The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2755-0907.htm

Research on heavy-haul adaptive technology and strengthening measures for existing railway steel bridge

Xiaochen Ju
China Academy of Railway Sciences Corporation Limited, Railway Engineering Research Institute, Beijing, China

Received 12 October 2023
Revised 13 October 2023
Accepted 13 October 2023

Abstract

Purpose – This research addresses the diverse characteristics of existing railway steel bridges in China, including variations in construction age, design standards, structural types, manufacturing processes, materials and service conditions. It also focuses on prominent defects and challenges related to heavy transportation conditions, particularly low live haul reserves and severe fatigue problems.

Design/methodology/approach – The study encompasses three key aspects: (1) Adaptability assessment: It begins with assessing the suitability of existing railway steel bridges for heavy-haul operations through comprehensive analyses, experiments and engineering applications. (2) Strengthening: To combat frequent crack defects in the vertical stiffener end structure of girder webs, fatigue performance tests and reinforcement scheme experiments were conducted. These experiments included the development of a hot-spot stress S-N curve for this structure, validating the effectiveness of methods like crack stop holes, ultrasonic hammering and flange angle steel. (3) Service life extension: Research on the cruciform welded joint structure (non-fusion transfer type) focused on fatigue performance over the long life cycle. This led to the establishment of a fatigue S-N curve, enhancing Chinese design codes.

Findings – The research achieved several significant outcomes: (1) Successful implementation of strengthening and retrofitting measures on a 64-m single-span double-track railway steel truss girder on an existing heavy-duty line. (2) Post-reinforcement, a substantial 26% to 32% reduction in live haul stress on bridge members was achieved. (3) The strengthening and retrofitting efforts met design expectations, enabling the bridge to accommodate vehicles with a 30-ton axle haul on the railway line.

Originality/value – This research systematically tackles challenges and defects associated with Chinese existing railway steel bridges, providing valuable insights into adaptability assessment, strengthening techniques and service life extension methods. Furthermore, the development of fatigue S-N curves and the successful implementation of bridge enhancements have practical implications for improving the resilience and operational capacity of railway steel bridges in China.

Keywords Heavy haul, Steel bridge, Adaptability, Reinforcement

Paper type Research paper

1. Background

With the rapid social and economic development in China and the steady progress of high-speed railway construction, fully tapping into the freight capacity of existing railways, improving railway transportation efficiency and alleviating the contradiction between transport capacity and demand have become the main development directions for existing

---

The author extends heartfelt gratitude to the China High-Speed Rail Joint Fund (U1934209) and the CARS Fund (2023YJ124) for their invaluable support during the course of this research project. Their unwavering commitment has been instrumental in the success of the author's endeavors.

Railway Sciences
Vol. 2 No. 4, 2023
pp. 459-469
Emerald Publishing Limited
e-ISSN: 2755-0915
p-ISSN: 2755-0907
DOI 10.1108/RS-10-2023-0035

railways in China. Especially as the passenger transportation network is gradually completed, the vigorous development of heavy-haul transportation on existing railway lines has become an inevitable trend for the development of railway freight transportation (Liu, 2013; Hu, 2015; Liu, 2015; Zhang & Zhao, 2019). In the revised version of the "Major Technical Policies for Railways" issued in China in 2013, heavy-haul railways were defined as railways that meet two out of three conditions: train traction mass of 8,000 tons or more, axle haul of 27 tons or more and annual transportation volume of over 40 million tons in at least a 150 km section.

From the perspective of two technical approaches for developing heavy-haul transportation Chinese railways, on one hand, existing railway networks are being strengthened and retrofitted to accommodate heavy axle hauls and high transportation volumes. On the other hand, new high-capacity freight lines are being constructed to facilitate the operation of heavy-haul, long-unit trains by introducing large axle hauls and long train formations. Within the current railway bridge system in China, although the proportion of steel bridges is relatively small, their role is crucial. Most of the railway bridges spanning the Yangtze and Yellow Rivers are steel bridges, and they hold an irreplaceable social significance. In the development of heavy-haul transportation on existing railways in China (Wang, 2012; Caglayan, Ozakgul, & Tezer, 2012; Bai, 2018; Wang, Wang, & Xu, 2018), two main aspects need to be considered: firstly, as the locomotive and rolling stock axle hauls increase with the operation of railway lines, the live haul effects on the bridge structures increase, leading to reduced haul reserves. Additionally, with the completion of dedicated passenger lines and the functional transformation of existing lines, the frequency of freight transportation operations will continue to rise. This results in an increase in both the amplitude of live haul stresses and the number of haul cycles, directly contributing to the accumulation of structural damage and a decrease in the service life of the bridges. Secondly, the existing steel bridges are constructed in different eras, with a wide range of construction ages. They also exhibit variations in design and construction standards, diverse structural types, different manufacturing processes and materials. Furthermore, significant differences exist in the service conditions of these bridge structures. With increasing years of service and the combined effects of haul and environmental factors, the structural performance of these steel bridges deteriorates. Some of them have already exhibited fatigue problems caused by structural defects. Based on the above, research is conducted in three aspects regarding the adaptability of existing railway steel bridges to heavy hauls and strengthening measures (Sun, 2014; Li & Luo, 2013; Walbridge & Liu, 2018; Cui, Zhang, Bao, Kang, & Bu, 2018; Wang, Wang, Duan, Wang, & Zhai, 2019; Li & Zhang, 2019; Zhang & Li, 2017; Wang, 2016; Zhang & Sun, 2019; Liu & He, 2020; Wang, 2018; Guo & Xu, 2017; Li, 2020; Al-Karawi, 2023; Han, Zhao, & Zhang, 2022; Wallin, Leander, & Karoumi, 2011; Han *et al.*, 2022; Yu, Shan, Yuan, & Li, 2018; Xiao, Luo, Liu, & Wang, 2020):

(1) Overall analysis of the adaptability of existing steel bridge structures to heavy hauls.

(2) Evaluation of fatigue life for existing steel bridges.

(3) Study of strengthening measures for existing steel bridges.

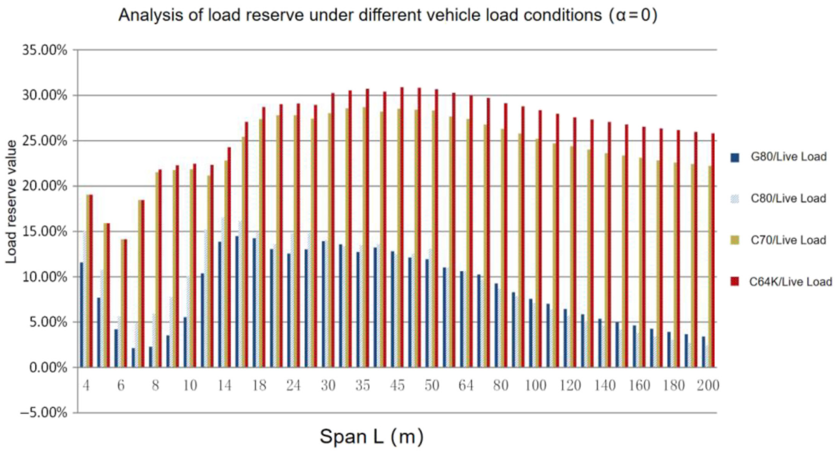
These research areas aim to comprehensively assess the adaptability of existing steel bridges to heavy hauls, evaluate their fatigue life and propose effective strengthening measures to address structural deficiencies caused by fatigue and other factors.

2. Analysis of overall overhaul adaptability for existing steel bridge structures

An analysis of the haul reserves under the demanding conditions of heavy-haul transportation can be effectively carried out by evaluating the live haul standards of existing bridge structures, bridge design parameters and the loading capacities imposed by heavy-haul vehicles. This comprehensive assessment involves intricate calculations, where the focus is on determining the effects of heavy-haul loads on bridges of various spans while considering evaluated live haul standards, high-axle-haul vehicles and design hauls from different historical periods. The primary objective of this analysis is to discern the potential adverse impacts of heavy-haul trains on the structural integrity of existing bridges. It is essential to pinpoint the specific bridge span ranges that exhibit significantly reduced or inadequate load-bearing capacity under such conditions. The results of this analysis play a crucial role in identifying the necessary capacity enhancements required to accommodate heavy-haul transportation effectively. Research findings have unveiled that, in the case of existing steel bridges in China, medium-span beam bridges, defined as those with spans less than 120 m, can generally withstand the operational demands of new heavy-haul vehicles with a 27-ton axle load. However, it is important to note that the load-carrying capacity of these bridges may experience a moderate reduction, typically ranging from 10% to 20%, as illustrated in Figures 1 and 2. When it comes to assessing the dynamic performance of existing steel bridges during heavy-haul train operations with a 27-ton axle load, the results indicate that these bridges can meet the required specifications, provided that the track conditions are good. Even when pushed to their limits, the dynamic performance indicators of these bridges remain within safe limits. However, in cases where track conditions are less than optimal, it is advisable to implement appropriate speed restrictions, with a recommended speed limit of less than 80 km/h to ensure safe operation.

3. Fatigue-life assessment of existing steel bridges

When it comes to the operation of heavy-haul transportation on existing steel bridges, the primary concern revolves around fatigue damage. This issue becomes particularly pronounced due to the upsurge in axle haul capacity and the redirection of passenger traffic to dedicated lines, resulting in a notable surge in the frequency of freight transport cycles. This, in turn, directly contributes to an escalation in fatigue-related wear and tear. In our pursuit of addressing this challenge comprehensively, we have diligently undertaken a systematic review and analysis of various fatigue-life assessment techniques. These encompass the S-N curve-based method, illustrated in Figure 3, approaches rooted in linear



Source(s): Authors own work

Figure 1.
Comparison of haul reserve for shear effects under different axle haul vehicles

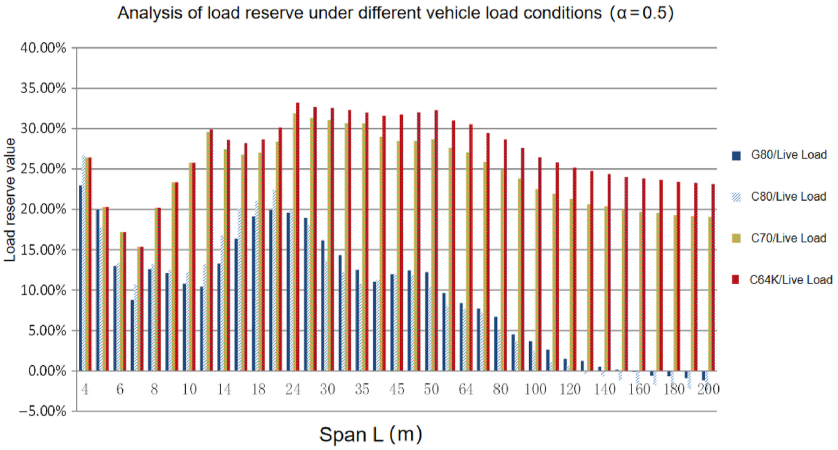


Figure 2. Comparison of haul reserve for bending moment effects under different axle haul vehicles

Source(s): Authors own work

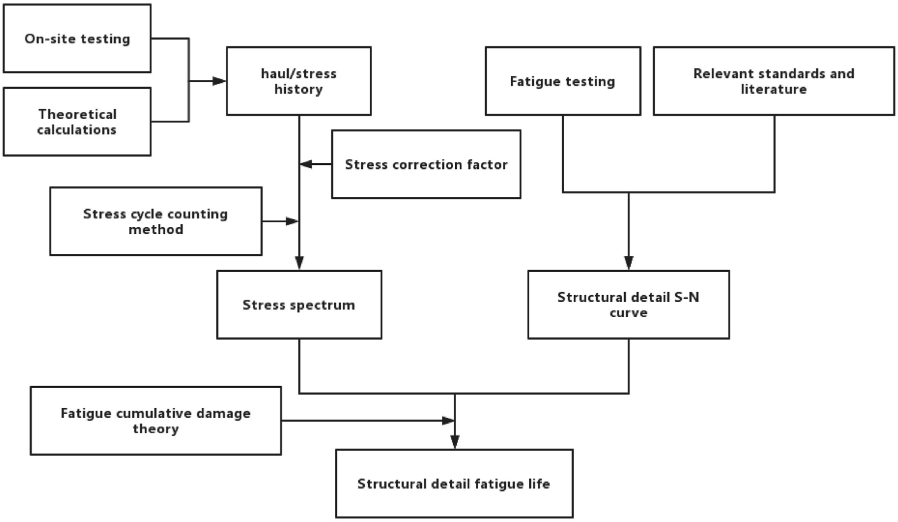
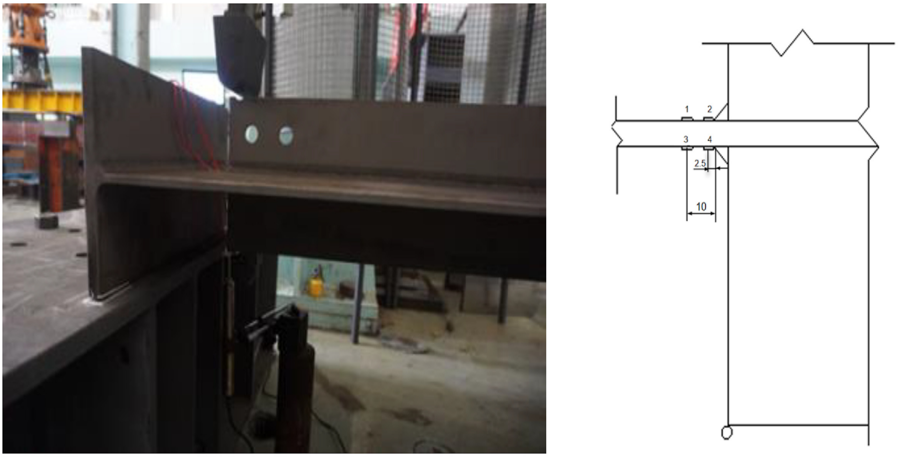


Figure 3. Fatigue-life assessment method for existing steel bridges based on S-N curve

Source(s): Authors own work

elastic fracture mechanics, and methods designed to gauge the reliability of fatigue-life assessments. Given the current state of technology and the unique context of our steel bridges in China, we have discerned that a synergistic approach combining the S-N curve-based fatigue-life assessment method with reliability assessment techniques offers the most suitable avenue for evaluating the integrity of existing steel bridges. This integrated approach yields results that are not only more scientifically robust but also facilitates the formulation of tailored fatigue-life assessment methodologies tailored specifically to the needs and conditions of Chinese steel bridges. This, in essence, allows us to draw more precise and informed conclusions in our pursuit of enhancing the longevity and safety of these critical infrastructure assets (see Figure 4).



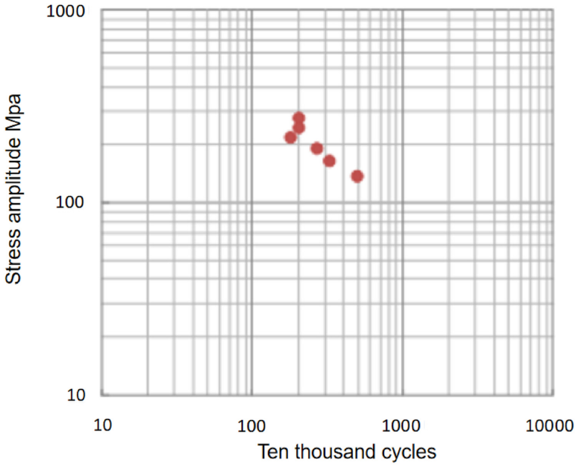
Source(s): Authors own work

Figure 4.
Experimental setup and hot-spot stress diagram for vertical stiffener end construction

A comprehensive assessment was conducted on the fatigue life of typical steel bridges, with a primary focus on enhancing their structural integrity and performance. The evaluation revealed the need for reinforcing the longitudinal beams, particularly for those spanning 4–8 m. In addition, a significant recommendation emerged from the assessment, advocating the replacement of riveted connections with bolted ones, especially in scenarios involving heavy-haul transportation. The impact of train composition on the fatigue damage experienced by the bridges was a central aspect of this study. Through rigorous analysis, we identified key insights and subsequently put forth recommendations for optimizing train composition to minimize fatigue-related deterioration in bridge structures.

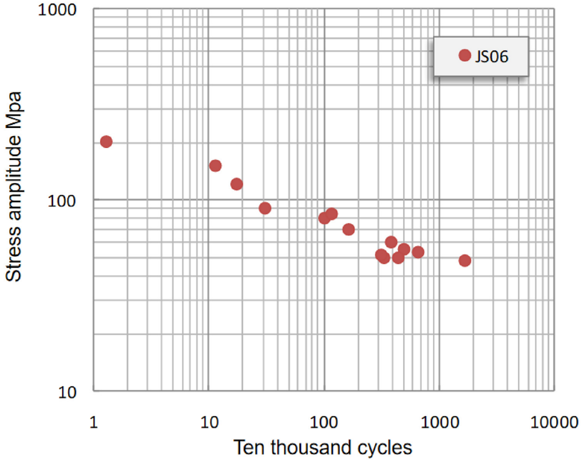
To validate the proposed enhancements and design criteria, an exhaustive series of fatigue performance tests were conducted on typical structural details. These tests covered a wide range of components, including the end regions of welded vertical stiffeners in girder-type beams and cruciform welded joints. The testing regimen included assessments of hot-spot stress and long-life-cycle fatigue. One striking result emerged from the investigation. The S-N curve slope for the end regions of the welded vertical stiffeners in girder-type beams was found to be $m = 1.3653$. This value significantly deviates from the conventional value of $m = 3$, indicating a steeper S-N curve. For the JS1-8 specimens, regression analysis of the test data yielded a fatigue strength of 97.27 MPa at five million cycles, after accounting for two standard deviations. In the case of the cruciform welded joints, fatigue-induced cracking was observed to initiate from the weld toe and propagate along the plate's width direction. Notably, the S-N curve exhibited a slope of $m = 3.8926$ for fewer than five million cycles and a steep increase to $m = 8.9586$ for more than five million cycles. This difference in slope values before and after five million cycles exceeded the specified value of 2 in European standards.

Ultimately, the fatigue strength at two million cycles was determined to be 50.8 MPa, a figure that falls below the specified 65 MPa threshold outlined in China's "Specifications for Inspection of Railway Bridges." These findings underscore the importance of implementing the proposed reinforcements and design changes to ensure the long-term durability and safety of steel bridges under varying conditions, especially in the context of heavy-haul transportation (see Figure 5 and Figure 6).



Source(s): Authors own work

Figure 5.
Fatigue test results of welded end construction for girder vertical stiffeners



Source(s): Authors own work

Figure 6.
Fatigue test results of cross-shaped welded joint construction

4. Research and application of strengthening measures for existing steel bridges

After conducting a comprehensive analysis of common defects found in currently operational railway steel bridges and evaluating their suitability for heavy-haul operations, it is imperative to embark on a corresponding study aimed at enhancing and retrofitting these structures. The application of these strengthening and fortification measures serves as an effective means of mitigating the live haul stress experienced by vulnerable components during heavy-haul transportation. Simultaneously, it serves as a preventive measure against the exacerbation of existing defects. This proactive approach is pivotal in ensuring the continued safe operation of these bridges and, equally important, in extending their overall service life. Consequently, this comprehensive strategy not only addresses the current vulnerabilities but also paves the way for the sustained and reliable functionality of these critical infrastructure elements in the context of heavy-haul transportation.

4.1 Reinforcement of typical defects in existing structures

(1) Reinforcement of cracks in the welded end of vertical stiffeners for box girder beams

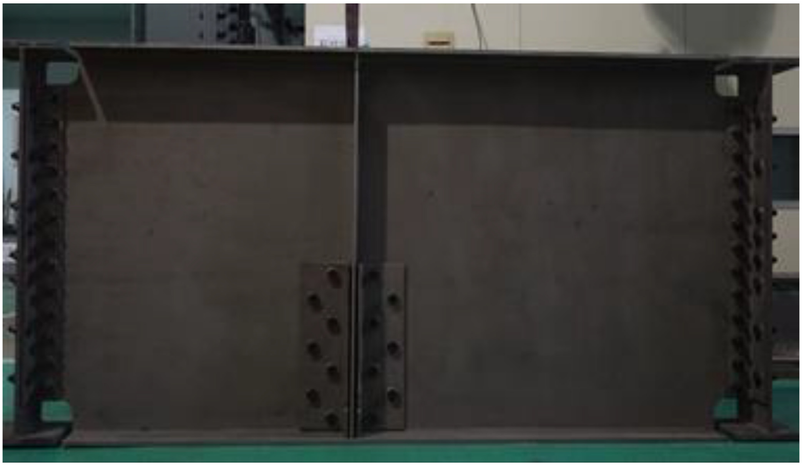
Regarding the common crack defects in the welded ends of the vertical stiffeners of I-beam girders, research has found that the causes include lateral vibration caused by train snake movement; eccentric vertical haul on the girder flange due to the difference between the track center distance and the girder center distance; and out-of-plane deformation of the girder flange caused by vertical haul and girder deformation. Due to the significantly greater stiffness of the stiffeners compared to the out-of-plane bending stiffness of the flange, the out-of-plane deformation of the flange mainly occurs at the small gap between the end of the stiffener weld and the tension flange. Studies have shown that the maximum bending stress occurs at the weld toe of the stiffener-flange connection angle, and the direction of the principal tensile stress is vertical. Therefore, fatigue cracks typically initiate from the end of the stiffener weld and propagate horizontally. To address the crack formation, various strengthening and retrofitting measures have been developed and validated through indoor testing, as shown in Plate 1. If cracks have already formed at the ends of the vertical stiffeners, adding angle steel to the flange can prevent further crack propagation. When cracks have not yet formed, this strengthening method can effectively slow down the generation and propagation rate of cracks.

Recommendations for treatment methods applied to actual bridges are as follows:

(1) Before cracks are detected, conducting ultrasonic hammering on the structure can delay the initiation of fatigue cracks.

(2) If cracks have already formed in the structure, drilling stop holes at the crack tips can help slow down the crack propagation.

(3) After crack initiation, a strengthening solution that connects the flange to the ends of the vertical stiffeners using angle steel can effectively prevent further crack propagation. If the strengthening is done before cracks form, it can prevent the occurrence of fatigue cracks in the structure. This method is simple yet effective, and it is recommended to be prioritized in the treatment of bridge defects.



Source(s): Authors own work

Plate 1.
Reinforcement method using angle steel

Please note that the recommendations provided are based on the information provided and may need to be further assessed and adapted to specific bridge conditions and engineering practices.

(1) Reinforcement of cracks in the welded joints of transverse T-connection plates for upper deck plate

Laboratory fatigue performance tests conducted on the welded connection plates of transverse and longitudinal T-joints, situated on top-supported steel truss girders or plate girders, have brought to light a significant concern regarding the presence of crack defects. These tests have yielded disconcertingly low fatigue-strength results, with a mere 50.8 MPa endurance limit over two million cycles. Consequently, it is strongly recommended that the existing structural configuration be overhauled by substituting the T-welded connection plates with hot-rolled sections. This modification aims to bolster the fatigue resistance at this critical juncture and mitigate the risk of crack defects. In line with the stipulations outlined in "Eurocode 3: Design of steel structures - Part 1-9: Fatigue," it is worth noting that hot-rolled sections exhibit a significantly higher fatigue strength of 160 MPa for T-connection plates, compared to the comparatively lower value of 149.5 MPa stipulated by Chinese standards. The adoption of this new structural configuration presents a substantial enhancement in fatigue strength, effectively serving as a robust safeguard against the emergence of structural defects at their root. Therefore, it is prudent to endorse the application of these redesigned structural elements as a worthy replacement for the original T-welded connection plates. However, it is of paramount importance to emphasize that any modifications undertaken should scrupulously adhere to the pertinent design codes and standards. Furthermore, comprehensive engineering analysis and evaluation must be diligently carried out to guarantee the appropriateness and integrity of the revamped structure.

4.2 Strengthening of vulnerable members under heavy-haul transportation conditions

In the realm of heavy-haul transportation, various structural components of bridges come under scrutiny for potential fatigue issues. Notably, tension members within the primary truss, bridge deck constituents and elements exhibiting localized corrosion pose particular concerns. Addressing these issues is essential to bolstering the longevity of such components under the relentless strains of live hauls. To achieve this objective, a recommended approach involves the implementation of local splicing using high-strength bolts for reinforcement. This method boasts a range of advantages, including dependable connection strength, exceptional fatigue resistance and a straightforward construction process. Furthermore, it finds its niche in existing bridges, as the reinforcement procedure can be carried out with minimal disruption to bridge operations. For tension members within the main truss, a research study has established a reinforcement technique that entails augmenting the cross-sectional area through the application of bolted steel plates to the flange plates. When it comes to longitudinal and transverse beams, the strategy involves the attachment of bolted steel plates to the lower flange, effectively enhancing their flexural stiffness. These reinforcement measures are instrumental in reducing stress amplitudes experienced by these structural elements during live hauls, thereby significantly prolonging the service life of bridges designed for heavy-haul transportation conditions. The efficacy of this method has been exemplified through its successful application in the rehabilitation and retrofitting of a 64-m-span double-track steel truss girder on the Shuo Huang Railway. Post-reinforcement, minimal alterations were observed in the stress distribution of unreinforced components, while reinforced components experienced a substantial reduction in stress levels. The magnitude of stress reduction ranged from 25% to 36%, aligning with the anticipated outcomes of the strengthening design. Notably, this reinforcement approach can accommodate the augmented transportation capacity requirements for 30-ton axle haul vehicles on dedicated coal transportation routes.

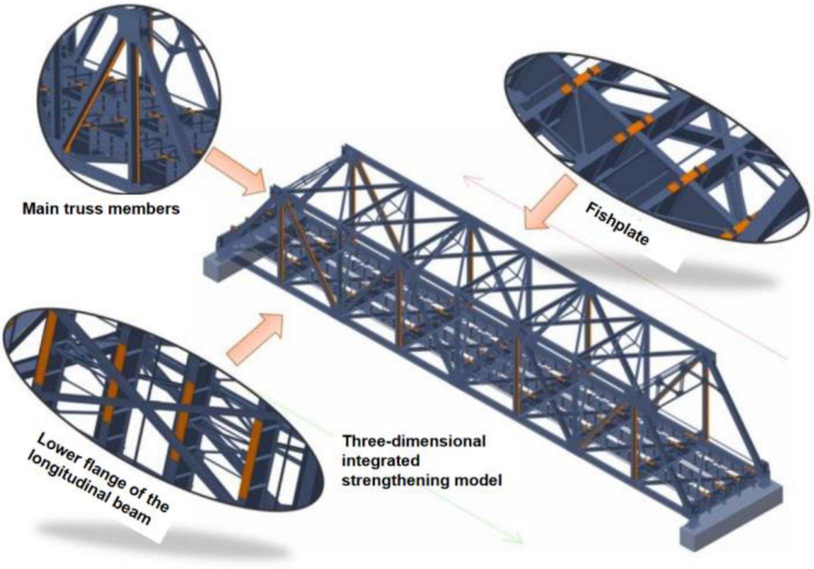
Nevertheless, it is imperative to underscore that the application of reinforcement measures must be subject to meticulous evaluation and design processes tailored to the unique conditions of each bridge and in compliance with established engineering standards. This diligent approach is essential to ensure both the effectiveness of the reinforcement measures and the structural integrity of the bridge. The success of the reinforcement method is evident in its application to rectify various defects at the terminus of longitudinal stiffeners within the primary girder of a dual-track steel truss bridge, boasting a 64-m span, as depicted in Figures 7 and 8 on the Shuo Huang Railway.

5. Conclusion

Through the research on the adaptability of existing railway steel bridges to heavy hauls and strengthening strategies, the following conclusions have been drawn:

(1) Identify the adverse effects of heavy-duty trains on existing bridge structures and determine the range of bridge spans with significantly reduced or inadequate haul reserves. Clearly define the carrying capacity that requires focused strengthening under heavy-haul transportation conditions. Beam bridges with medium spans (less than 120 m) are capable of accommodating new heavy-duty vehicles with a 27-ton axle haul but exhibit relatively reduced haul reserves, with a decrease of approximately 10% to 20%. When heavy-duty trains with a 27-ton axle haul operate under poor track conditions, appropriate speed restriction measures should be implemented, with a recommended speed limit below 80 kilometers per hour.

(2) Conduct theoretical and experimental research on the fatigue performance and reinforcement schemes for vulnerable fatigue crack defects in the vertical stiffeners of existing steel bridges. Develop S-N curves for the hot-spot stresses in the studied



Source(s): Authors own work

Figure 7. Schematic diagram of strengthening and rehabilitation areas for a 64-m steel truss girder

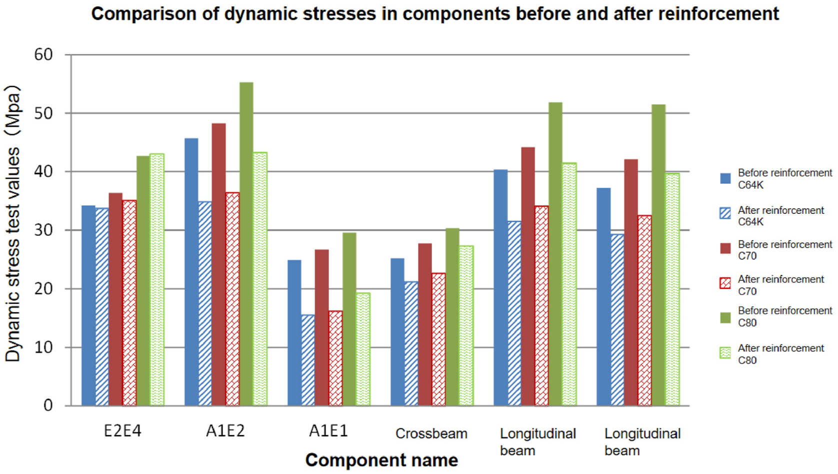


Figure 8.
Comparison of dynamic stress test values before and after reinforcement

Source(s): Authors own work

structural details. Validate the effectiveness and applicability of various reinforcement schemes, such as crack arrest holes, ultrasonic hammering and flange angle steel, to provide specific recommendations and implementation plans for actual bridge reinforcement.

(3) Establish a comprehensive technical system for the adaptability assessment and strengthening of existing railway steel bridges under heavy hauls in China. Successfully apply this system to a double-track steel truss girder bridge with a single span of 64 m on a dedicated coal transportation line. Through adaptability assessment, research on strengthening technologies and implementation of reinforcement projects, the bridge is now capable of meeting the capacity expansion requirements for operating heavy-duty trains with high axle hauls.

References

Al-Karawi, H. (2023). Fatigue design and assessment guidelines for high-frequency mechanical impact treatment applied on steel bridges. *Weld World*, *67*, 1809–1821.

Bai, Y. (2018). Fatigue assessment of existing steel railway bridges under heavy traffic hauling. *Engineering Structures*, *169*, 88–100.

Caglayan, O., Ozakgul, K., & Tezer, O. (2012). Assessment of existing steel railway bridges. *Journal of Constructional Steel Research*, *69*(1), 54–63.

Cui, C., Zhang, Q., Bao, Y., Kang, J., & Bu, Y. (2018). Fatigue performance and evaluation of welded joints in steel truss bridges. *Journal of Constructional Steel Research*, *148*, 450–456.

Guo, S., & Xu, L. (2017). Experimental study on the fatigue behavior of welded joints in railway steel bridges. *Engineering Failure Analysis*, *82*, 524–534.

Han, N., Zhao, W., & Zhang, B. (2022). Performance assessment of railway multispan steel truss bridge bearing by thermal excitation. *Journal of Civil Structural Health Monitoring*, *12*, 163–178.

Hu, Y. (2015). *Key technologies research on external prestressing strengthening method for overhauled railway bridges*. Beijing: Beijing Jiaotong University.

Li, H. (2020). Assessment and strengthening of railway steel truss bridges for heavy haul hauls. *Structure and Infrastructure Engineering*, *16*(11), 1550–1563.

Li, M., & Luo, X. (2013). Research on transverse vibration detection and reinforcement of overhauled railway bridges. *Shenhua Science and Technology*, *11*(5), 80–83.

Li, J., & Zhang, C. (2019). Structural assessment and retrofitting of aging railway steel bridges: A case study. *Journal of Bridge Engineering*, *24*(2), 04018137.

Liu, Q. (2013). *Research on reinforcement methods for overhauled railway bridges*. Central South University.

Liu, S. (2015). Research on standardization technology for deterioration assessment of overhauled railway bridges. *Journal of Shijiazhuang Tiedao University (Natural Science Edition)*, *28*(1), 22–27. doi: 10.13319/j.cnki.sjztddxxbzrb.2015.01.05.

Liu, X., & He, Y. (2020). Reinforcement and retrofitting strategies for steel railway bridges subjected to heavy axle haul traffic. *Journal of Performance of Constructed Facilities*, *34*(6), 04020151.

Sun, Y. (2014). *Research on the application of external prestressing technology in reinforcement of overhauled railway bridges*. Central South University.

Walbridge, S., & Liu, Y. (2018). Fatigue design, assessment, and retrofit of bridges. *Journal of Bridge Engineering*, *23*(12), 02018001.

Wallin, J., Leander, J., & Karoumi, R. (2011). Strengthening of a steel railway bridge and its impact on the dynamic response to passing trains. *Engineering Structures*, *33*(2), 635–646.

Wang, L. (2012). Operational performance and reinforcement evaluation of double-column railway bridge piers under overhaul. *Defense Transportation Engineering and Technology*, *10*(5), 31–34, doi: 10.13219/j.gjgyat.2012.05.013.

Wang, L. (2016). Fatigue performance evaluation and strengthening of steel railway bridges with welded details. *Journal of Structural Engineering*, *142*(11), 04016118.

Wang, Q. (2018). Structural assessment and rehabilitation of railway steel bridges with fatigue-prone details. *Journal of Constructional Steel Research*, *147*, 101–113.

Wang, C., Wang, Q., & Xu, Y. (2018). Fatigue evaluation of a strengthened steel truss bridge. *Structural Engineering International*, *23*(4), 443–449.

Wang, C., Wang, Y., Duan, L., Wang, S., & Zhai, M. (2019). Fatigue performance evaluation and cold reinforcement for old steel bridges. *Structural Engineering International*, *29*(4), 563–569.

Xiao, Y., Luo, X., Liu, J., & Wang, K. (2020). Dynamic response of railway bridges under heavy-haul freight trains. *Advances in Civil Engineering*, *2020*(4), 1–14.

Yu, Z., Shan, Z., Yuan, J., & Li, X. (2018). Performance deterioration of heavy-haul railway bridges under fatigue loading monitored by a multisensor system. *Journal of Sensors*, *2018*, 1–14.

Zhang, Z., & Li, W. (2017). Research on the strengthening technology of existing railway steel bridges. *Procedia Engineering*, *210*, 239–245.

Zhang, Y., & Sun, X. (2019). Study on fatigue evaluation and reinforcement technology of existing railway steel bridges. *Advances in Structural Engineering*, *22*(14), 3055–3069.

Zhang, Q., & Zhao, J. (2019). Retrofitting techniques for existing railway steel bridges in China: A comprehensive review. *Journal of Traffic and Transportation Engineering*, *6*(6), 664–678.

Corresponding author
Xiaochen Ju can be contacted at: juxc2008@163.com
