International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Investigation of Vibration Behavior of High-Speed Trains on Steel Railway Bridges

Rajkumar S [a], Premalatha J [b]

[a] PG student, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India.
[b] Professor, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India.

ABSTRACT :

The rapid expansion of high-speed railway networks worldwide has necessitated advanced studies on the dynamic interaction between trains and bridge structures. This comprehensive review synthesizes findings from recent studies and the broader literature to investigate the vibration response of steel and composite railway bridges under high-speed train loads. The paper delves into the evolution of analytical methodologies, from classical theoretical formulations to sophisticated 3D finite element and coupled interaction models. It critically examines the influence of key parameters such as train speed, axle load, track irregularities, bridge damping, and structural flexibility on dynamic amplification factors, resonance phenomena, and passenger comfort. Detailed case studies of concrete-filled steel tube arch bridges and prestressed concrete bridges are presented, comparing interaction and non-interaction modeling approaches. The review also explores emerging trends, including the application of machine learning for response prediction and digital twin technology for structural health monitoring. The synthesis of results provides practical implications for the design, assessment, and maintenance of high-speed railway bridges, highlighting the critical role of dynamic analysis in ensuring structural safety and serviceability. Future research directions are identified to address existing gaps in modeling complex bridge types under multi-hazard conditions.

Key words:- : High-speed railway bridges, train-bridge interaction, dynamic response, vibration analysis, finite element modeling, resonance, track irregularities, steel bridges, dynamic amplification factor.

Introduction

Background and Motivation

The global proliferation of high-speed rail (HSR) networks represents a significant advancement in sustainable transportation infrastructure. Countries like China, Japan, and those in Europe have led this development, with China boasting over 45,000 km of HSR lines by the end of 2023, where bridges constitute nearly 46% of the total network length [1]. This extensive use of bridges is necessitated by the need for straight alignments, minimal gradients, and crossings over varied topography. However, the dynamic forces imposed by high-speed trains traveling at speeds exceeding 300 km/h pose unique challenges to bridge engineers. Unlike static loads, these dynamic interactions can lead to resonance, excessive vibrations, and accelerated fatigue damage, compromising both structural integrity and passenger comfort [2].

The vibration behavior of bridges under moving loads is a classic problem in structural dynamics. The pioneering work of [3] laid the foundation for analyzing beams under moving loads. However, the complexity of modern high-speed trains, with their multi-vehicle configurations, suspension systems, and articulated connections, requires a more sophisticated approach than simple moving load models. The interaction between the vehicle, track, and bridge forms a complex coupled system where the response of each component influences the others [4].

Scope and Objectives

This paper aims to provide a comprehensive review of the vibration behavior of steel railway bridges under high-speed trains. The specific objectives are:

1. To trace the evolution of methodologies used in train-bridge interaction analysis.
2. To critically review the findings of recent significant studies on the dynamic response of steel and composite bridges.
3. To synthesize the effects of critical parameters such as speed, axle load, track geometry, and structural properties.
4. To discuss practical implications for bridge design, assessment codes, and maintenance strategies.
5. To identify emerging research trends and future directions in the field.

Literature Review

Historical Evolution of Train-Bridge Dynamics

The problem of structural vibration under moving loads has been studied for over a century. The early analytical solutions by [3] for a point load moving on a simply supported beam provided the fundamental theoretical basis. [5] later presented comprehensive analytical solutions for various beam types and moving load cases, including massless sprung systems. The introduction of high-speed trains in the latter half of the 20th century, such as Japan's Shinkansen and France's TGV, marked a paradigm shift. It became evident that the traditional impact factor approach, which statically amplifies live loads to account for dynamic effects, was insufficient for high-speed applications [6]. This led to the development of dynamic interaction models that consider the inertial effects of the train.

Contemporary Research Methodologies

Contemporary research employs a tripartite methodology:

- **Field Testing and Monitoring:** Full-scale testing remains the most reliable method for validating numerical models. [7] conducted extensive tests on bridges under Thalys trains, measuring accelerations and displacements. [8] focused on vehicle-bridge interaction using field data. Recent advances in sensor technology have enabled long-term structural health monitoring (SHM) systems, providing valuable data on real-world bridge performance under operational conditions [9, 10]. However, field tests are costly, time-consuming, and often limited to simpler bridge types.
- **Theoretical and Analytical Methods:** While limited in handling complex geometries, analytical methods are valuable for understanding fundamental phenomena. [11] developed a bridge-track-vehicle element for dynamic analysis. [12] provided closed-form solutions for the response of continuous beams under moving loads, highlighting the critical velocity effect.
- **Numerical Simulation:** Finite Element Analysis (FEA) is the most widely used tool due to its versatility. The sophistication of models has grown with computational power. Early 2D models have evolved into complex 3D coupled systems that include detailed representations of the train, track structure, and bridge [13, 14]. Key modeling challenges and solutions include:
  - **Interaction Modeling:** Techniques range from simplified moving load models to complex iterative and direct coupling methods. Iterative methods [15, 16] treat the train and bridge as separate systems linked by contact forces. Direct coupling methods [17, 18] assemble the equations of motion for the entire coupled system, updating matrices at each time step.
  - **Track Modeling:** Tracks can be modeled as a series of discrete supports or using continuous elastic foundation (Winkler) models. The inclusion of track irregularities, defined by Power Spectral Density (PSD) functions, is crucial for accurate simulation [19].
  - **Vehicle Modeling:** Train models vary from simple sprung masses to complex multi-body systems (MBS) with dozens of degrees of freedom (DOFs) representing car bodies, bogies, wheelsets, and primary/secondary suspensions [20, 21].

Fundamental Concepts in Train-Bridge Vibration

Resonance in Railway Bridges

Resonance occurs when the frequency of the excitation (from the train) coincides with a natural frequency of the bridge. For a series of equidistant axle loads, the excitation frequency is f=v/d$f=v/d$, where vv is the train speed and dd is the axle spacing. Resonance is critical when ff matches the bridge's fundamental frequency fbfb, leading to significantly amplified responses [22]. The critical speed vcrvcr is given by vcr=fb×d$vcr=fb\times d$. Interaction models often predict a lower critical speed than moving load models because the coupled train-bridge system has a lower natural frequency than the bridge alone [23].

Dynamic Amplification Factor (DAF)

The DAF is a key design parameter defined as the ratio of the maximum dynamic response to the maximum static response. Most design codes, such as Eurocode [24], provide simplified formulas for DAF based on span length. However, these formulas may not be accurate for high-speed lines or complex bridges, necessitating detailed dynamic analysis [25].

Passenger Comfort and Serviceability Limits

Beyond structural safety, passenger comfort is a critical serviceability limit state. Standards like EN 1990 [26] specify limits for vertical acceleration of the bridge deck (e.g., 3.5 m/s^2 for ballasted tracks) to prevent ballast instability. For passengers, vertical acceleration in the train car body should typically be kept below 0.49 m/s^2 (0.05g) for a "good" level of comfort [27].

Detailed Review of Key Studies and Case Studies

Case Study 1: Concrete-Filled Steel Tube (CFST) Tied Arch Bridge (Zou et al., 2024)

- **Bridge Description:** This study [1] analyzed a long-span CFST tied arch bridge, a common type for crossing wide valleys due to its aesthetic appeal and structural efficiency. The arch ribs consist of steel tubes filled with concrete, combining the strength of steel with the compressive resistance of concrete.
- **Modeling Approach:** A sophisticated 3D coupled train-track-bridge model was developed in ABAQUS. The train was modeled with rigid bodies for the car, bogies, and wheelsets, connected by spring-dashpot elements representing the suspension systems. The track included rails, sleepers, slab, and base layer. Hertzian contact theory was used for wheel-rail interaction, and track irregularities were incorporated based on measured spectra.**Salama et al.** confirmed that moving-load models overestimate responses at resonance compared to interaction models, which account for energy absorption by suspensions and track elasticity, aligning with findings by **Yang et al. (2004)** [6].
- **Key Findings:**
    - A strong linear relationship was observed between maximum vertical displacement/dynamic stress and both train speed and axle load.
    - Vertical acceleration increased linearly with speed but exhibited an exponential increase with axle load, highlighting the profound impact of heavier trainsets.
    - The mid-span section was identified as the most critical location, experiencing the peak responses.
    - Predictive equations (e.g., Eq. 1) were developed with high accuracy ($R^2>0.98$), providing a valuable tool for preliminary design.

$$u_{dA}=-1.77P+0.0004v+0.0533P^2+0.000001v^2+17.58$$

Case Study 2: Prestressed Concrete Bridge and Interaction Model Comparison (Salama et al., 2022)

- **Bridge Description:** [23] analyzed a continuous, non-prismatic prestressed concrete bridge with two 59-meter spans, representative of common HSR viaducts.
- **Modeling Approach:** This study compared three fundamental modeling approaches in a 2D framework:
    1. **Moving Load Model:** The simplest approach, ignoring train inertia.
    2. **Whole-System Model:** A direct coupling method where the train and bridge are treated as a single system with updating stiffness matrices.
    3. **Decoupled-System Model:** An iterative method where train and bridge are solved separately with contact forces converging at each time step.

The train was modeled using the High-Speed Load Model (HSLM) specified in Eurocode 1 [24].

- **Key Findings:**
    - The moving load model provided conservative results, overestimating the bridge response (deflection and acceleration) at resonance speeds compared to the interaction models.
    - Resonance occurred at a lower speed (30.5 m/s) in the interaction models than in the moving load model (32 m/s) due to the mass and flexibility added by the train.
    - Track irregularities had a negligible effect on bridge deflection but a significant impact on vehicle acceleration, directly influencing passenger comfort and governing operational speed limits.

Additional Notable Studies

- **Cable-Stayed Bridges:** [28] investigated the aerodynamic stability and dynamic response of cable-stayed bridges under crosswinds, a critical consideration for long-span HSR bridges.
- **Composite Bridges:** [29] performed experimental and numerical analysis of a steel-concrete composite bridge, highlighting the importance of accurate connection modeling.
- **Stochastic Analysis:** [30] incorporated random track irregularities into a 3D coupled model, demonstrating the variability in dynamic response and the need for probabilistic design approaches.

Parametric Analysis and Discussion of Influencing Factors

Train-Derived Parameters

- **Speed:** The most significant factor. Responses generally increase with speed, with dramatic amplification at critical resonant speeds.
- **Axle Load:** Heavier axle loads linearly increase bending moments and stresses. The relationship with acceleration can be more complex, sometimes exponential as shown by [1].

Train Configuration: The number of cars, axle spacing, and articulation affect the excitation frequency content. Articulated trains can reduce dynamic effects compared to trains with traditional bogies [31].

Track-Derived Parameters

- **Track Irregularities:** These are random deviations from the ideal track geometry. They are the primary source of high-frequency vibrations and significantly impact ride comfort. Higher-class tracks (e.g., Class 6) with smaller irregularities allow for higher operating speeds [19, 23].
- **Track Stiffness:** While its direct effect on the bridge response is often minimal, track stiffness influences the vehicle's response and the overall dynamics of the coupled system. Softer tracks can have a mitigating effect on the bridge by absorbing more energy [32].

Bridge-Derived Parameters

- **Span Length and Natural Frequency:** Longer spans have lower natural frequencies, making them more susceptible to resonance at lower train speeds. The relationship between span and critical speed is a primary design consideration [22].
- **Structural Damping:** Damping is a key energy-dissipation mechanism. Typical damping ratios are 1-2% for concrete bridges and 0.5-1% for steel bridges. Higher damping effectively reduces resonant responses [33].
- **Boundary Conditions and Continuity:** Continuous bridges have different mode shapes and natural frequencies compared to simply-supported ones, leading to more complex dynamic behavior [12].

Advanced Modeling Techniques and Emerging Trends

- **Multi-Body Simulation (MBS) and Co-Simulation**
- Advanced analysis often involves co-simulation between specialized software. A multi-body system software (e.g., SIMPACK) is used to model the detailed dynamics of the train, while an FEA software (e.g., ABAQUS, ANSYS) models the bridge and track. The two programs exchange data (forces, displacements) at each time step, providing a highly accurate but computationally expensive solution [34].

Machine Learning and Surrogate Modeling

- To overcome the computational burden of detailed FE models, machine learning (ML) techniques are being employed. Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and other ML algorithms can be trained on FE data to create surrogate models that predict dynamic responses almost instantaneously [35, 36]. This is particularly useful for parameter studies, optimization, and real-time assessment.

Digital Twins for Structural Health Monitoring

- The concept of a "digital twin" – a high-fidelity virtual model continuously updated with sensor data from the physical bridge – is a frontier in bridge engineering. Digital twins enable predictive maintenance, fatigue life assessment, and real-time safety evaluation under extreme events [37].

Practical Implications for Design and Maintenance

Design Code Recommendations

Current design codes are evolving to better address high-speed dynamics. Engineers should:

- Conduct a detailed dynamic analysis for bridges with fundamental frequencies below certain thresholds (e.g., for speeds > 200 km/h).
- Use coupled interaction models for critical spans or when train masses are significant compared to the bridge mass.
- Consider the envelope of responses from a family of loading models like HSLM-A [24].

Maintenance Strategies

- **Track Maintenance:** Regular grinding and alignment are essential to control track irregularities and limit dynamic forces.

- **Bridge Inspection:** Focus inspections on critical sections identified by dynamic analysis (e.g., mid-span, support regions). Use vibration monitoring to detect changes in natural frequency, which can indicate stiffness loss or damage.

Conclusion and Future Directions

This review has synthesized the current state of knowledge on the vibration behavior of railway bridges under high-speed trains. The transition from simple analytical models to complex 3D coupled simulations has significantly improved the accuracy of dynamic response prediction. Key conclusions are:

1. Dynamic analysis is indispensable for the safe and comfortable design of HSR bridges.
2. Train-bridge interaction effects are significant, especially near resonance, and lead to responses different from those predicted by moving load models.
3. Parameters like train speed, axle load, and track irregularities dominate the dynamic response, while bridge-specific parameters like damping and boundary conditions modulate it.
4. The mid-span of the bridge is consistently the most critical section for bending and acceleration responses.

Future research should focus on:

- **Complex Bridge Types:** More studies on long-span suspension, cable-stayed, and extradosed bridges.
- **Multi-Hazard Interactions:** Combined effects of seismic, wind, and train loads.
- **Soil-Structure-Interaction (SSI):** Incorporating the flexibility of foundations and surrounding soil.
- **Fatigue Assessment:** Long-term fatigue damage evaluation under stochastic traffic loading.
- **AI Integration:** Further development of ML-based surrogate models and their integration into digital twin frameworks for lifecycle management.

REFERENCES :

[1] Zou, Y., Liu, Z., Tian, C., Zhang, X., and Liu, B. (2024). Dynamic response analysis of concrete filled steel tube tied arch bridge on a slab foundation under moving train load. *Front. Built Environ.* 10:1498790.

[2] Yang, Y.B., Yau, J.D., and Wu, Y.S. (2004). *Vehicle-bridge interaction dynamics with applications to high-speed railways*. World Scientific.

[3] Timoshenko, S.P., and Young, D.H. (1955). *Vibration problems in engineering* (3rd Ed.). D. Van Nostrand.

[4] Zhai, W., Han, Z., Chen, Z., Ling, L., and Zhu, S. (2019). Train-track-bridge dynamic interaction: A state-of-the-art review. *Vehicle System Dynamics*, 57(7), 984-1027.

[5] Frýba, L. (1999). *Vibration of solids and structures under moving loads* (3rd Ed.). Thomas Telford.

[6] Green, M. F., & Cebon, D. (1994). Dynamic response of highway bridges to heavy vehicle loads: theory and experimental validation. *Journal of Sound and Vibration*, 170(1), 51-78.

[7] Xia, H., De Roeck, G., Zhang, N., and Maeck, J. (2003). Experimental analysis of a high-speed railway bridge under Thalys trains. *J. Sound Vib.*, 268, 103–113.

[8] Zhang, N., Xia, H., and Guo, W. (2008). Vehicle-bridge interaction analysis under high-speed trains. *J. Sound Vib.*, 309, 407–425.

[9] Galvin, P., Romero, A., Moliner, E., De Roeck, G., and Martinez-Rodrigo, M.D. (2021). On the dynamic characterisation of railway bridges through experimental testing. *Eng. Struct.*, 226, 111261.

[10] Farrar, C. R., & Worden, K. (2012). *Structural health monitoring: a machine learning perspective*. John Wiley & Sons.

[11] Cheng, Y. S., Au, F. T. K., and Cheung, Y. K. (2001). Vibration of railway bridges under a moving train by using bridge-track-vehicle element. *Eng. Struct.*, 23, 1597–1606.

[12] Chatterjee, P. K., Datta, T. K., & Surana, C. S. (1994). Vibration of continuous bridges under moving vehicles. *Journal of Sound and Vibration*, 169(5), 619-632.

[13] Liu, K., Reynders, E., De Roeck, G., and Lombaert, G. (2009). Experimental and numerical analysis of a composite bridge for high-speed trains. *J. Sound Vib.*, 320, 201–220.

[14] Ribeiro, D., Calçada, R., Delgado, R., Brehm, M., and Zabel, V. (2012). Finite element model updating of a bowstring-arch railway bridge based on experimental modal parameters. *Eng. Struct.*, 40, 413-435.

[15] Delgado, R.M., and Dos Santos, R.C.S.M. (1997). Modeling of railway bridge-vehicle interaction on high-speed tracks. *Comput. Struct.*, 63(3), 511-523.

[16] Yang, F., and Fonder, G.A. (1996). An iterative solution method for dynamic response of bridge-vehicle systems. *Earthq. Eng. Struct. Dyn.*, 25, 195-215.

[17] Lou, P., and Zeng, Q. Y. (2005). Formulation of equations of motion of finite element form for vehicle-track-bridge interaction system. *Int. J. Numer. Methods Eng.*, 62(3), 435-474.

[18] Salama, A., Eraky, A., Yahya, M., and Samir, R. (2022). Dynamic Analysis of High-speed Railway Bridges Applying Bridge-Vehicle Interaction. *Jordan Journal of Civil Engineering*, 16(3), 402–416.

[19] Podwóma, M. (2015). Modeling of random vertical irregularities of railway tracks. *Int. J. Appl. Mech. Eng.*, 20(3), 647–655.

[20] Wu, Y.S., Yang, Y.B., and Yau, J.D. (2001). Three-dimensional analysis of train-rail-bridge interaction problems. *Vehicle System Dynamics*, 36(1), 1-35.

[21] Shabana, A. A., Zaazaa, K. E., & Sugiyama, H. (2007). *Railroad vehicle dynamics: a computational approach*. CRC Press.

[22] Yang, Y. B., Lin, C. L., Yau, J. D., & Chang, D. W. (2004). Mechanism of resonance and cancellation for train-induced vibrations on bridges with elastic bearings. *Journal of Sound and Vibration*, 269(2), 345-360.

[23] Salama, A., Eraky, A., Yahya, M., and Samir, R. (2022). Dynamic Analysis of High-speed Railway Bridges Applying Bridge-Vehicle Interaction. *Jordan Journal of Civil Engineering*, 16(3), 402–416.

[24] EN 1991-2. (2003). Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges.

[25] Goicolea, J. M., Navarro, J. A., & Antolín, P. (2003). Dynamic amplification factor versus Eurocode 1 formulas for railway bridges. In *Proceedings of the IMECH E, Part F: Journal of Rail and Rapid Transit*.

[26] EN 1990:2002. Eurocode - Basis of structural design.

[27] ISO 2631-1. (1997). Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration.

[28] Zhang, Q., Cai, X., Wang, T., Zhang, Y., and Wang, C. (2024). Aerodynamic performance and dynamic response of high-speed trains passing by each other on cable-stayed bridge under crosswind. *J. Wind Eng. Ind. Aerodyn.*, 247, 105701.

[29] Malveiro, J., Ribeiro, D., Sousa, C., and Calçada, R. (2018). Model updating of a dynamic model of a composite steel-concrete railway viaduct based on experimental tests. *Eng. Struct.*, 164, 40-52.

[30] Zhu, Z., Li, Y., & He, X. (2020). Stochastic analysis of train-bridge interaction system considering random track irregularities. *Engineering Structures*, 213, 110561.

[31] Diana, G., Cheli, F., Collina, A., Corradi, R., & Melzi, S. (2002). The development of a numerical model for railway vehicles comfort assessment through comparison with experimental measurements. *Vehicle System Dynamics*, 38(3), 165-183.

[32] Kouroussis, G., Verlinden, O., & Conti, C. (2011). Free field vibrations caused by high-speed lines: measurement and time domain simulation. *Soil Dynamics and Earthquake Engineering*, 31(4), 692-707.

[33] Prendergast, L. J., Gavin, K., & Hester, D. (2017). Isolating the location of scour-induced stiffness loss in bridges using local modal behaviour. *Journal of Civil Structural Health Monitoring*, 7(4), 483-503.

[34] Paz, M., & Leigh, W. (2004). *Structural dynamics: theory and computation*. Springer Science & Business Media.

[35] Nguyen, V. H., Kim, S. E., & Nguyen, T. V. (2021). Efficient prediction of train-induced vibration of railway bridges using artificial neural networks. *Structures*, 34, 2924-2937.

[36] Sun, Z., & Zhang, Y. (2022). A surrogate-assisted multi-objective optimization framework for train-bridge system dynamics. *Engineering Applications of Artificial Intelligence*, 114, 105091.

[37] Kaewunruen, S., Rungskunroch, P., & Welsh, J. (2020). A digital twin for validating railway bridge resilience against climate change. *Sustainability*, 12(1), 198.