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Research Paper

Determine train load and speed based on dynamic displacement results

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ABSTRACT

The load and operational speed of trains on railway bridges play a significant role. In the context of increasing demand for rail transport, accurately determining these parameters not only helps ensure safety but also brings economic benefits and optimizes system efficiency. This research aims to determine the load and speed of trains based on dynamic displacement results obtained from sensors installed on railway bridges. The study was applied on a real urban railway bridge. The dynamic displacement data of the railway bridge under the influence of passing trains is collected using high-sensitivity LVDT sensors. By applying finite element models (FEM) and real-time displacement data analysis combined with optimization algorithms, the estimation of train load and speed is performed. The analysis results show that the estimated load and speed values are relatively accurate compared to reality. This method helps to accurately monitor and manage train load and speed. The research findings will contribute to improving safety, operational efficiency, and provide a solid scientific foundation for enhancing the railway transportation system.

1 Introduction

The railway system is essential in the socio-economic development of a nation because it serves numerous crucial functions [1]. Regarding freight transportation, railways are often cheaper and more efficient than road transport, especially for heavy and bulky goods [2]. Trains have a large carrying capacity, making them withstand the heavy use placed on road systems and lower maintenance costs. Regarding passenger transportation, railways are concerned with quick and safe service, time-saving, cost transversing, and de-congestion of traffic. The system further improves regional connectivity, increases trade and economic exchange, and helps industrial zones meet their logistical need by transporting raw material input and products [3]. Environmentally, trains emit less greenhouse gases compared to trucks and cars, contributing to

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reduced air pollution and energy savings. In the fields of security and defense, railways can quickly transport troops and equipment, as well as support emergency response in disaster situations. Furthermore, the railway system contributes to sustainable urban development, enhancing the connection between residential areas and city centers and encouraging economic and social development around train stations. In summary, railways are not only an essential means of transportation but also significantly contribute to the sustainable development of a nation in various aspects [4].

Railway bridges are a crucial part of the railway system, playing a key role in connecting rail lines over obstacles such as rivers, valleys, gorges, and urban areas. Railway bridges allow rail lines to cross both natural and artificial barriers, creating seamless and efficient routes while enhancing regional connectivity, promoting trade, and economic exchange. Ensuring the safety of railway bridges is one of the essential factors for maintaining smooth and efficient rail traffic. The safety of railway bridges ensures that trains can move smoothly without encountering breakdowns or accidents, thereby increasing the reliability and efficiency of the rail transportation system [5, 6]. When railway bridges are well-maintained, they not only ensure the safety of passengers and cargo but also help minimize delays, optimize transportation flow, and reduce maintenance and unexpected repair costs.

Vietnam's urban railway system is laying its initial foundations on the path of development [7, 8]. **Figure 1** shows the urban railway development plan in Hanoi, Vietnam. In this process, researching and ensuring safety is of utmost importance. Safety not only guarantees the well-being of passengers but also enhances the reputation and operational efficiency of the entire system. This requires authorities and contractors to adhere to international safety standards, conduct thorough testing, and continuously update the most advanced technologies. Only by ensuring safety can the urban railway system develop sustainably and bring long-term benefits to the community.



bridges. By using high-sensitivity LVDT sensors [18, 19] to collect dynamic displacement data of the bridge under the impact of passing trains, along with applying the finite element method (FEM) model and real-time data analysis, this study estimated the load and speed of the trains.

The analysis results show that the estimated load and speed values are relatively accurate compared to reality. This method helps accurately monitor and manage the load and speed of trains, optimizes maintenance procedures, and extends the lifespan of railway bridges. The findings from this study will contribute to improving safety and operational efficiency and providing a solid scientific foundation to enhance the railway transportation system.

2 Methodology

2.1 Data collection

In this study, dynamic displacement data was collected on the Cat Linh – Ha Dong urban railway line, which is part of the Cat Linh – Ha Dong elevated railway (**Figure 2**). The dynamic displacement data of the railway bridge under the influence of passing trains was collected using high-sensitivity Linear Variable Differential Transformer (LVDT) sensors. The collected data includes information on the amplitude and timing of dynamic displacements, helping to identify important dynamic characteristics of the bridge under train loads. Using high-sensitivity LVDT sensors ensures that the collected data is highly accurate, providing researchers and engineers with a solid scientific basis for making decisions related to the management and maintenance of railway bridges.



Fig. 2 – Cat Linh – Ha Dong urban railway line [20]

The bridge span selected for data collection is located near Yen Nghia Station on the Cat Linh – Ha Dong line (**Figure 3**). This is a box girder span, classified as a 32m span type, one of the representative structures of this elevated railway line. The selection of the bridge span near Yen Nghia Station was based not only on its strategic location but also on the structural characteristics of the span, ensuring the representativeness and accuracy of the collected data. To ensure the comprehensiveness and reliability of the dynamic displacement data, two specific data collection points were identified. The first position is at a cross-section 5m away from the bridge support, where displacement changes near the bridge support can be recorded—an important location for understanding the structural responses under load. The second position is at the midspan cross-section, where displacement information at the midpoint of the bridge span can be collected, providing an overall view of the dynamic behavior of the entire span under the impact of passing trains.

The LVDT sensor is carefully installed to ensure reliable and stable measurement results. First, the LVDT sensor is securely mounted on a specialized bracket and connected to the bridge structure via a thin, non-deformable steel wire. After fixing the LVDT sensor, the magnetic core of the LVDT is aligned to the central position of the coil when the bridge span is in a balanced. This ensures that the sensor can detect deformation in both directions when the bridge span is subjected to external loads. Next, the LVDT device is connected to a signal conditioner to convert the voltage signal into readable

measurement data. After completing the installation steps, the device is calibrated by applying specific load states to the bridge span to determine the LVDT's response and adjust the measurement range accordingly.

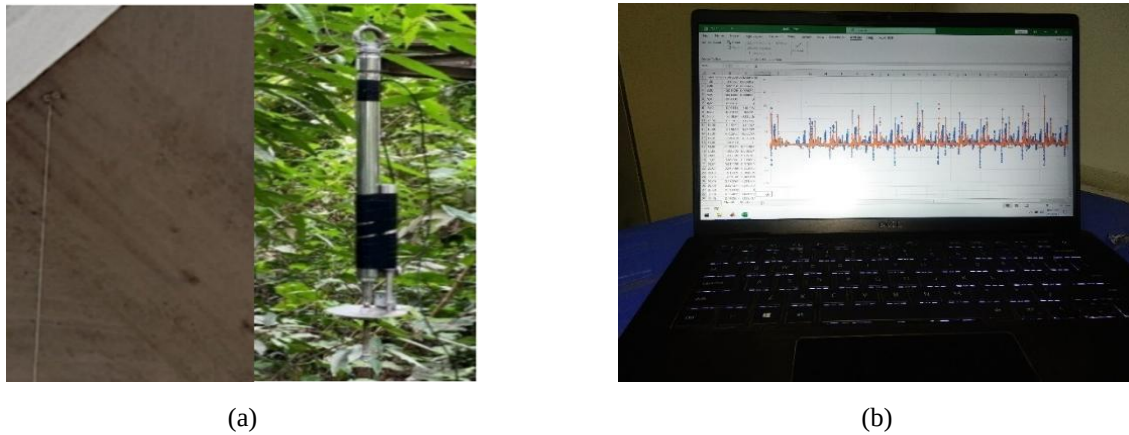


Fig. 3 –Collect data using LVDT at Cat Linh – Ha Dong line [8, 19].

2.2 Application of hybrid CNN-GRU network for data enrichment (data reconstruction)

During the experiment, some errors may arise, so a data enrichment solution (data reconstruction) is proposed to avoid the risks and improve the performance of the method. This research employs a hybrid architecture that integrates Convolutional Neural Networks (CNN) with Gated Recurrent Units (GRU) to improve and reconstruct dynamic displacement data obtained from LVDT sensors. The approach leverages CNN's prowess in feature extraction and GRU's strength in learning temporal sequences, resulting in enhanced data quality and the filling of gaps in missing or noisy measurements. The dynamic displacement data collected from the Cat Linh-Ha Dong urban railway bridge underwent initial preprocessing to remove noise and outliers using a low-pass filter. Subsequently, the data were segmented into overlapping time windows to serve as inputs for the hybrid network, and each segment was normalized to improve training convergence.

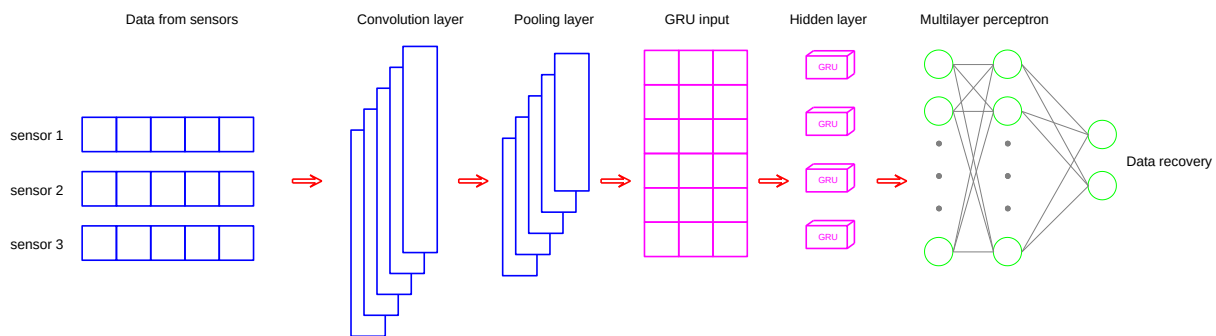


Fig. 4 – Data enrichment process

The CNN component comprised multiple convolutional layers that extracted spatial features from the input data, capturing localized patterns in displacement signals, such as abrupt shifts or oscillations caused by train loads. These features were then forwarded to the GRU component, which modeled sequential dependencies and temporal dynamics inherent in the data. The hybrid network was trained on a dataset of labeled dynamic displacement measurements. During training, the objective was to minimize the mean squared error between the network's predictions and the actual values. A subset of the dataset was set aside for validation to evaluate the network's performance in generalization.

After training, the network was employed to reconstruct missing portions of the displacement data and to improve noisy recordings. The enhanced dataset was compared against experimental measurements and FEM simulations to verify its accuracy. The upgraded displacement data were incorporated into the FEM to boost the precision of train load and speed estimations. The hybrid CNN-GRU network optimized the process by supplying high-quality input data and minimizing parameter estimation errors. Figure 5 shows the results of CNN-GRU training process.

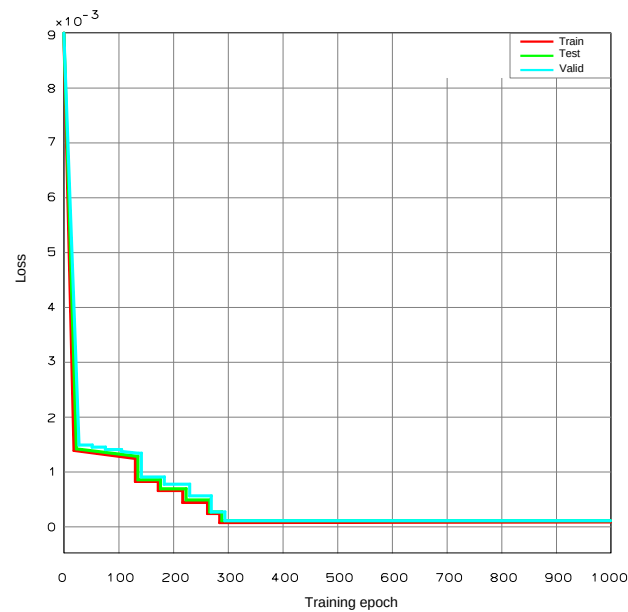


Fig. 5 – CNN-GRU training results

2.3 Determine train load and speed

A finite element model was constructed based on the as-built documentation of the Cat Linh – Ha Dong elevated railway line. This model was designed to include two simply supported box girders (**Figure 6 and 7**). The structure of the model is detailed as follows:

- 1 The two main girders are designed with a box cross-section, a common and efficient design for bearing heavy loads and providing high stiffness. The box cross-section also enhances the girders' resistance to bending and torsion, ensuring stability and safety for the railway bridge system.
- 2 At the top of each girder, two railway tracks are simulated and rigidly connected to the girder. This rigid connection not only accurately replicates the real-world interaction between the rails and the girder but also plays a crucial role in transmitting loads from the rails to the girder. Accurate simulation of this connection enhances the model's precision, ensuring that the load and displacement analysis results closely match real-world conditions.
- 3 Elements within the model are used to assign loads and enhance interaction between the model components. Proper load assignment is a critical factor to ensure the model accurately reflects the actual working conditions of the railway bridge. This includes simulating loads from trains, wind loads, temperature loads, and other types of loads the bridge may encounter during its operation.
- 4 The girders are made of concrete with strength of 40MPa. Other materials, such as prestressed cables and rails, are directly taken from the as-built documentation of the bridge.
- 5 The train load and speed will be simulated through dynamic load functions. The dynamic load of the train includes vertical forces, lateral forces, and impact forces caused by the wheels' contact with the rails. These forces vary over time and with the train's position on the bridge. This simulation accurately replicates the complex force interactions that the train exerts on the bridge structure. The speed of the train is a crucial factor affecting the dynamic load. Higher speeds result in greater impact forces and faster load variations.

Essentially, the process of determining the speed and weight of a train traveling over a bridge involves combining structural modeling and experimental data. Specifically, this process focuses on adjusting the unknown parameters of the train (such as speed and weight) within the Finite Element Model (FEM) so that the simulation results match the actual measurement data collected from sensors installed on the bridge.

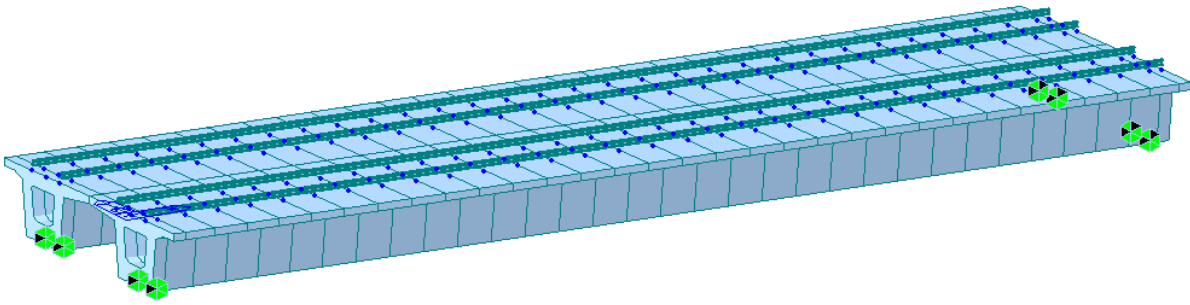


Fig. 6 – Finite element model of a span of Cat Linh Ha Dong line.

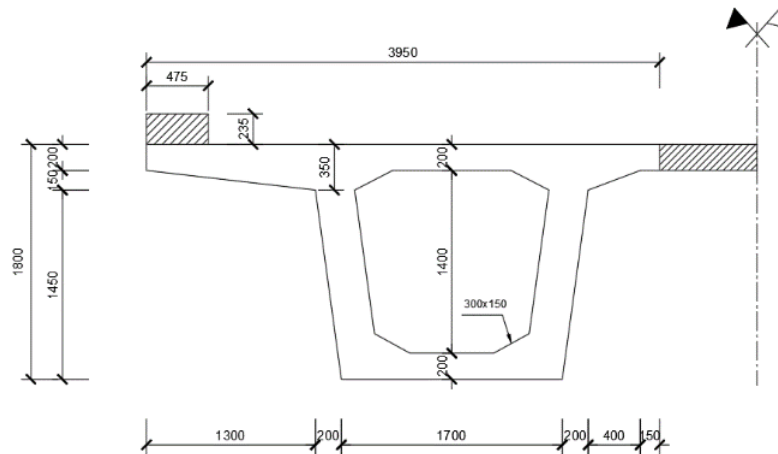


Fig. 7 – Girder bridge cross-section [21]

After constructing the FEM that simulates the bridge structure (including material properties, geometry, and boundary conditions), the train is modeled as a moving load. This load depends on parameters such as the train's speed and weight. These are the variables that need to be determined in the problem.

The FEM is used to calculate the dynamic responses of the bridge under the influence of the train, including parameters such as displacement, velocity, and acceleration at specific points on the bridge. These results are then compared with the experimental data obtained from dynamic sensors. Once the FEM is built and simulation results are calculated, the optimization process is carried out to determine the train parameters, namely speed and weight, so that the difference between the simulation results and experimental data is minimized. During the optimization process, the objective function is constructed to measure the discrepancy between the simulated values from the FEM and the actual experimental values. This objective function is typically the sum of squared errors between the simulated and real values. The goal of the optimization algorithm is to find the set of speed and weight values that minimize this objective function

$$J(v, W) = \sum_{i=1}^n (y_{\text{exp}}(t_i) - y_{\text{sim}}(t_i, v, W))^2 \quad (1)$$

Where: $y_{\text{exp}}(t_i)$ is the experimental value of displacement at time t_i ; $y_{\text{sim}}(t_i, v, W)$ is the simulated value of displacement calculated from the FEM at time t_i dependent on the train's speed v and weight W ; n is the total number of experimental data points

3 Results and discussion

The optimizer was launched, and the results are shown in Figure 8. The plot illustrates the convergence process, which occurred rapidly and efficiently. During the first 10 iterations, the objective function value dropped significantly from a high level to nearly zero, highlighting the effectiveness of the optimization algorithm in minimizing the error between the

simulation model and the experimental data. After about 20 iterations, the objective function value stabilized, indicating that the optimization process had reached convergence, and the parameters were successfully optimized.

The vertical axis in Figure 8 indicates that the objective function value reached a very small magnitude (on the order of 10^{-2}), suggesting that the difference between the simulated and real-world data is minimal, implying that the model has been well-calibrated. Furthermore, the number of iterations required to reach convergence was relatively low, with fewer than 100 iterations needed, demonstrating that the optimization process was not only effective but also computationally efficient. Calculation time takes 428s. This indicates that the optimizer was able to quickly adjust the parameters to achieve accurate results while conserving computational resources.

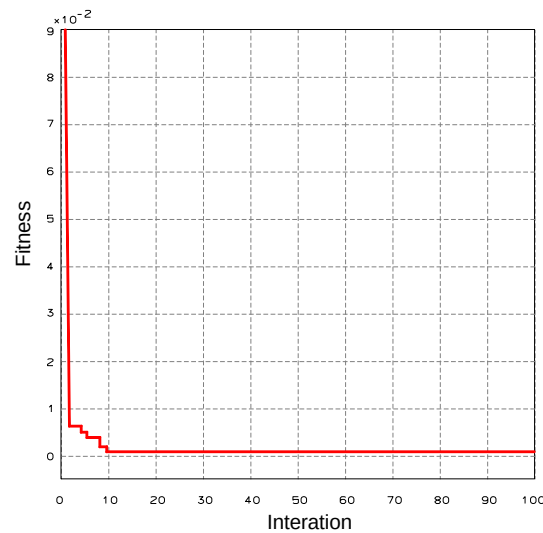


Fig. 8 – Optimization process convergence curve

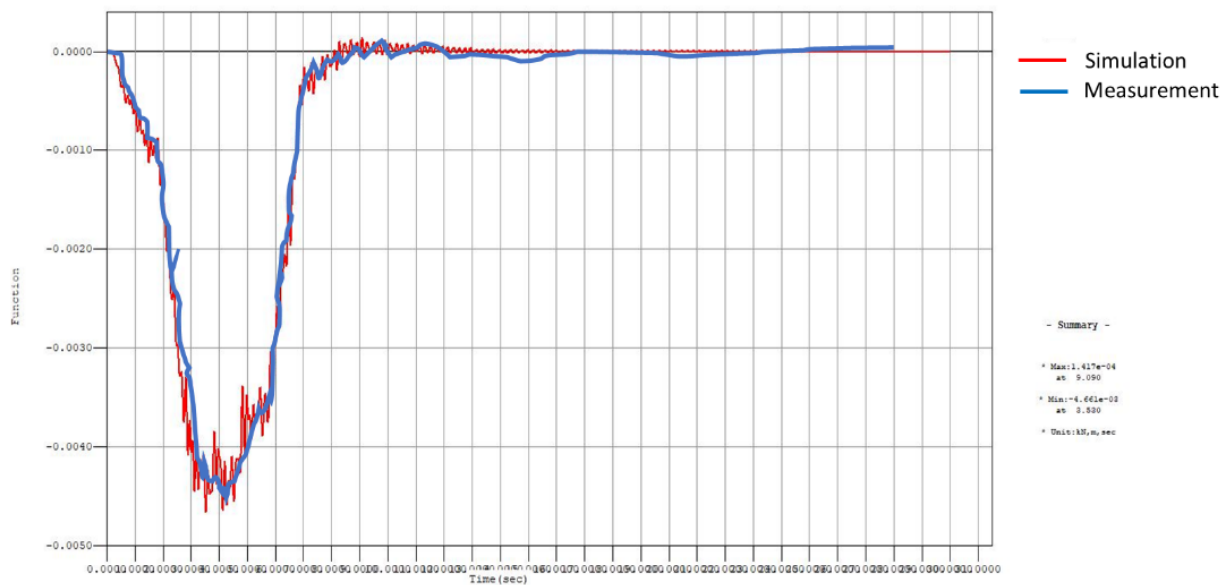


Fig. 9 – Displacement results from numerical simulations and measurement at the middle of span

Figure 9 and Figure 9 show the displacement of the numerical simulation and measurement after the model update. The dynamic displacement between the simulation and reality is relatively consistent, showing the accuracy of the model after the update. The results after the optimization process is completed are the speed and load of the train. The results are shown in Table 1

The optimization results for the train parameters demonstrate a high level of accuracy of the model compared to real-world conditions. Specifically, the model predicts a speed of 56.2 km/h, while the actual speed is 55.6 km/h, with an error of only 1.07%. This indicates that the model's speed prediction is very accurate, with the minor discrepancy potentially due to factors such as the condition of the tracks or environmental conditions that are not fully captured in the model. Similarly, the model predicts an axle load of 11.9 tons compared to the actual load of 12 tons [21], with an error of just 0.8%. This small difference shows that the model also accurately predicts the axle load, with minor variations possibly due to the actual weight of the trains or adjustments in operational conditions. With such small errors, the model can be considered reliable and reflective of real-world conditions.

Table 1 - Results of determining train velocity and load

	Model	Real	Error
Velocity	56.2 km/h	55.6 km/h	1.07%
Axleload	11.9T	12T	0.8%

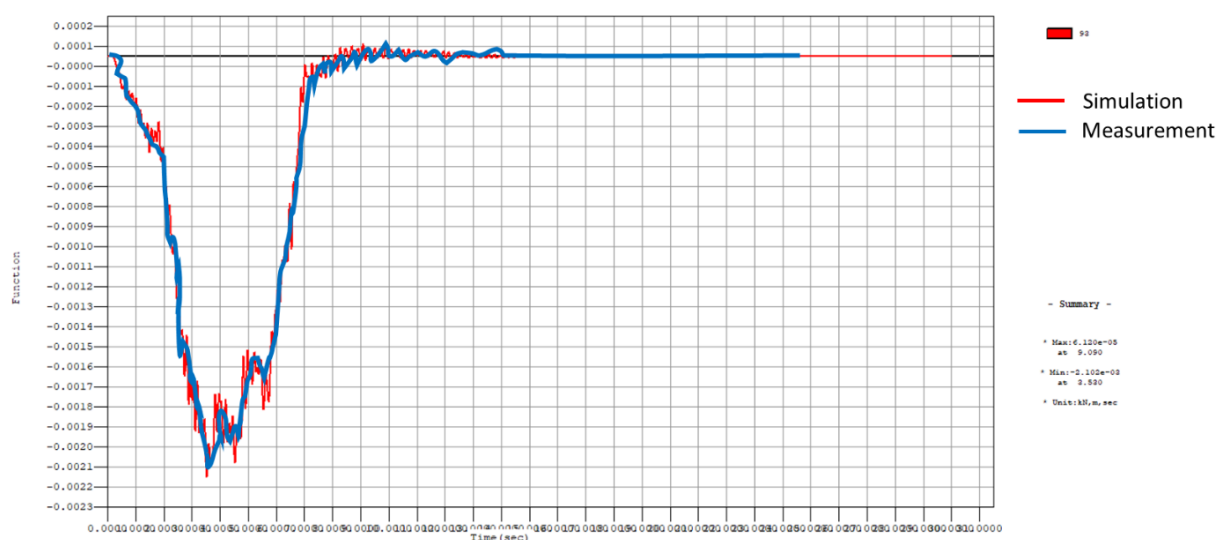


Fig. 10 – Displacement results from numerical simulations and measurement at cross-section 5m from bearing

4 Conclusion

This study proposes a method for determining the load and speed of trains by measuring the dynamic displacement of railway bridges. Dynamic displacement is a crucial metric in assessing and monitoring the structural health of railway bridges, particularly in urban railway networks. Monitoring and analyzing dynamic displacement help infrastructure managers make timely decisions regarding maintenance and repairs to ensure operational safety and efficiency. The research findings demonstrate that the method of determining load and speed through dynamic displacement measurement achieves high accuracy. By integrating precise measurement technology and modern data analysis methods, data collected from dynamic displacement can provide accurate information about the load and speed of passing trains. Applying this method improves the efficiency of managing and operating railway bridges. Information gathered from dynamic displacement measurements not only supports periodic maintenance planning but also assists managers in making strategic decisions on upgrading railway infrastructure to meet the increasing transportation demands in major cities. The study also opens up the potential for development in applying this dynamic displacement measurement method to various railway systems worldwide. Sharing experiences and technologies among countries can lead to significant advancements in the global management and maintenance of railway transportation infrastructure.

Acknowledgments

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