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Article

Research on dynamic characteristics of reinforced concrete supported girder bridges strengthened by plate–truss combination

Mulin Pang[1], Wenxin Gou[1], Xiaoli Xie[1], Donglin Meng[2,3,*], Feng Cao[2]

[1] Key Laboratory of Disaster Prevention and Structural Safety of China Ministry of Education, College of Civil Engineering and Architecture, Guangxi University, Nanning 530004, China

[2] Guangxi University Engineering Research Center for Green and Low-Carbon Urban Regeneration Construction, School of Architecture and Electrical Engineering, Hezhou University, Hezhou 542899, China

[3] Guangxi Heyuan Technology Development Limited Liability Company, Hezhou 542899, China

*** Corresponding author:** Donglin Meng, 201200024@hzxy.edu.cn

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Abstract: Existing strengthening methods for reinforced concrete simply supported girder bridges are predominantly based on local reinforcement, which limits their effectiveness in improving global structural performance. To address this limitation, a novel strengthening approach, namely the Method of Plate–Truss Combination Reinforcement (MPTCR), is proposed to transform the structural force system. In this method, steel trusses and a bridge deck system are integrated with the existing girder through reliable connectors to form a plate–truss composite system (PTCS), thereby enhancing stiffness and redistributing internal forces. An engineering case study is investigated using finite element analysis and field dynamic load testing. The results show that the fundamental frequency increases by 31.5% after strengthening, while the deflection is reduced by 38.2%. The measured fundamental frequency (9.452 Hz) agrees well with the numerical result (8.883 Hz), with a relative error of 6.4%. Moreover, the measured impact coefficients are significantly lower than the code-based value, indicating improved dynamic performance. The findings demonstrate that the proposed method effectively enhances global stiffness, mitigates tensile stress in the original girder, and improves the dynamic behavior of the structure. This study provides a practical and efficient solution for the rehabilitation of aging girder bridges.

Keywords: the method of plate-truss combination reinforcement; dynamic load test; natural frequency; impact coefficient; in-plane stiffness; dynamic performance

1. Introduction

Reinforced concrete (RC) simply supported hollow-slab bridges have been widely used in highway and railway bridge construction due to their simple structure, ease of construction, adaptability, and excellent economic performance. However, as traffic volumes increase and vehicle loads rise, these bridges often develop cracks after prolonged service. The resulting decrease in stiffness leads to a decline in dynamic performance, making the structures highly susceptible to resonance and collapse when vehicles pass over them. Given the large number of such bridges and their frequent location on major transportation routes, complete demolition and reconstruction would not only cause traffic disruptions but also entail extremely high costs. Conversely, continuing to operate them in their current condition poses significant safety risks. Therefore, conducting research on the retrofitting and reinforcement of RC simply supported hollow-slab bridges holds significant practical engineering importance.

Currently, the primary reinforcement methods for RC simply supported hollow-slab bridges include the steel plate bonding method, the fiber-reinforced polymer (FRP) bonding method, and the external prestressing method [1–3]. Among these, the steel plate bonding method can improve the member's flexural capacity and suppress crack propagation to a certain extent; however, it places high demands on the quality of steel plate anchoring and adhesion [4]. Under repeated fatigue loading, steel-concrete delamination is likely to occur, leading to a loss of reinforcement effectiveness [5, 6]. Furthermore, this method requires periodic anti-corrosion treatment, resulting in high long-term maintenance costs [7–9]. Although FRP materials offer advantages such as high strength, high efficiency, light weight, fatigue resistance, and corrosion resistance [10–12], they have low stiffness, poor fire resistance and energy dissipation capacity, and are prone to brittle failure [13–16]. The two methods mentioned above are essentially local reinforcements that can only barely maintain the structure's existing load-bearing capacity and are unable to effectively enhance its overall mechanical performance. The external prestressing reinforcement method can significantly improve a member's flexural strength and crack resistance [17–19]; however, it requires the installation of anchorage devices or deflection blocks, involves complex construction techniques, suffers from significant stress concentration in the anchorage zone, and the exposed prestressing tendons are susceptible to corrosion, resulting in poor durability and adaptability [20–23]. It is evident that current reinforcement methods primarily focus on increasing the structural load-bearing capacity; however, none of these methods alter the force-bearing mechanism of the structural system. Consequently, they cannot fundamentally improve the structural stiffness, and the dynamic characteristics of the structure remain unaddressed. Therefore, starting from the renovation of the structural system to enhance the stiffness of damaged hollow-slab bridges and thereby improve their dynamic characteristics is an effective approach to ensuring that old bridges meet current traffic demands.

It is well known that truss structures, due to the significant vertical spacing between their upper and lower chords, possess an effective beam height that is far greater than that of solid beams of the same span [24]. Since the bending stiffness of a structure is proportional to the square of the beam height, truss structures can significantly increase the bending stiffness of the cross-section while using a comparable amount of material. Based on this mechanical principle, the concrete slab of the existing hollow-slab bridge can be utilized as the lower chord of a composite section, while the newly added steel truss serves as the upper chord and web system. The two components are connected through reliable shear connectors to form an integrated load-bearing structure. This construction method artificially increases the calculated height of the composite section without altering the original bridge deck elevation, thereby substantially enhancing the overall flexural stiffness of the structure. The increased stiffness directly limits deflection and rotational deformation under vehicle loads, thereby improving the bridge's dynamic characteristics, such as increasing the natural frequency, reducing the impact coefficient, and enhancing vibration stability. Compared to localized reinforcement methods that rely solely on surface strengthening—such as bonding steel plates or FRP—the addition of steel trusses fundamentally transforms the original bridge from a weak flexural member into a composite truss structure by altering the structural load-bearing system. This approach achieves a fundamental improvement in the stiffness and dynamic performance of the existing bridge. Therefore, this method offers clear mechanical advantages and promising application prospects for addressing engineering issues such as insufficient stiffness reserves and severe dynamic responses in existing RC simply-supported hollow-slab bridges.

Dynamic characteristics are key indicators for assessing bridge stiffness and structural integrity, as well as vehicle safety and ride comfort [25,26]. Therefore, using a dynamic detection method, focusing on the dynamic characteristics of the reinforced structure, has important guiding significance. Specifically, dynamic parameters such as the bridge's natural frequencies and mode shapes directly reflect the distribution of the structure's overall stiffness and the actual boundary conditions; meanwhile, the impact coefficient and vibration response under vehicle loads determine ride smoothness and passenger comfort, while also indicating, to a certain extent, the structure's fatigue performance and safety margin during long-term service. For RC simply supported hollow-slab bridges reinforced with a composite slab-truss system, the significant increase in the stiffness of the composite cross-section directly leads to an increase in the first-order vertical natural frequency. This shifts the structure away from the excitation frequency range of common vehicle loads, thereby effectively reducing the risk of resonance [27–29].

A novel strengthening method, namely the Method of Plate–Truss Combination Reinforcement (MPTCR), is proposed to improve reinforced concrete simply supported girder bridges by transforming the original structural force system rather than relying on conventional local strengthening techniques. The underlying mechanical mechanisms of the proposed method are clarified from the perspectives of stiffness enhancement, tensile stress reduction, and internal force redistribution. The effectiveness and feasibility of the method are further verified through a combination of finite element analysis and field dynamic load testing. In addition, the improvements in dynamic characteristics, including natural frequency and impact response, are quantitatively evaluated. The findings of this study provide both theoretical support and practical guidance for the rehabilitation and upgrading of aging girder bridges.

2. The MPTCR and mechanics principle

The Method of Plate–Truss Combination Reinforcement (MPTCR) is a strengthening approach that transforms the original structural force system and optimizes the stress distribution of the bridge. In this method, the reinforcement bars of the existing main girder are firmly connected to those of the truss by means of uplift-resistant shear connectors. Subsequently, concrete is cast in situ for both the truss and the bridge deck to further ensure the reliability and integrity of the connection. As a result, a plate–truss composite structural system (PTCS), consisting of the truss, bridge deck, and main girder, is formed, as shown in **Figure 1**. With the introduction of the truss system, the structural behavior is transformed from that of the original girder-dominated system to a plate–truss composite force system, thereby fully utilizing the superior load-carrying efficiency of the truss and improving the overall structural performance.

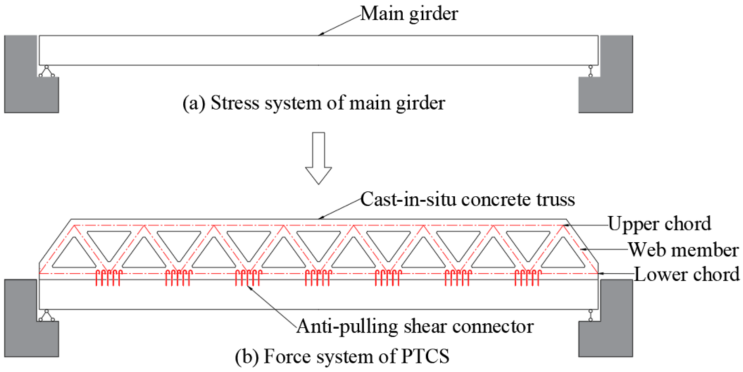


Figure 1. The Method of Plate-Truss Combined Reinforcement.

The mechanical principles of the proposed method are described as follows.

2.1. Increasing the girder depth to enhance structural stiffness and natural frequency

In reinforced concrete bridges, self-weight constitutes a significant proportion of the total load, which often limits the feasible depth of the girder.

$$\sigma_{max} = \frac{M_{max}h}{I} = \frac{M_{max}}{W}, \tag{1}$$

where W is elastic section modulus, for a rectangular section, $W = bh^2/6$.

It can be observed that the maximum normal stress of the girder is inversely proportional to the square of the girder depth. In other words, under a constant load, increasing the girder depth significantly enhances the flexural stiffness of the structure while reducing the stress level. However, directly increasing the depth of the original section would substantially increase the structural self-weight and may even lead to adverse effects. To overcome this limitation, the proposed MPTCR method increases the effective structural depth by introducing truss members, thereby improving the bending stiffness with only a minor increase in dead load.

According to the structural vibration equation,

$$[K - \omega^2 M]\varphi = 0, \tag{2}$$

where K is the structural mass matrix, M is the mass matrix, ω is the natural circular frequency, and φ is the mode shape vector.

It can be observed that the natural frequency (fundamental frequency) of a structure is positively correlated with stiffness and negatively correlated with mass. Therefore, a truss system with relatively low self-weight and high stiffness is introduced to enhance the flexural stiffness and natural frequency of the structure.

2.2. Full utilization of the compressive capacity of concrete and rational stress distribution

When the normal section of a reinforced concrete girder (or slab) is subjected to bending moments, the concrete above the neutral axis is in compression, whereas the region below the neutral axis is in tension. For conventionally reinforced flexural members using concrete grades up to C50, when both the longitudinal tensile reinforcement and the concrete in the compression zone simultaneously reach their design strengths, the relative depth of the compression zone, ξ_b generally ranges from 0.56 to 0.62 [30]. This indicates that, under normal service conditions, the region above the neutral axis remains in a fully compressed state, at least within a depth of 0.56 h_0. For the PTCS proposed in this study, the lower chord of the truss is firmly connected to the upper compression zone of the existing main girder through uplift-resistant shear connectors. Since the connected components possess compatible material properties and reliable composite action, relative slip or separation at the interface is effectively prevented. As a result, the vertical and longitudinal deformations of the two components remain compatible, leading to coordinated stress behavior. Under dead and live loads, both the upper edge of the upper chord and the lower edge of the lower chord of the truss remain in compression, meaning that the truss is subjected to an overall compressive stress state (as shown in **Figure 2**). Consequently, the favorable compressive performance of concrete can be effectively utilized.

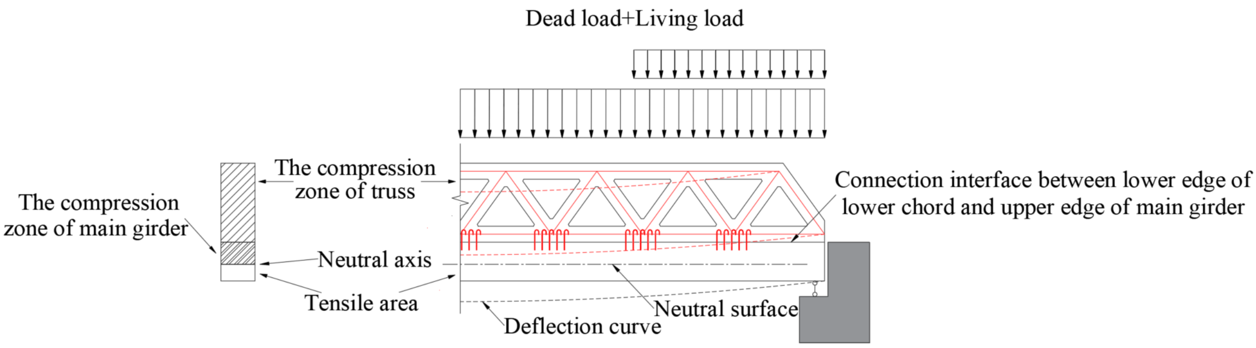


Figure 2. Mechanical diagram.

In addition, for aging RC bridges, tensile cracking at the bottom of the girder is a critical issue. The proposed MPTCR method contributes to mitigating this problem by redistributing tensile stresses. After reinforcement, part of the tensile force originally carried by the bottom of the girder is transferred to the lower chord of the truss through reliable connectors. As a result, the tensile stress in the original concrete girder is significantly reduced, thereby suppressing crack initiation and propagation. Meanwhile, the formation of the plate–truss composite system enhances the overall stiffness, further decreasing tensile strain under service loads.

2.3. Load redistribution based on relative stiffness

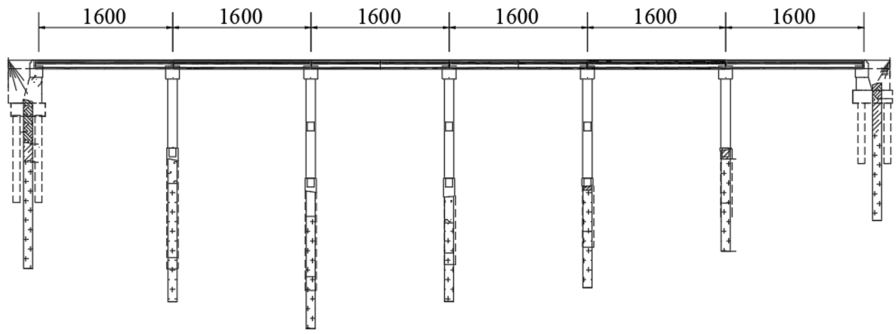
Within the PTCS force system, the truss, bridge deck, and main girder are integrally connected through the reinforcement framework and cast-in-place concrete, forming a reliable composite structural system. This ensures effective force transfer and coordinated deformation among all components.

According to the principle of stiffness-based load distribution, structural members with greater stiffness attract a larger proportion of the applied load. Therefore, as the truss possesses relatively high stiffness, it undertakes a significant share of the external load, thereby reducing the actual load carried by the original girder. Consequently, the plate–truss composite system exhibits a higher overall load-carrying capacity than the original girder system.

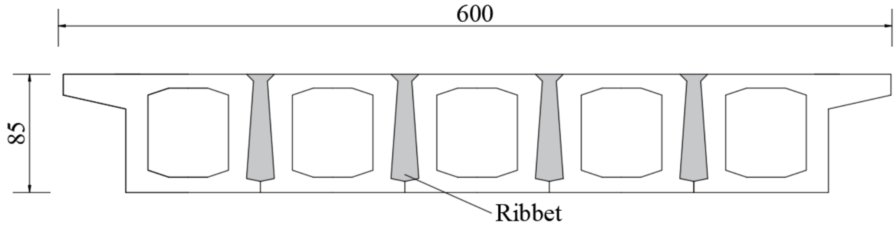
3. Engineering application

3.1. Structural form and main diseases

The bridge considered in this study is a reinforced concrete simply supported hollow slab bridge with a structural arrangement of 6 × 16 m. Five hollow slabs are arranged transversely, resulting in a total bridge width of 6.0 m. The structural depth is 0.85 m, corresponding to a depth-to-span ratio of 1/18.8. The elevation and cross-sectional configurations of the bridge are shown in **Figure 3**.



(a) The layout of elevation (Unit: cm).



(b) The layout of the cross-section (Unit: cm).

Figure 3. The structural layout.

After the erection of all hollow slabs was completed, the bridge exhibited transverse cracking of varying severity at the bottom of the slabs and therefore required strengthening.

3.2. Condition assessment

According to the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62-2012), the recommended span of a reinforced concrete simply supported hollow slab bridge should not exceed 10 m, and the recommended depth-to-span ratio should range from 1/16 to 1/11. However, the bridge investigated in this study has a span of 16 m and a depth-to-span ratio of only 1/18.8, which falls outside the recommended range. This indicates insufficient flexural capacity and inadequate overall stiffness of the structure.

3.3. Strengthening scheme

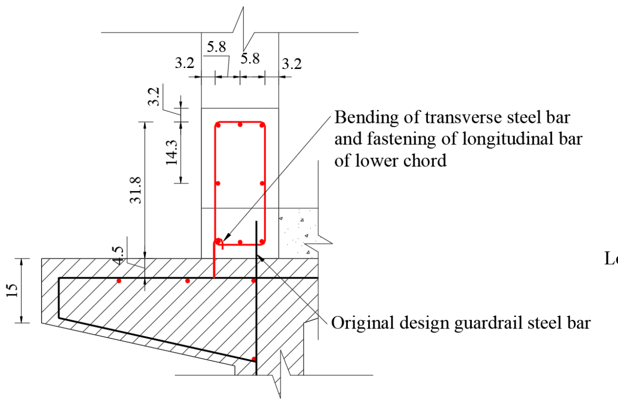
To address the above deficiencies, the proposed MPTCR method was adopted. The strengthening procedure is described as follows:

(1) Groove cutting

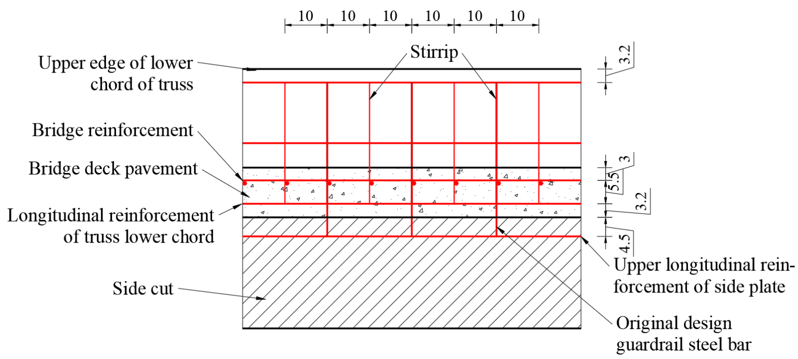
Along the longitudinal direction of the bridge, rectangular grooves measuring 30 cm in length and 15 cm in width were cut at 2 m intervals at the locations of the original guardrail reinforcement (i.e., the outer webs of the two exterior hollow slabs), until the upper reinforcement layer was exposed.

(2) Installation of connectors

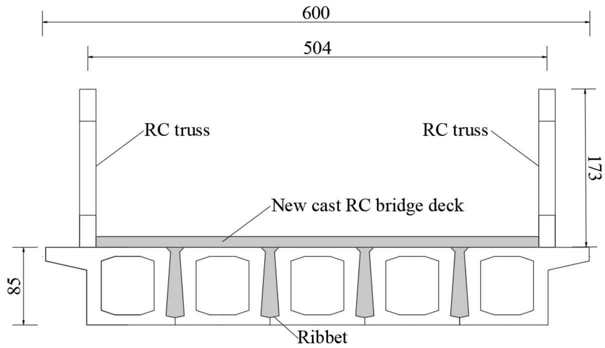
The transverse reinforcement bars exposed in the grooves were bent upward and fastened to the lower chord reinforcement of the truss, thereby forming reinforcing bar connectors, as shown in **Figure 4a**,**b**.



(a) The sectional view of the node connection part (Unit: cm).



(b) The elevation view of the connection part (Unit: cm).



(c) The sectional view of the reinforced structure (Unit: cm).

Figure 4. Process of consolidation.

(3) Reinforcement placement

- Truss reinforcement: The grooves were used as anchorage nodes for the lower chord of the truss reinforcement cage. Reinforcement trusses were then erected on both sides of the bridge deck. The original guardrail reinforcement passed through the lower chord of the truss, while the bent transverse reinforcement was connected to the longitudinal reinforcement of the lower chord, ensuring effective composite action between the hollow slab and the truss system, as shown in **Figure 4a**,**b**.
- Deck reinforcement: The existing bridge deck concrete was roughened and partially removed where necessary, after which reinforcement mesh was placed on the deck with a concrete cover thickness of 3 cm.

(4) Concrete casting

C40 concrete was cast for both the truss system and the bridge deck reinforcement. The casting sequence involved first pouring the truss concrete to form the reinforced concrete truss after reaching the required design strength, followed by casting of the bridge deck slab. The final strengthened structural configuration is shown in **Figure 4**.

Through the bridge deck reinforcement, bent transverse reinforcement, and original guardrail reinforcement, the hollow slabs, bridge deck, and truss system were integrally connected to achieve composite action. In particular, the 1.73 m deep concrete truss (approximately twice the depth of the original hollow slab) significantly enhanced the flexural stiffness of the structure. In addition, the strengthened bridge deck improved the transverse load distribution among the five hollow slabs and enhanced the lateral stability of the truss system.

4. Finite element simulation

4.1. Finite element model

Finite element models of the simply supported girder bridge before and after strengthening were established using Midas Civil. The boundary conditions were defined as follows: both ends of the main girder were modeled as simply supported, and the concrete truss was assumed to be rigidly connected to the existing main girder.

The design loads considered in the analysis included:

- First dead load: the self-weight of the structure;
- Second dead load: an additional permanent load of 3 kN/m^2;
- Moving load: Highway-II live load.

It should be noted that a rigid connection assumption was adopted between the truss and the main girder in the numerical model. Although the measured and simulated natural frequencies show good agreement, this assumption may not fully capture the local interaction behavior at the interface between the existing and newly cast concrete. Therefore, further experimental studies focusing on interface behavior and composite action mechanisms are required.

4.2. Analysis of natural frequency and deflection

Natural frequency is one of the most important indicators of structural dynamic characteristics and is closely related to structural stiffness [31]. Variations in natural frequency can effectively reflect changes in the global stiffness and stress condition of a structure. In addition, natural frequency can be measured accurately and is widely recognized as a reliable parameter for evaluating bridge stiffness [32]. In this study, the improvement in structural stiffness was assessed by comparing the natural frequencies before and after strengthening. The first six natural frequencies and corresponding mode shapes are summarized in **Table 1**.

Table 1. The first 6 natural frequencies and mode shapes of the model.

Modes	Before reinforcement		After reinforcement		Frequency increase (%)
	Frequency /Hz	Mode of vibration	Frequency /Hz	Mode of vibration	
1	6.755	First-order in-plane synchronous vertical bending	8.883	First-order in-plane synchronous vertical bending	31.5

Table 1. *Cont.*

Modes	Before reinforcement		After reinforcement		Frequency increase (%)
	Frequency /Hz	Mode of vibration	Frequency /Hz	Mode of vibration	
2	12.972	First-order in-plane asynchronous vertical bending	13.461	First-order in-plane asynchronous vertical bending	3.8
3	20.385	Second-order in-plane synchronous vertical bending	20.610	Second-order in-plane synchronous vertical bending	1.1
4	26.100	Third-order in-plane synchronous vertical bending	30.136	Third-order in-plane synchronous vertical bending	15.5
5	30.407	Fourth-order in-plane synchronous vertical bending	31.950	Fourth-order in-plane synchronous vertical bending	5.1
6	32.384	Fifth-order in-plane synchronous vertical bending	36.527	Fifth-order in-plane synchronous vertical bending	12.8

Before strengthening, the dominant vibration modes of the simply supported hollow slab bridge were all characterized by in-plane vertical bending. When all hollow slabs vibrate in the same direction and with similar amplitude, the mode is identified as synchronous vertical bending, such as the first and fourth modes. In contrast, when the vibration direction or amplitude differed among the hollow slabs, the mode was classified as asynchronous vertical bending, such as Modes 2, 3, 5, and 6.

Further examination of higher-order modes (up to the 20th and 40th orders) revealed the same general pattern, indicating that the vibration behavior of the bridge was dominated by synchronous or asynchronous vertical bending of the hollow slabs. After strengthening, the vibration characteristics of the hollow slab system remained generally similar, while additional out-of-plane vibration modes appeared in the truss components. This behavior can be attributed to the relatively high transverse stiffness of the multi-slab bridge system compared with its weaker vertical stiffness. As a result, vertical vibration remained the dominant response even at higher frequencies.

As shown in **Table 1**, the first occurrence of in-plane synchronous vertical bending (i.e., the fundamental mode) exhibited a frequency increase of 31.5% after strengthening. By comparison, the first asynchronous vertical bending mode increased by only 3.8%. For the first six vibration modes, the frequency enhancement of synchronous vertical bending modes was consistently greater than that of asynchronous modes, indicating that the proposed strengthening method significantly improved the global vertical stiffness of the structure.

Based on the above results, the MPTCR method substantially increases the natural frequency of the bridge in its overall in-plane vibration modes and effectively addresses the problem of insufficient global vertical stiffness in multiple simply supported hollow slab bridges.

To quantify the internal force redistribution, the stresses at key sections were compared before and after strengthening. The results indicate that the bending stress in the main girder is reduced by approximately 25%–35%, while the truss system undertakes an increasing proportion of the load. This confirms that the plate–truss composite system effectively redistributes internal forces and alleviates stress concentration in the original structure.

5. Bridge dynamic load test

The bridge dynamic load test was conducted to evaluate the strengthening effectiveness of the proposed MPTCR method. The natural frequency and vibration modes of the structure were identified through a pulsation test, while the impact coefficients under vehicle passage and braking conditions were obtained through driving vibration tests, including both running and braking cases. Based on these measured parameters, the dynamic response of the strengthened bridge was comprehensively assessed.

Due to practical constraints, dynamic testing before strengthening was not conducted. Therefore, the evaluation is based on numerical comparison before and after strengthening, together with experimental validation after strengthening.

5.1. Pulsation test

The pulsation method determines the natural frequency of a bridge by measuring the small-amplitude vibrations induced by ambient and irregular external excitations [33]. A 2D001V magnetoelectric sensor was employed, and the vertical acceleration responses of the bridge were recorded using the DHDAS dynamic signal acquisition and analysis system. The sampling frequency was set to 100 Hz, and the data acquisition duration was no less than 30 min. Test points were arranged along the bridge centerline at $L/4$, $L/2$, and $3L/4$.

The natural frequency of the strengthened structure was identified from the pulsation test, and the corresponding spectrum is shown in **Figure 5**. According to the test results, the first in-plane vibration frequency of the strengthened bridge was measured as 9.452 Hz. This value differs from the theoretical prediction of 8.883 Hz by only 6.4%, indicating good agreement between the experimental and numerical results. In addition, the measured in-plane vibration mode was consistent with that predicted by the finite element model. These results verify the effectiveness of the proposed MPTCR method in improving the overall vertical stiffness of the structure.

5.2. Driving vibration test

In the driving vibration test, the vehicle load was kept constant, with a total gross weight of 36.0 t. Two test conditions were considered: a running test and a braking test. The test vehicle speeds were set at 10, 20, 30, and 40 km/h, respectively.

During the running test, the vehicle crossed the bridge at a constant speed. During the braking test, the vehicle applied sudden braking at mid-span. A JM3840 dynamic load meter was used to record the dynamic strain time histories induced by vehicle loading.

To reduce random experimental errors, each test condition at each speed was repeated twice. Considering the structural symmetry of the bridge, dynamic strain gauges were installed at the $L/2$ and $L/4$ sections. In the transverse direction, measuring points were arranged on the middle girder, the intermediate side girder, and the exterior side girder from the bridge centerline toward the edge, as shown in **Figure 6**.

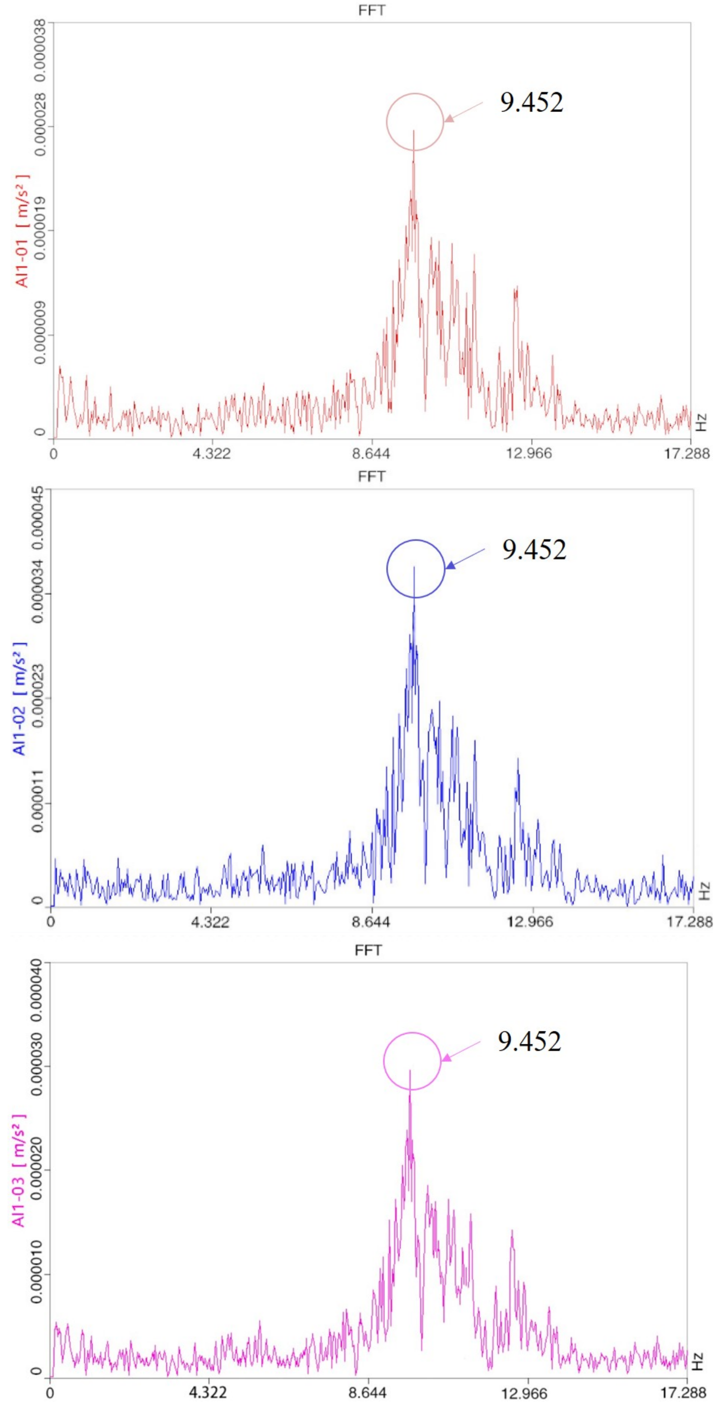
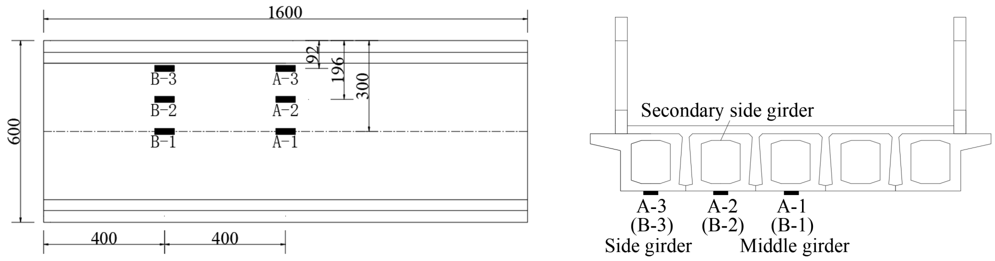


Figure 5. The acceleration-time curve of the pulsation test.



(a) The layout plan (Unit: cm). **(b)** The crosswise arrangement (Unit: cm).

Figure 6. Layout of dynamic strain measuring points.

According to the General Specifications for Design of Highway Bridges and

Culverts (JTG D60-2015), the vehicle impact factor, μ, is calculated as follows:

$$\mu = \begin{cases} 0.05,\ f < 1.5\text{Hz}, \\ 0.1767Inf - 0.0157,\ 1.5\text{Hz} \le f \le 14\text{Hz}, \\ 0.45, f > 14\text{Hz}, \end{cases} \tag{3}$$

where f is the structural fundamental frequency (Hz).

Based on the measured fundamental frequency of 9.452 Hz, the corresponding impact coefficient was calculated as 0.381 according to the design specification.

For the dynamic strain time histories recorded at each measuring point, the three-point peak method was adopted to determine the measured impact coefficient for the corresponding location. Provided that the recorded data were valid and reliable, the average impact coefficient obtained under the same test condition, vehicle speed, and measuring point was taken as the final test result.

The results are presented in **Table 2**. Under the two test conditions, the measured impact coefficients ranged from 0.041 to 0.256, corresponding to only 10.8% to 67.2% of the calculated specification value (0.381). This indicates that the measured dynamic amplification of the strengthened bridge was significantly lower than the code-based prediction.

Table 2. Measured value of impact coefficient.

Velocity (km/h)	Driving test						Braking test					
	A-1	A-2	A-3	B-1	B-2	B-3	A-1	A-2	A-3	B-1	B-2	B-3
10	0.085	0.073	0.062	0.068	0.067	0.041	0.103	0.084	0.075	0.084	0.077	0.065
20	0.098	0.087	0.079	0.085	0.084	0.068	0.152	0.132	0.094	0.124	0.092	0.083
30	0.147	0.118	0.092	0.136	0.109	0.094	0.214	0.142	0.127	0.169	0.157	0.096
40	0.223	0.192	0.135	0.182	0.164	0.108	0.256	0.216	0.163	0.226	0.188	0.158

Overall, the bridge exhibited a relatively small dynamic response under vehicle loading, demonstrating satisfactory dynamic performance. Within the tested speed range, the impact coefficients obtained from both the running and braking tests increased with increasing vehicle speed. At the same speed and under the same loading condition, the impact coefficients measured near the bridge centerline were consistently greater than those measured near the edges. This suggests that the vertical vibration response at the bridge edges was milder than that at the centerline under moving vehicle excitation. These observations confirm that the proposed strengthening method effectively improved the dynamic response and vibration behavior of the structure.

6. Conclusion

A novel strengthening method for reinforced concrete simply supported girder bridges, namely MPTCR, is proposed and validated through numerical simulation and field testing. The following conclusions can be drawn:

1. The proposed method significantly enhances the global stiffness of the structure. The fundamental frequency increases by 31.5%, indicating a substantial

improvement in overall structural performance.

2. The plate–truss composite system effectively redistributes internal forces, reducing the bending stress in the original girder and mitigating tensile cracking at the bottom.
3. The measured dynamic responses show that the impact coefficients are considerably lower than the code-based values, demonstrating improved dynamic behavior and vibration performance.
4. The good agreement between numerical and experimental results confirms the effectiveness of the proposed method, although further studies are needed to investigate interface behavior and long-term performance.

Overall, the MPTCR method provides an efficient and practical solution for improving both the static and dynamic performance of aging girder bridges.

This study is based on a single engineering case, and the general applicability of the proposed method requires further validation. In addition, the long-term performance and durability of the composite system, as well as the interface behavior between new and existing concrete, should be investigated in future studies.

Author contributions: Conceptualization, MP, XX and DM; methodology, MP, XX and DM; software, MP, WG and FC; validation, MP and XX; investigation, MP, WG, DM and FC; writing—original draft preparation, MP; writing—review and editing, WG, XX, DM and FC; funding acquisition, DM. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest: The authors declare no conflict of interest.

AI use statement: The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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