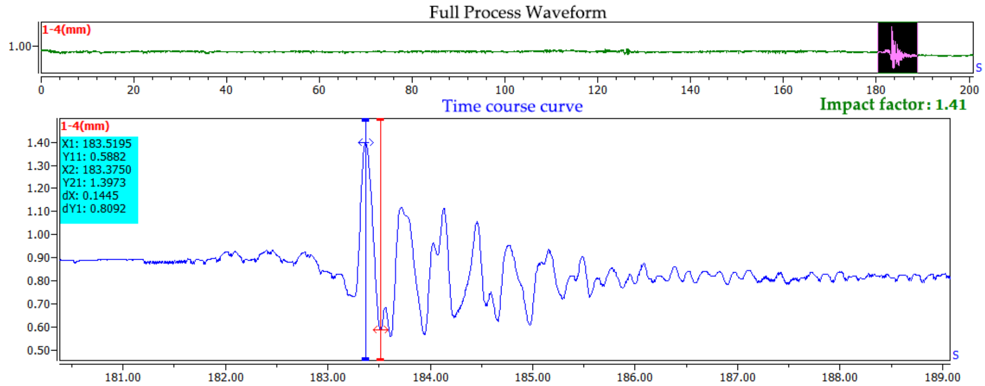

Figure 21 Time history segment analysis before reinforcement when bumping

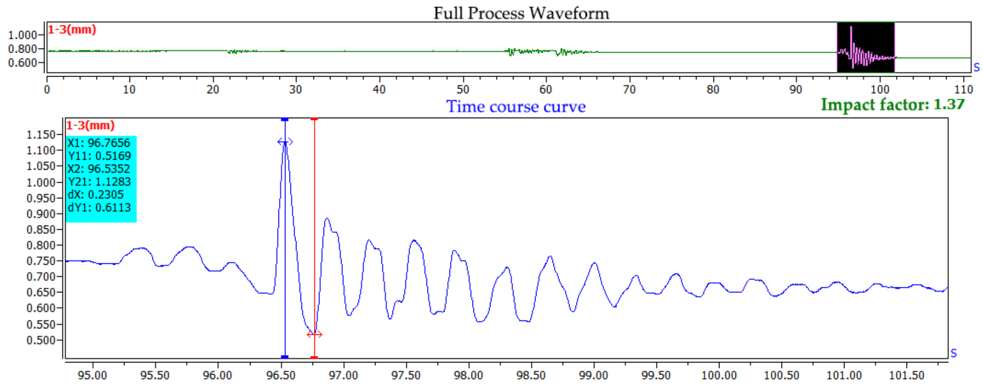

Figure 22 Time history segment analysis after reinforcement when bumping

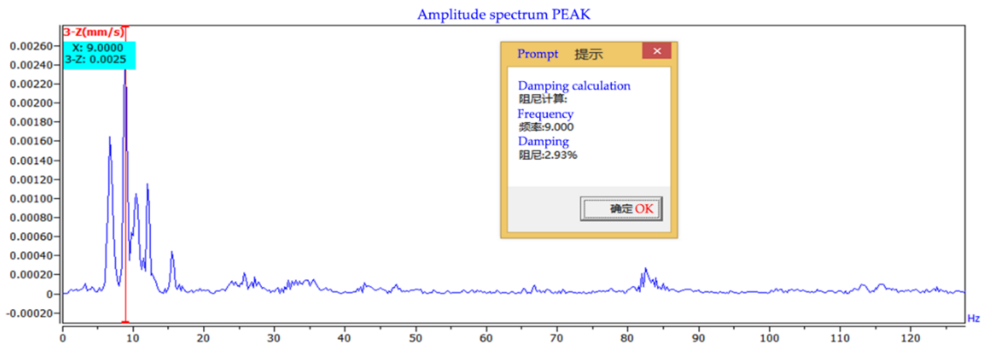

Figure 23 Spectra before reinforcement when bumping

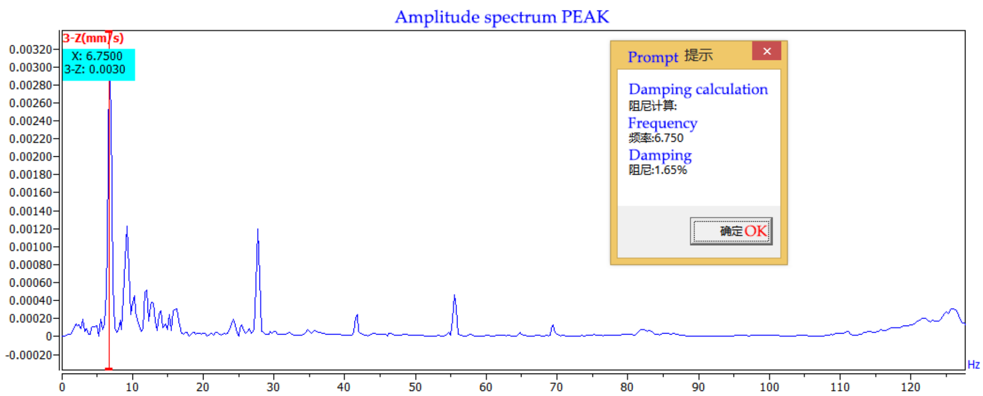

Figure 24 Spectra after reinforcement when bumping

A comparison between the results of the bumping test before and after reinforcement is shown in Table 8.

Table 8 Comparison of results before and after reinforcement under bumping conditions

No.	Test Item	Before Reinforcement	After Reinforcement	Change Rate
1	Impact Coefficient	1.40	1.37	-2.14%
2	Damping ratio	2.93%	1.65%	-43.69%

It can be seen in the table showing the comparison of results before and after reinforcement under bumping conditions that the impact coefficient and damping ratio before and after reinforcement both declined, with a larger decrease in damping ratio, reaching 43.69%.

5 Conclusions

(1) It can be seen in the forced vibration characteristics and natural vibration characteristics of the bridge before and after reinforcement under the action of dynamic load excitation and fluctuating load that the bridge has good dynamic characteristics, which are further improved after reinforcement.

(2) The modal analysis results show that, due to the inherent properties of CFRP materials, the construction of prestressed CFRP plates has little impact on the bridge structure.

(3) The moving vehicle test results indicate that the mid-span dynamic displacement, dynamic strain of concrete, and impact coefficient change after reinforcement, which means the overall stiffness of the structure has been improved after reinforcement.

(4) In the braking test, the impact coefficient increases compared to the normal moving vehicle test at the same speed, which also proves the recovery of structural performance.

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