International Journal on
Advanced Science
Engineering
Information Technology

Vol.14 (2024) No. 2
ISSN: 2088-5334

Online Real-Time Monitoring System of a Structural Steel Railway Bridge Using Wireless Smart Sensors

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***Abstract*—Railway bridges are crucial for transferring passengers and commodities in the transportation network. Railway bridges require continuous monitoring to observe their performance. A structural health monitoring system is one method for assessing the viability of a railway bridge structure. The functioning of railroad bridge structures has been extensively observed using wireless technology. This research aims to implement smart wireless sensors for monitoring the structural health of the railway bridge online in real-time during operation. Many sensors were installed on the railway bridge, including strain gauges, accelerometers, linear variable displacement transducers, and proximity sensors. Geometric modeling and numerical simulation were performed to find critical frame locations on the railway bridge where the instrumentation sensors would be placed. In this study, MONITA® is employed for data acquisition modules. The MONITA® system consists of a combination of hardware and software that functions to retrieve, send, store, and process data. This paper describes the result of establishing this method to comprehend the performance of the steel railway bridge structure in real-time via the human-machine interface display dashboard. As a result, the monitoring system can appropriately assess a structural railway bridge in real time. This study may be helpful to practicing engineers and researchers in future studies of steel railway bridge evaluation. This could be a valuable reference for future studies in implementing such systems as the railway bridge early warning system technique in detecting bridge damage.**

***Keywords*—Display dashboard; instrumentation sensors; online real-time monitoring; railway bridges; structural health monitoring.**

Manuscript received 18 Jul. 2023; revised 30 Aug. 2023; accepted 9 Jan. 2024. Date of publication 30 Apr. 2024.

I. INTRODUCTION

Due to the increasing demand for capacity to transport goods and people in recent decades, many countries have significantly expanded their rail infrastructure. The train is an alternative for the transportation of goods and passengers. Railway lines were built to connect separate areas with relatively dense traffic density. When railroads cross obstacles, such as valleys, rivers, highways, or seas, bridges are needed to connect them. Railway bridges are essential infrastructure for the rail transportation network and need effective structural monitoring [1]–[7].

In Indonesia, railway bridges are primarily constructed in remote areas. In addition, railway bridges are exposed to various external influences, such as increased traffic loads and harsh environmental conditions. Loading conditions on railway bridges have changed in recent decades due to increased cargo volumes. As a result, the performance of railway bridges gradually deteriorates over time. For some reason, railway bridges must be continuously monitored to detect localized damage caused by these impacts [8]–[18].

By utilizing the data obtained from structural health monitoring systems (SHMS), many researchers have developed techniques for evaluating the evaluation of the parameter identification, damage detection, model update, safety assessment, and sustainability of civil engineering infrastructure. A model-based damage detection technique can identify modal civil structural characteristics according to observational data from the SHMS [19]–[26]. Long-term system monitoring is developed further by these SHMS. However, it is also possible to evaluate railway bridge sustainability, serviceability, and safety using the data collected by the SHMS. SHMS has utilized the advancement of new sensing technologies over the past few decades [27]–

[35]. Because of the advantages and tremendous benefits for applications that demand access to civil engineering structures, wireless approaches have been frequently used for SHMS [36]–[45].

Wireless sensors are also frequently used and placed in railway bridge SHM [40], [46], [47]. All wireless sensor investigations and implementations have demonstrated the potential to use wireless technology in railway bridge monitoring and management. The SHMS was initially implemented on Indonesia's BH 77 railway bridge. The railway bridge is a steel structure that is a single simple span bridge [48], [49].

The application and improvement of SHMS have substantially advanced with the development of contemporary information and communication systems, signal processing technology, the internet, and structural analysis. It should be understood that there are still significant issues with the SHMS that will need to be taken into account in the future, including improving the accuracy of the sensory system, high-frequency and accurate data sampling, knowledge development and data mining, diagnostic techniques, and analysis and modeling of big data collected from the SHMS and used for management and maintenance decisions [25], [50]–[53].

This research utilizes advances in the development of recent information system technology, modern communication, signal processing technology, and the Internet of Things to monitor and assess steel railway bridges operating with the maximum combination of working loads. The field is where the data acquisition station for the automatic data transmission and acquisition system's automatic monitoring system is located. The real-data information can be helpful for safety assessment and prioritizing railway bridge maintenance and repair.

II. MATERIALS AND METHOD

A. Structural Health Monitoring System (SHMS)

The application of SHMS on the railroad bridge is connected to using big data to create an expert system. The Internet of Things (IoT) and artificial intelligence (AI) are related to this technology. Furthermore, the expert system can be adopted for civil engineering purposes [13], [41], [54], [55]. The development of expert systems covers user interfaces, knowledge bases, engine interfaces, and development engines [12], [48], [52], [54]. User interfaces are used to monitor the condition of the railway bridge at the location using sensors installed at the railway bridge. The knowledge base describes the problem domain and presentation techniques that use facts according to logic. The engine interface generates reasoning utilizing the defined expert system's knowledge base contents in a particular order. The development engine creates rules for the system development process using a perspective on programming languages and the expert systems section.

The main objective of the SHMS of the railway bridge is to provide serviceability, safety, and sustainability monitoring and assessment of the railway bridges during operation. A long-term SHM should include decision support systems, data management systems, data processing systems, data gathering and transmission systems, and sensory systems to achieve the objective above [16], [17], [27], [46]. All the systems should be integrated into one coordination and efficiently utilized by the manager to take actions and policies on the results.

B. Field Instrumentation Schemes

The instrumentation scheme was generated to address the defined objectives. It was determined by identifying critical locations which would give sufficient and precise information. It is imperative to validate the suggested model with more straightforward solutions before creating a numerical model of the railway bridge that incorporates the combination of loadings.

Geometric modeling and numerical simulation were performed to observe critical frame locations on the railway bridge where the instrumentation sensors would be placed. A detailed model of the railway bridge in three dimensions (3D) was developed. Fig. 1. illustrates a schematic plan of the instrumentation sensor locations. The strain gauges and accelerometers were placed at the critical members of the railway bridge. The vital locations were determined based on the numerical simulation. The placement of strain gauges and LVDT locations are shown in Fig. 2. Schematic placement of the accelerometer sensors is illustrated in Fig. 3. The locations of these accelerometers are determined based on the results of numerical simulations, which indicate the critical location of the stress that occurs on the railway bridge when the loading combinations were applied. The placement of the accelerometer is determined by the outcomes of numerical simulations performed when the railway is under dynamic loading. The natural frequency for this critical position in mode 1 is 3.22 Hz, and the vibration period is 0.311 seconds.

In this study, an analytical calculation of this railway bridge was carried out using finite element analysis. The finite element analysis was executed by employing STAAD—Pro software [56]. The span length of the railway bridge for simulation modeling was 40.0 meters, with a width of 4.40 m and a height of 6.60 m, respectively. In the finite element analysis, the abutment end of the bridge was assumed to be supported by hinges, while roller support was at the other end. The supports are believed to have no frictional resistance, causing translational restraint without inducing rotational restraint. The loading combinations were implemented for this numerical simulation and followed the applicable standards and regulations [57]–[60].

C. Interfacing and Data Processing

The user interface for offline data analysis is carried out using appropriate and helpful software packages. The user interface comprises modules for the observed parameters, nonlinear dynamic response, generated force, vibration response, and deformation phenomena. The user interface makes it simple to keep track of a bridge's status.

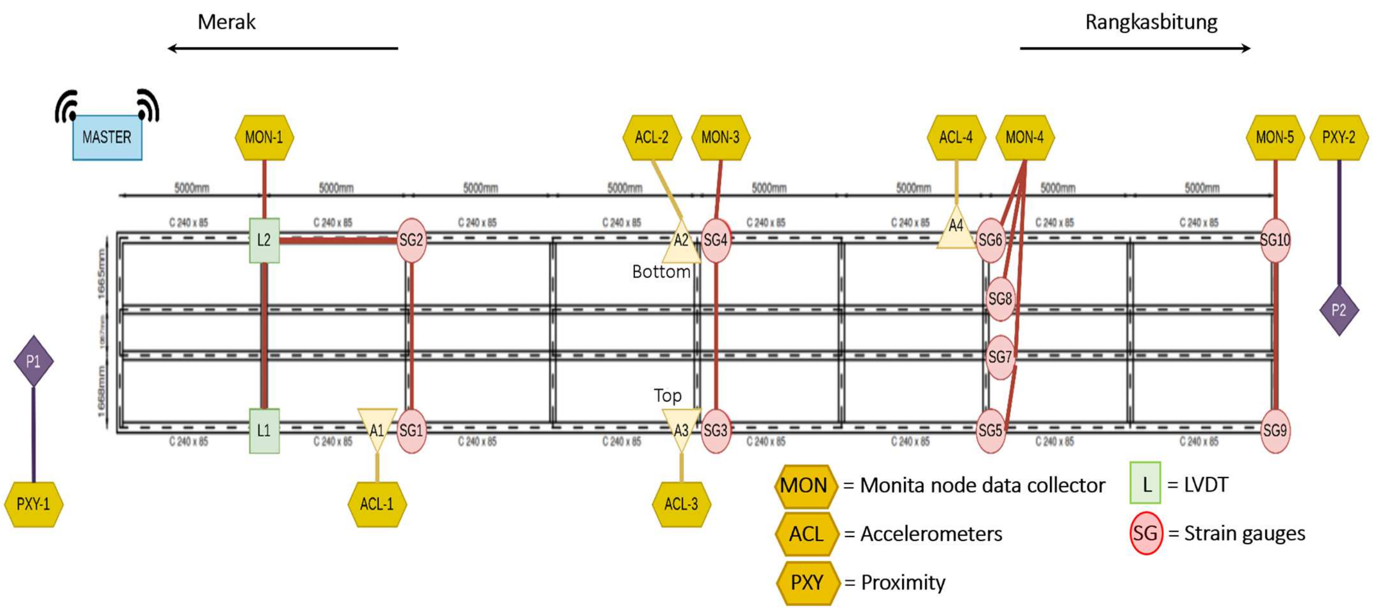

Fig. 1 Schematic plan of sensor installation locations

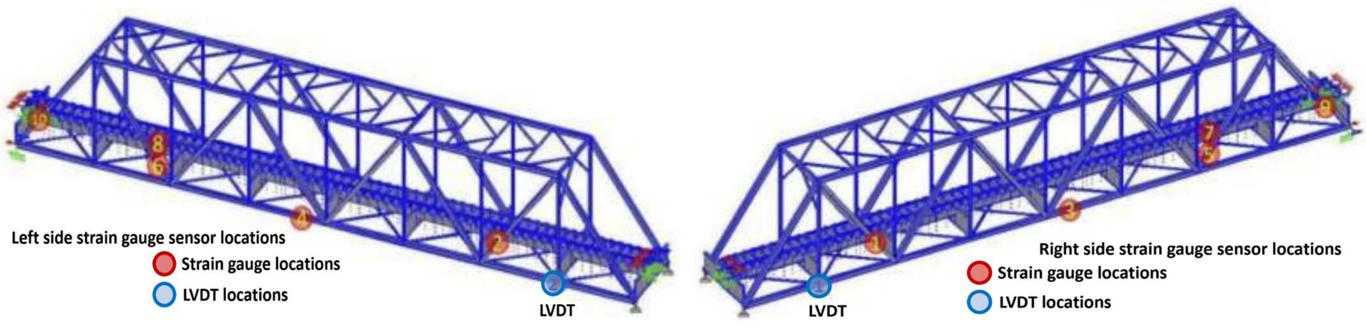

Fig. 2 Placement locations of strain gauges and LVDT

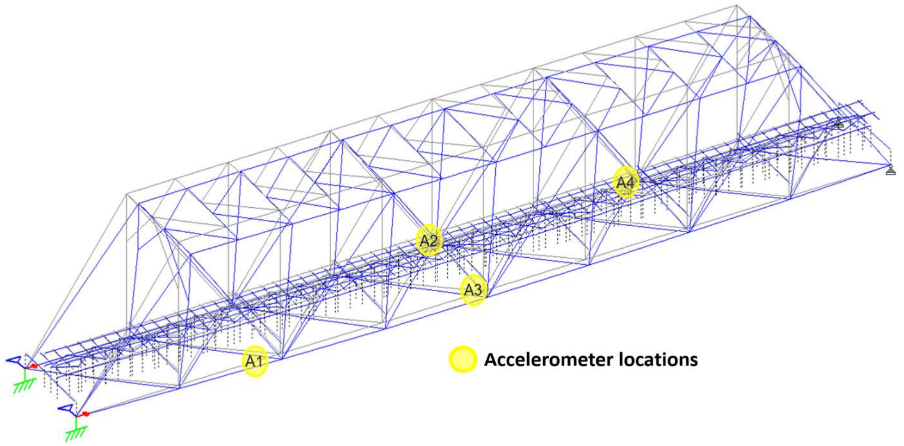

Fig. 3 Schematic locations of the accelerometers at the railway bridge

The user interface receives information from the data processing as well. The railway bridge can also be monitored remotely using the equipment set up at the command center. A server cluster, a significant network, and server maintenance tools are used primarily to run the command center. During the operation of the railway bridge, the data processing system can process both dynamic and static data. Remote monitoring can be possible depending on the equipment at the monitoring center. A server group, central network switching equipment, and other server maintenance equipment comprise most of the command center's equipment, an acquisition station, and workstations. According to data on strain signals, deformations brought on by stresses, and operating forces in the main components of the railway bridge, a structural health monitoring and evaluation system can evaluate the safety of railway bridges.

D. Sensory System

The primary factors considered in a sensory system include the kind of sensor used and where it is placed on the railway bridge. It should be noted that the position of the sensors should be considered for future railway bridge maintenance and rehabilitation. All sensors were installed on the railway bridge to obtain the required parameters. On the railway bridge, many sensors were installed, including ten units of strain gauges, four units of accelerometers, two units of proximity sensors, five units of node/data loggers, nine units of solar panels located on the railway bridge top, and one at the guardhouse rooftop.

1) Strain gauges: The strain gauge is one of the most used sensors for measuring stress applied to a structural element. The sensor location of strain gauges can be seen in Fig. 4. The strain gauges are attached to the flanges of the railway bridge girders using a powerful epoxy glue with firm adhesion.

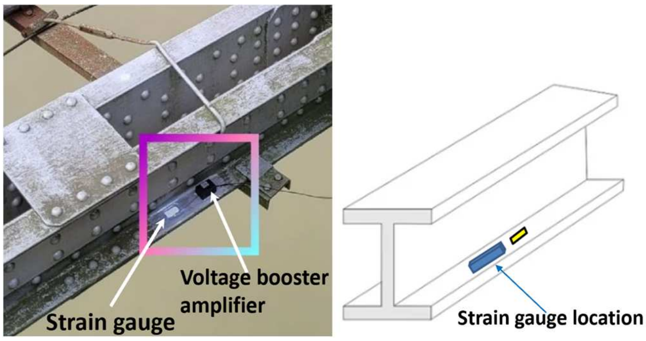

Fig. 4 Strain gauge sensors utilized for this SHMS

The strain gauge sensor is in the form of metal foil or metal wire, which conducts an electric current attached to the object to measure strain where the amount of strain comes from loading. This sensor is connected directly to the object whose strain is measured. The strain gauge works based on changes in pressure, resulting in changes in resistance. The strain gauge produces a change in the stress value proportional to the change in strain. The change is entered into the electrical circuit as a Wheatstone bridge. After that, how much voltage is in the strain gauge will be known. The technical specifications of the strain gauge are presented in Table 1.

TABLE I
STRAIN GAUGE TECHNICAL SPECIFICATION

No	Specification	Remarks
1	Operating voltage	24 V
2	Sensor type	Metal foil strain gauge – full bridge
3	Resistance	350 Ohm
4	Output signal analog	0 – 5 V
5	Output cable	Coaxial
6	Measurement range	> 5,000 με
7	Grid length	3 mm / 6mm
8	Gauge factor	– 2

The strain gauge calibration used is the shunt method. Using a single-leg shunting bridge, the shunt calibration method simulates the strain in a Wheatstone bridge circuit. The strain gauge used is 350 Ohm with a gauge factor of ~1.98, terminated using a 47k Ohm resistor in a Wheatstone bridge circuit to simulate compression on a 3,722.9 με strain gauge.

2) Accelerometer sensors: Accelerometer sensors were to be used for the evaluation of structural member vibration of the railway bridge. These accelerometers measure the vibration of stiffening trusses and the main girder. Vibration sensors or accelerometers that can read three directions (*X*, *Y*, and *Z* axes) were installed on the bottom side of the structure bridge to read the vibration of the structure from the right and left and up and down dynamic loadings. These sensors work based on changes in position that cause vibrations.

This study used a particular type of accelerometer with an excellent low-frequency property to measure the vibrations of the main girder and stiffening truss. Table 2 provides specific information on the chosen accelerometer sensors utilized in this study. As many as four accelerometers are installed for the needs of the SHMS in this study. The accelerometer sensor bracket as a handle for the sensor to railway bridge structure and installation technique is illustrated in Fig. 5.

TABLE II
TECHNICAL SPECIFICATION OF ACCELEROMETERS

No	Specification	Remarks
1	Operating voltage	3.300 V
2	Output signal	SPI protocol
3	Data rate	125 samples per second (sps)
4	Response frequency	0.078 – 13.250 Hz
5	Output cable	10 meters
6	Measurement range	Maximum 8 G
7	Protection index	IP68

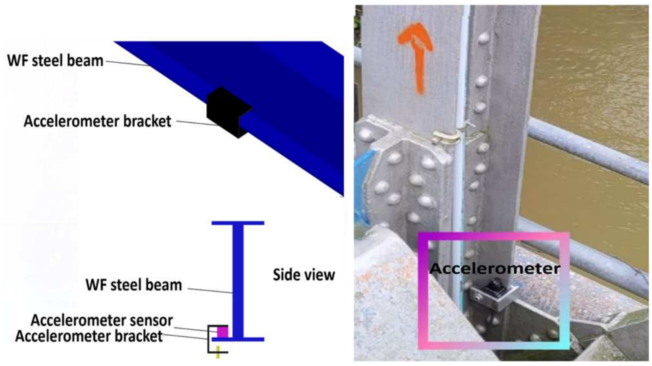

Fig. 5 Installation of accelerometer sensors

3) Proximity sensors: Proximity instrumentations detect when a train passes over a railroad bridge. When the train passes through the railway bridge, the proximity sensor will start working and send signals to all sensors so that all sensors record the required data with a predetermined sampling rate. For this reason, proximity sensors are necessary at both ends of the railway bridge at a distance of 5 meters from the outside of the bridge. Installation of 2 proximity sensors is placed on the railroad. Schematic location and installation of the proximity sensors are illustrated in Fig. 6. Detailed specifications of the selected proximity sensors used in this research are presented in Table 3.

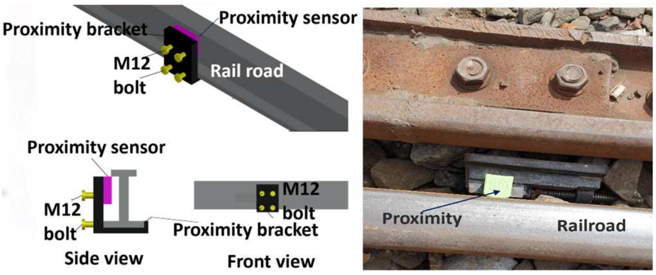

Fig. 6 Schematic placement and installation of proximity sensors

TABLE III

TECHNICAL SPECIFICATION OF PROXIMITY SENSOR

No	Specification	Remarks
1	Sensor type	Magnetic induction
2	Maximum distance	15 mm
3	Cable connection	3 wires
4	Input voltage	10 – 30 V
5	Protection index	IP67

4) LOBELIA™ node logger: The LOBELIA™ data recording node is a module that collects data recorded by each sensor. LOBELIA™ is one type of module from the MONITA® system. The data gathered in the LOBELIA™ data logger is then sent via the wireless system to the MONITA® SEVER device via the MASTER NODE. Data transmission from LOBELIA™ DAQ to MASTER NODE uses a 2.4 GHz Wi-Fi network. The appearance of LOBELIA™ is shown in Fig. 7. Furthermore, data transmission from the MASTER NODE to MONITA® SERVER uses the 4G GSM network. The MONITA® SERVER device is located at the head office. The LOBELIA™ data recording node installation is shown in Fig. 8.

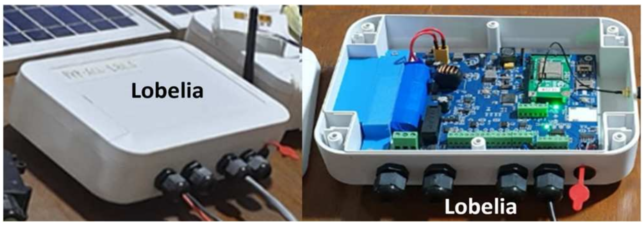

Fig. 7 LOBELIA™ node logger

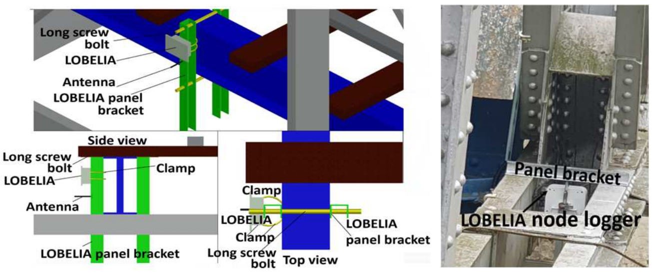

Fig. 8 Schematic installation of LOBELIA™ data logger

5) Linear Variable Displacement Transducer (LVDT): Linear Variable Displacement Transducer (LVDT) sensors are usually used to measure or detect small movements to the slightest possible movements. The LVDT sensor has two secondary coil parts: the primary coil and the ferromagnetic material core. All coils have a coil on the pipe, while the point is in the middle. A typical form of electromechanical transducer called an LVDT may translate the rectilinear motion of an item that is mechanically connected into an associated electrical signal, for example, a latching sensor which will convert a linear position or latching mechanical reference into an electrical signal proportional to the phase and amplitude.

This study measured the vertical deformation of railway bridges using an LVDT. The LVDT sensor is placed at one end of the railway bridge for security reasons. The schematic placement of LVDT locations and components can be seen in Fig. 9. The type of LVDT used to measure vertical deformation in this study can measure vertical deformation up to ±0.0762 meters. The LVDT is an electromechanical transducer that converts mechanically coupled mechanical movement into an electrical signal (voltage). The technical specifications of the LVDT are listed in Table 4.

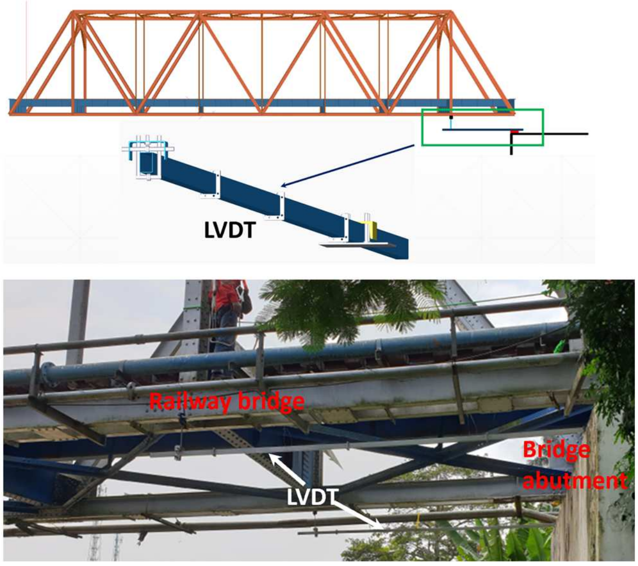

Fig. 9 Schematic of the LVDT sensor installation

TABLE IV

TECHNICAL SPECIFICATION OF THE LVDT

No	Specification	Remarks
1	Operating voltage	24 V
2	Sensor type	analog
3	Analog Signal Outputs	0 – 5 V
4	Cable output	Coaxial
5	Measurement range	- 10 up to + 10 cm
6	Dimension	500 x 20 x 5 cm

E. Data Acquisition and Transmission Module

The data-acquiring system can process all data while the existing railway bridge is used throughout its entire life cycle. The data acquisition and transmission system primarily choose data acquisition tools, processes, and sampling configurations. Researchers have developed a wireless data acquisition system for application on SHMS [40], [46], [47]. However, for the accuracy of data acquisition and transmission systems, it should always be checked for high frequencies, especially for long-distance transmission, which can transmit signal distortion [61], [62].

The transmission network comprises a field-integrated data-gathering station and a server group of modules. The field data acquisition system connects the bus transmission network to the acquisition modules. The comprehensive distribution system sensors, centralized control, distributed acquisition, and data uploading are installed in the railway bridge data collection stations to prevent signal distortion or sounds brought on by distance transmission. This technique uses some data acquisition modules and collection nodes. Fig. 10 depicts the automatic monitoring system's schematic data collecting and transmission configuration.

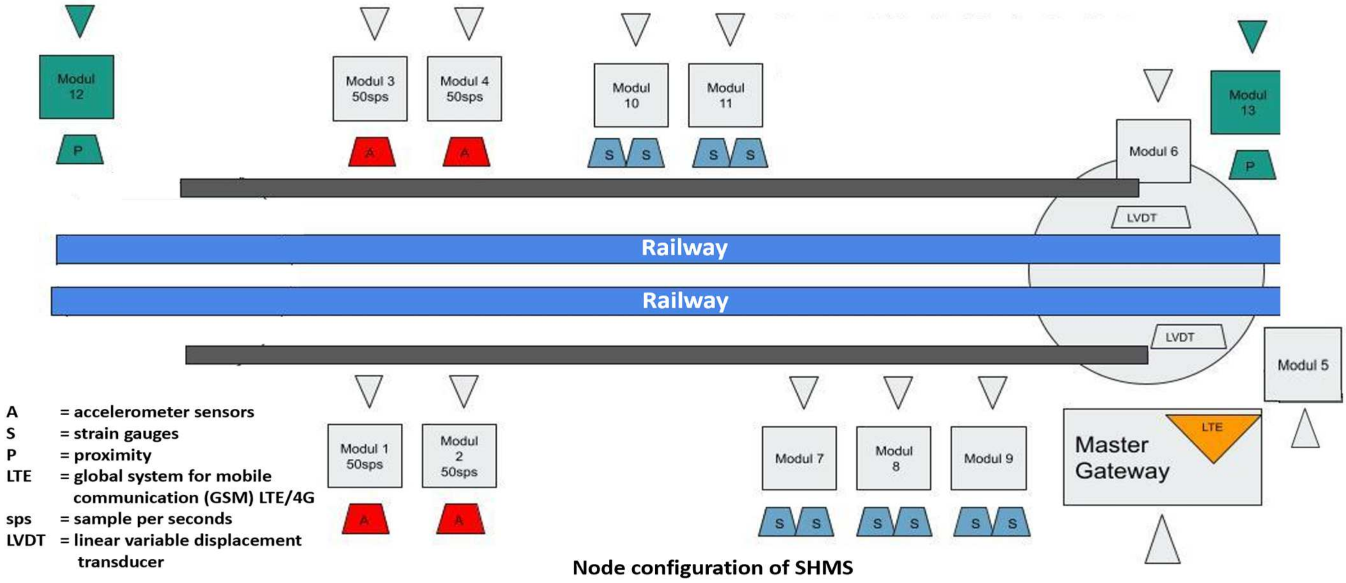

Fig. 10 Schematic arrangement of data acquisition and transmission of an automatic monitoring system

In this study, MONITA® is utilized for data acquisition modules. The MONITA® is a system for continuously acquiring data. The MONITA® system consists of a combination of hardware and software that functions to retrieve, send, store, and process data. The leading transmission network includes instrumentation sensors (strain gauges and accelerometers), LVDTs, and proximity. When the train passes over the railway bridge, proximity will signal all instrumentation sensors to record the required data parameters. The recorded data will be processed in DAQ modules, sent to the server, and stored as a database.

Readings by field instrumentation sensors are connected to MONITA® DAQ modules. Under the measured parameters, the various modules can gather a variety of signals, including voltage, current, and alignment signals. The traffic flow monitoring system terminal connects to the monitoring center's computers through fiber ethernet, and the monitoring data is saved locally in a database before being transferred to the server for use in calls and queries. The schematic topology traffic flow diagram of the SHMS is illustrated in Fig. 11. The DAQ Module used in this system is the MONITA® analog module. The analog module functions to read analog data and send data to the server, and it can be stored in the database before the data is transferred to users.

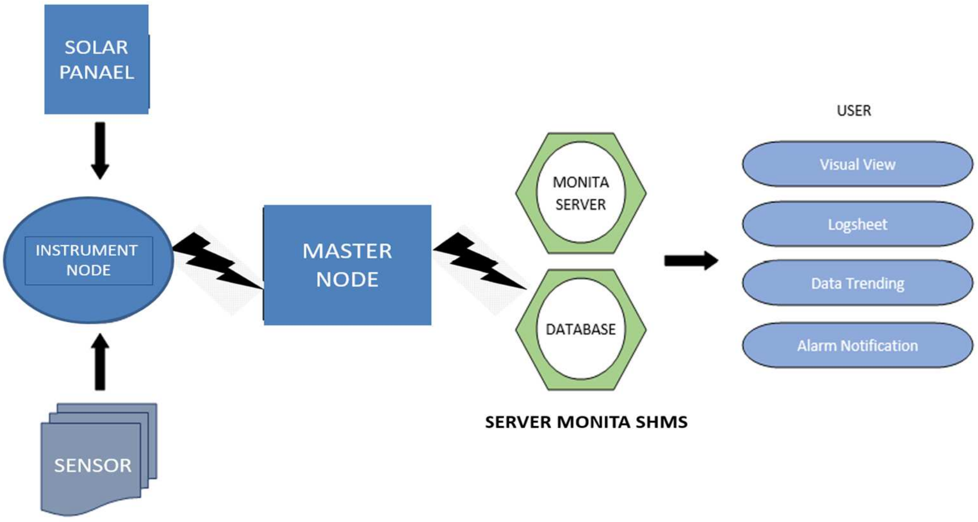

Fig. 11 Schematic topology traffic flow diagram of the SHMS

F. Calibration and Validation

Calibration and validation are essential in ensuring the performance of sensors used in SHMS, including their accuracy and dependability. These processes involve establishing the relationship between sensor outputs and the physical quantities being measured and verifying the accuracy of sensor measurements under real-world operating conditions.

During calibration, each sensor used in the SHMS is carefully calibrated using appropriate calibration techniques. This involves subjecting the sensors to known inputs or reference standards and recording their outputs. Calibration curves or coefficients are developed to convert sensor outputs into meaningful physical measurements accurately [63].

Validation is conducted to assess the performance and accuracy of the calibrated sensors in real-world scenarios. This includes comparing the sensor measurements obtained from the SHMS with reference measurements or data from traditional monitoring methods or analytical models. The goal is to ensure the sensor measurements align with the expected values and exhibit consistency and reliability. Long-term stability analysis is a crucial validation aspect, where the sensors' performance is continuously monitored over an extended period. This allows for detecting any drift or degradation in sensor accuracy over time, ensuring the reliability of long-term monitoring [64].

By performing calibration and validation, SHMSs can provide accurate and reliable measurements for assessing the health and condition of structures. These processes enhance monitoring effectiveness, enabling timely and informed decision-making for maintenance, repairs, and structural modifications.

III. RESULTS AND DISCUSSION

A. *Remote Monitoring System of the Railway Bridge*

The SHMS monitoring system is not carried out at the railway bridge location but is monitored remotely in real-time. This monitoring system is via the Human Machine Interface (HMI) dashboard. The design of the BH 340 railway bridge HMI dashboard in the SHMS application resembles modeling the actual state of the railway bridge by following the 3D model used in the previous stage. A screenshot of the dashboard display is shown in Fig. 12.

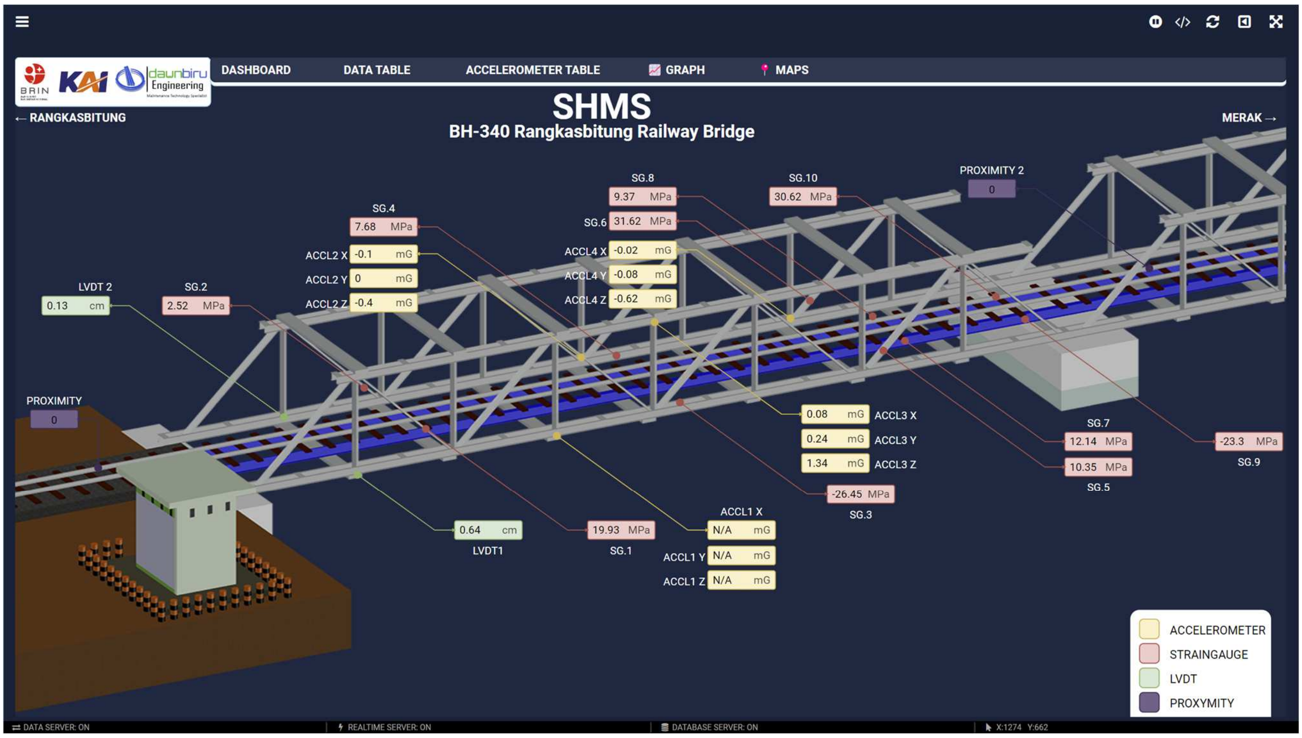

Fig. 12 Dashboard overview on HMI display

From the dashboard in Fig. 12, real-time reading values for each sensor can be obtained in the form of numbers and units of measurement. Information that can be received from the dashboard includes the position of each installed sensor, namely ten units of strain gauges, four units of tri axes vibration accelerometers, two units of LVDTs, and two units of proximity sensors to detect the presence of a train crossing the railway bridge. The actual reading of the sensor value is based on the train passing through the BH 340 railway bridge, which is triggered by the proximity sensors. Furthermore, historical data stored on the server can be accessed for further analysis.

B. *Structural Monitoring of the Railway Bridge*

To analyze the condition of the railway bridge structure, it is necessary to monitor the railway bridge via wireless sensors of strain gauges installed on the bridge. The system was designed to control and keep track of the sensors' state, wireless connections between the master instrument node, and gateways to the MONITA$^{®}$ SHMS server. The user interface has been thoughtfully created to make the most of the wireless sensors, which can be easily added or removed. The primary differences from a conventional wire-based management system are flexible addition, subtraction, and replacement of sensors and graphical representations.

The stress state of the railway bridge is shown in Fig. 13 while a train passes over it. Under moving loads, the railway truss bridge experiences tension and compression. The strain gauge monitoring windows show clearly when the train enters and leaves the railway bridge. Fig. 13 indicates that the tension steel frame of the train before and after leaving the railway bridge shows a stable position. However, when the train crosses the bridge, the tension in the steel frame experiences a change in stress.

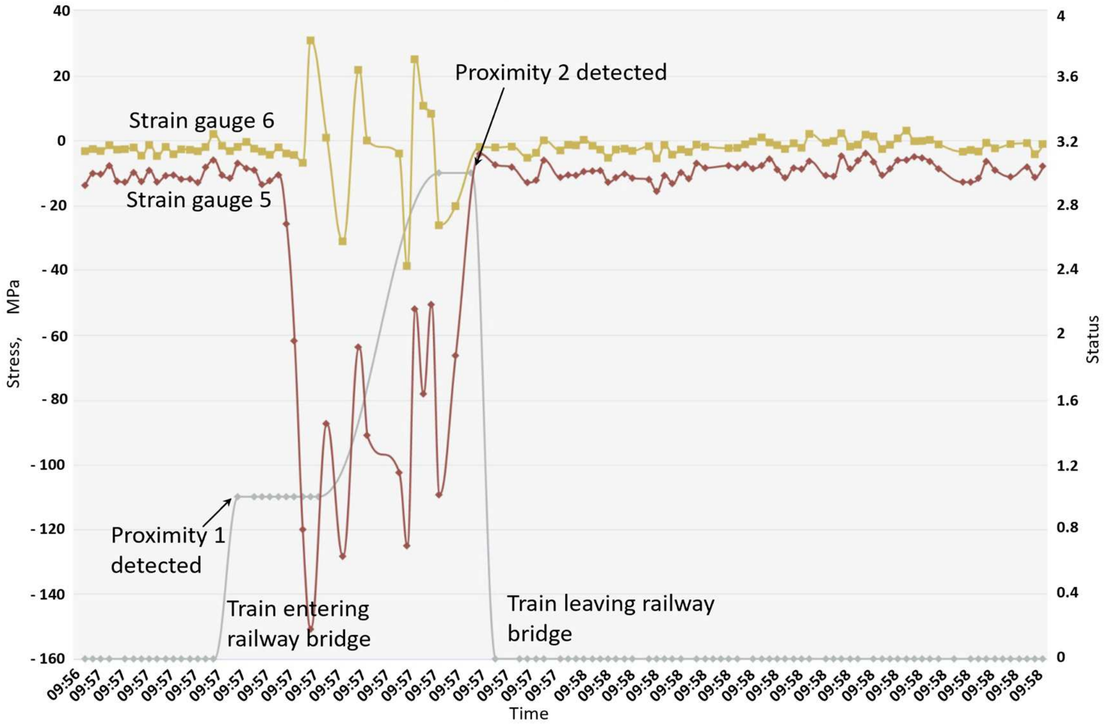

Fig. 13 Trend of steel frame structure data based on strain gauge sensor readings under moving loads

C. *Steel Railway Bridge Deformation Indicator*

They were carried out using two units of LVDT sensors. The two LVDT sensors are mounted at the end of the railway bridge, on its left and right, respectively. Fig. 14 shows the results of the deformation measurements of the BH 340 railway bridge. Based on the data in Fig. 14, it can be seen that there is a significant deflection that is read by the LVDT sensor when the locomotive passes the BH 340 railway bridge. As seen in the LVDT data (blue and green lines), the railway bridge deflects vertically to a maximum distance of 0.360 cm to 0.720 cm from its original position. It returns to a near-zero position when the locomotive moves away from the BH 340 railway bridge.

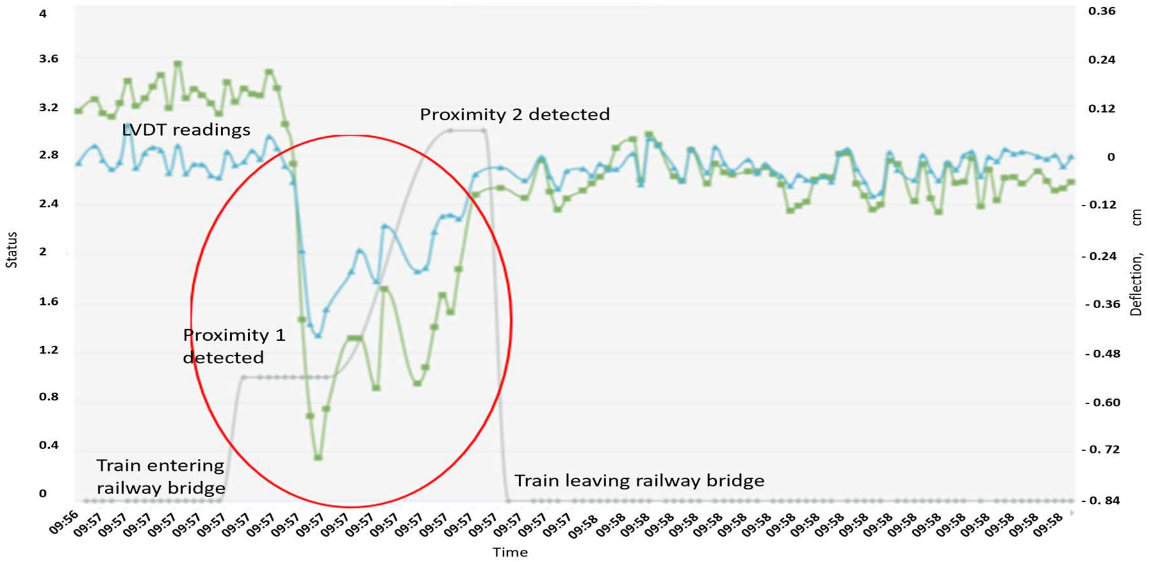

Fig. 14 Deformation due to moving loads recorded by LVDT

Compared to the deformation from the numerical simulation results, the deformation does not show a significant difference. The deformation resulting from numerical simulation calculations is 50.580 mm and appears in the middle of the span [45]. This deflection occurs due to the loading of the RM 1921 load. According to PM 60 2012 [57], a steel frame bridge's maximum permissible vertical deformation is 1/1,000 of its span. In this study, the span of the railway bridge is 40.000 meters, so the maximum allowable deformation is 40.000 mm.

D. *Dynamic Analysis of the Railway Bridge*

Vibration readings are obtained from the readings from 4 units of accelerometer sensors. The reading of 1 accelerometer sensor produces 3 data, namely the horizontal, vertical, and axial axes obtained simultaneously. Fig. 15 shows the vibration graph on the railway bridge when the locomotive passes the BH 340 railway bridge. The vertical axis represents the maximum acceleration, while the horizontal axis shows the time history. Fig. 15 also illustrates the time history of accelerations at the upper frame and the lower frame at midspan in three directions: towards the *X*, *Y*, and *Z* axes. The three accelerations are almost similar and in agreement. Therefore, all three of them are difficult to distinguish in the figure.

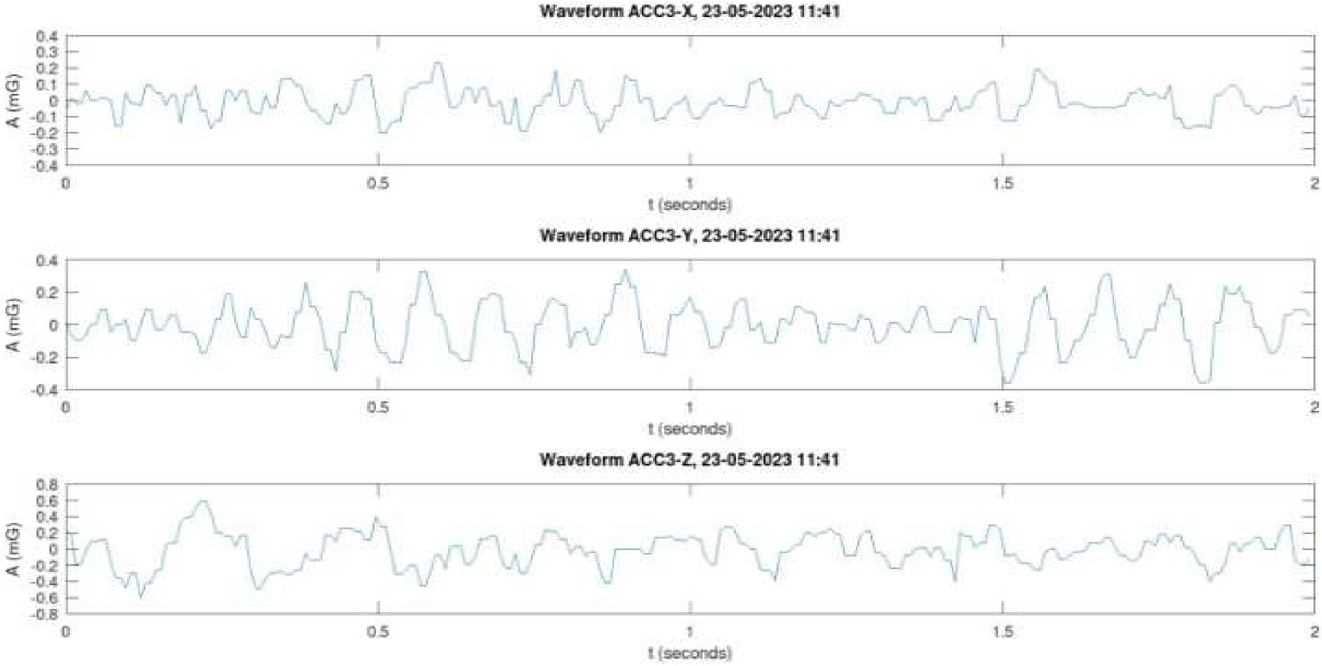

Fig. 15 Time history of the railway bridge due to moving loads

The three-way acceleration is transformed via a Fast Fourier Transform (FFT) to find a more precise understanding. Fig. 16 shows the FFT acceleration of the railway bridge due to moving loads. From the FFT data in Fig. 16, the highest natural frequency data on the *X*-axis is 6.250 Hz. This figure corresponds to the number generated from numerical analysis, which gives a natural frequency result of 6.103 Hz and occurs in 0.164 seconds [65]. The dynamic response of the bridge can be obtained by applying a similar analysis to the recorded accelerations during and after the passing of trains over the railway bridge. Decaying vibration is expected after the passing of the train so that the dynamic response with no train can also be observed.

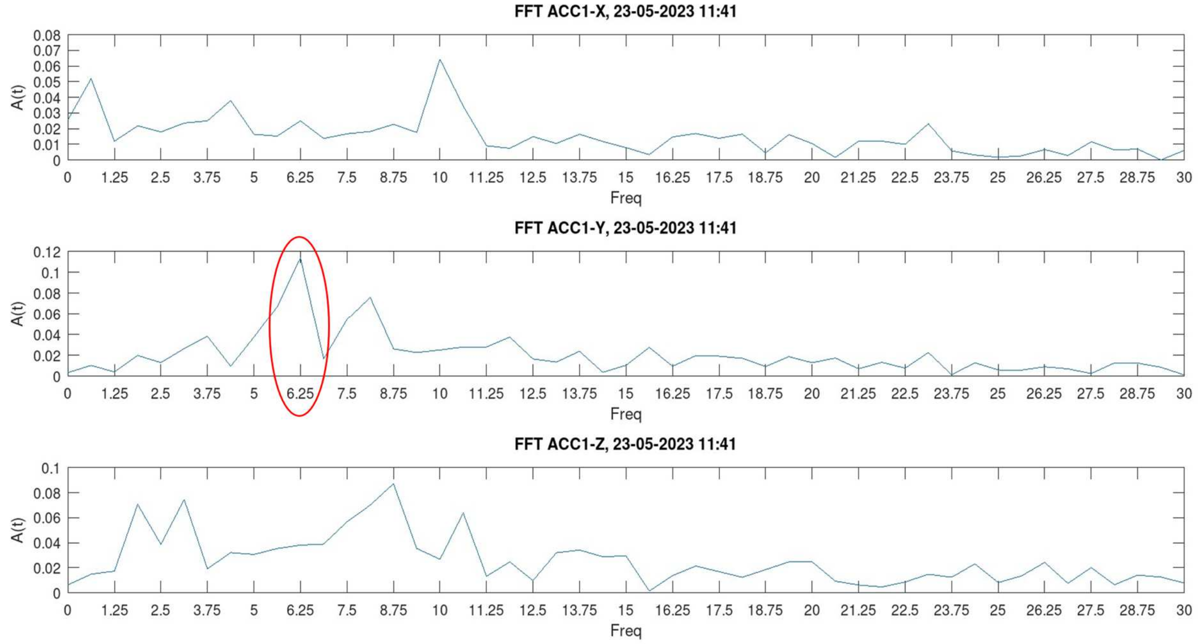

Fig. 16 Fast Fourier Transform (FFT) acceleration of the railway bridge due to moving loads

IV. CONCLUSION

A structural steel railway bridge's online real-time monitoring system is observed using smart wireless sensors. The following concluding remarks elaborate on the findings of the study. This paper has presented a real-time structural steel railway bridge monitoring system using smart wireless sensors. As a result, the monitoring system can appropriately assess a structural railway bridge in real-time.

The HMI dashboard in the SHMS application displays real-time reading values for each sensor, which can be obtained in the form of numbers and units of measurement. Information can be received from the display dashboard. The data sent via the transfer tool will also be entered into the document control and data interface. As a result, analysis can be done automatically through the expert system placed in the Control Center, and the results will show up on the display dashboard for policymakers to make decisions and actions based on the outcomes of these readings.

The data generated from sensor readings in real-time can be used to verify the results of numerical calculations using a finite element analysis approach. Therefore, this monitoring system is an assessment technique and does not need to carry out direct observations on-site. Further studies are recommended to be carried out, especially to detect the substructure and loading combinations due to seismic activity.

ACKNOWLEDGMENT

This paper is part of the National Research Priority of Railways performed at the Research Centre for Transportation Technology (PR TT) - National Research and Innovation Agency (BRIN), Indonesia, and PT. Daun Biru Engineering Indonesia. The study could be conducted with financial support from PR TT - BRIN via the National Research Budget, Research and Innovation for Advanced Indonesia scheme, and LPDP grants. These organizations provided financial support, without which this study would not have been possible. The authors would like to express gratitude for the institutions' financial support. PT. KAI (Indonesian Railway Company) supports this study. The authors would like to thank the company for the support they received. The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to impact the research presented in this study. No conflicts of interest exist, according to the authors, with the publishing of this paper. The authors acknowledged that the paper is original and no plagiarism is involved. The authors would also like to thank the reviewers who actively provided constructive suggestions.

REFERENCES

[1] E. OBrien, M. A. Khan, D. P. McCrum, and A. Žnidarič, "Using Statistical Analysis of an Acceleration-Based Bridge Weigh-In-Motion System for Damage Detection," *Applied Sciences*, vol. 10, no. 2, 2020, doi: 10.3390/app10020663.

[2] A. Malekjafarian, C.-W. Kim, E. J. OBrien, L. J. Prendergast, P. C. Fitzgerald, and S. Nakajima, "Experimental Demonstration of a Mode Shape-Based Scour-Monitoring Method for Multispan Bridges with Shallow Foundations," *Journal of Bridge Engineering*, vol. 25, no. 8, p. 4020050, 2020, doi: 10.1061/(ASCE)BE.1943-5592.0001586.

[3] M. A. Khan, D. P. McCrum, L. J. Prendergast, E. J. OBrien, P. C. Fitzgerald, and C.-W. Kim, "Laboratory investigation of a bridge scour monitoring method using decentralized modal analysis," *Struct Health Monit*, vol. 20, no. 6, pp. 3327–3341, 2021, doi:10.1177/1475921720985122.

[4] B. Bachinilla, A. Evangelista, M. Siddhpura, A. N. Haddad, and B. B. F. da Costa, "High-Speed Railway Bridge and Pile Foundation: A Review," *Infrastructures (Basel)*, vol. 7, no. 11, 2022, doi:10.3390/infrastructures7110154.

[5] Q. He *et al.*, "Intelligent construction for the transportation infrastructure: a review," *Intelligent Transportation Infrastructure*, vol. 1, p. liac007, Sep. 2022, doi: 10.1093/iti/liac007.

[6] V. Chakraborty and S. Dutta, "Indian railway infrastructure systems: global comparison, challenges and opportunities," *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction*, vol. 175, no. 3, pp. 127–140, 2022, doi: 10.1680/jsmic.22.00014.

[7] E. F. Souza, C. Bragança, A. Meixedo, D. Ribeiro, T. N. Bittencourt, and H. Carvalho, "Drive-by Methodologies Applied to Railway Infrastructure Subsystems: A Literature Review—Part I: Bridges and Viaducts," *Applied Sciences*, vol. 13, no. 12, 2023, doi:10.3390/app13126940.

[8] W. Barasa, T. Fiantika, D. A. Purnomo, and W. Aspar, "The Comparative Study of Railway Bridge Design Load Between PM 60/2012 and EN 1991: 2-2003," *Majalah Ilmiah Pengkajian Industri (Journal of Industrial Research and Innovation)*, vol. 14, no. 2, pp. 107–116, 2020, doi: https://doi.org/10.29122/mipi.v14i2.4196.

[9] M. A. B. Nadi, Nurfaizia, M. N. Karunia, W. A. N. Aspar, W. Barasa, and A. Fudholi, "Characterization of Site Effect and Natural Frequency of Railway Bridges," *International Journal of Sustainable Development and Planning*, vol. 17, no. 1, pp. 243–249, Feb. 2022, doi: 10.18280/ijsdp.170124.

[10] Y. Ren, E. J. OBrien, D. Cantero, and J. Keenahan, "Railway Bridge Condition Monitoring Using Numerically Calculated Responses from Batches of Trains," *Applied Sciences*, vol. 12, no. 10, 2022, doi:10.3390/app12104972.

[11] W. Barasa, W. A. N. Aspar, D. A. Purnomo, M. A. B. Nadi, T. Fiantika, and S. P. Primadiyanti, "Assessment of an existing steel railway bridge structure," *AIP Conf Proc*, vol. 2689, no. 1, p. 040019, Jul. 2023, doi: 10.1063/5.0116333.

[12] O. S. Sonbul and M. Rashid, "Algorithms and Techniques for the Structural Health Monitoring of Bridges: Systematic Literature Review," *Sensors*, vol. 23, no. 9, 2023, doi: 10.3390/s23094230.

[13] Z. Deng, M. Huang, N. Wan, and J. Zhang, "The Current Development of Structural Health Monitoring for Bridges: A Review," *Buildings*, vol. 13, no. 6, 2023, doi: 10.3390/buildings13061360.

[14] X. Zhang and W. Zhou, "Structural Vibration Data Anomaly Detection Based on Multiple Feature Information Using CNN-LSTM Model," *Struct Control Health Monit*, vol. 2023, p. 3906180, 2023, doi:10.1155/2023/3906180.

[15] A. Meixedo, D. Ribeiro, J. Santos, R. Calçada, and M. Todd, "Progressive numerical model validation of a bowstring-arch railway bridge based on a structural health monitoring system," *J Civ Struct Health Monit*, vol. 11, no. 2, pp. 421–449, 2021, doi: 10.1007/s13349-020-00461-w.

[16] K. Maes, L. Van Meerbeeck, E. P. B. Reynders, and G. Lombaert, "Validation of vibration-based structural health monitoring on retrofitted railway bridge KW51," *Mech Syst Signal Process*, vol. 165, p. 108380, 2022, doi: https://doi.org/10.1016/j.ymssp.2021.108380.

[17] A. Pourtarki, H. B. Ghavifekr, and H. Afshin, "Study on the dynamic behaviour of Bafgh-Bandar Abbas lane railway bridge for structural health monitoring purpose," *Australian Journal of Structural Engineering*, vol. 24, no. 3, pp. 243–253, 2023, doi:10.1080/13287982.2022.2149975.

[18] X. Li, Y. Xiao, H. Guo, and J. Zhang, "A BIM Based Approach for Structural Health Monitoring of Bridges," *KSCE Journal of Civil Engineering*, vol. 26, no. 1, pp. 155–165, 2022, doi: 10.1007/s12205-021-2040-3.

[19] M. R. Azim and M. Gül, "Damage detection framework for truss railway bridges utilizing statistical analysis of operational strain response," *Struct Control Health Monit*, vol. 27, no. 8, p. e2573, 2020, doi: https://doi.org/10.1002/stc.2573.

[20] A. Meixedo, J. Santos, D. Ribeiro, R. Calçada, and M. Todd, "Damage detection in railway bridges using traffic-induced dynamic responses," *Eng Struct*, vol. 238, p. 112189, 2021, doi:10.1016/j.engstruct.2021.112189.

[21] M. R. Azim, "A Data-Driven Damage Assessment Tool for Truss-Type Railroad Bridges Using Train Induced Strain Time-History Response," *Australian Journal of Structural Engineering*, vol. 22, no. 2, pp. 147–162, 2021, doi: 10.1080/13287982.2021.1908710.

[22] M. R. Azim and M. Gül, “Damage Detection of Steel-Truss Railway Bridges Using Operational Vibration Data,” *Journal of Structural Engineering*, vol. 146, no. 3, p. 4020008, 2020, doi:10.1061/(ASCE)ST.1943-541X.0002547.

[23] Z.-W. Li, X.-Z. Liu, and S.-X. Chen, “A reliability assessment approach for slab track structure based on vehicle-track dynamics and surrogate model,” *Proc Inst Mech Eng O J Risk Reliab*, vol. 236, no. 1, pp. 79–89, 2022, doi: 10.1177/1748006X211028405.

[24] M. J. Khosraviani, O. Bahar, and S. H. Ghasemi, “Global and Local Damage Detection in Continuous Bridge Decks Using Instantaneous Amplitude Energy and Cross-Correlation Function Methods,” *KSCE Journal of Civil Engineering*, vol. 25, no. 2, pp. 603–620, 2021, doi:10.1007/s12205-020-0622-0.

[25] S. Karimi and O. Mirza, “Damage identification in bridge structures: review of available methods and case studies,” *Australian Journal of Structural Engineering*, vol. 24, no. 2, pp. 89–119, 2023, doi:10.1080/13287982.2022.2120239.

[26] Z. Li, Y. Lan, and W. Lin, “Investigation of Frequency-Domain Dimension Reduction for A2M-Based Bridge Damage Detection Using Accelerations of Moving Vehicles,” *Materials*, vol. 16, no. 5, 2023, doi: 10.3390/ma16051872.

[27] M. Zhao, A. Sadhu, and M. Capretz, “Multiclass anomaly detection in imbalanced structural health monitoring data using convolutional neural network,” *Journal of Infrastructure Preservation and Resilience*, vol. 3, no. 1, p. 10, 2022, doi:10.1186/s43065-022-00055-4.

[28] C. Qu, H. Zhang, R. Zhang, S. Zou, L. Huang, and H. Li, “Multiclass Anomaly Detection of Bridge Monitoring Data with Data Migration between Different Bridges for Balancing Data,” *Applied Sciences*, vol. 13, no. 13, 2023, doi: 10.3390/app13137635.

[29] M. A. Mousa *et al.*, “Application of Digital Image Correlation in Structural Health Monitoring of Bridge Infrastructures: A Review,” *Infrastructures (Basel)*, vol. 6, no. 12, 2021, doi:10.3390/infrastructures6120176.

[30] Y.-W. Wang, Y.-Q. Ni, and S.-M. Wang, “Structural health monitoring of railway bridges using innovative sensing technologies and machine learning algorithms: a concise review,” *Intelligent Transportation Infrastructure*, vol. 1, p. liac009, Sep. 2022, doi:10.1093/iti/liac009.

[31] Z. He, W. Li, H. Salehi, H. Zhang, H. Zhou, and P. Jiao, “Integrated structural health monitoring in bridge engineering,” *Autom Constr*, vol. 136, p. 104168, 2022, doi: 10.1016/j.autcon.2022.104168.

[32] J. Xin, Y. Jiang, J. Zhou, L. Peng, S. Liu, and Q. Tang, “Bridge deformation prediction based on SHM data using improved VMD and conditional KDE,” *Eng Struct*, vol. 261, p. 114285, 2022, doi:10.1016/j.engstruct.2022.114285.

[33] A. Malekjafarian, R. Corbally, and W. Gong, “A review of mobile sensing of bridges using moving vehicles: Progress to date, challenges and future trends,” *Structures*, vol. 44, pp. 1466–1489, 2022, doi:10.1016/j.istruc.2022.08.075.

[34] P. Russo and M. Schaerf, “Anomaly detection in railway bridges using imaging techniques,” *Sci Rep*, vol. 13, no. 1, p. 3916, 2023, doi:10.1038/s41598-023-30683-z.

[35] D. Ribeiro, R. Calçada, M. Brehm, and V. Zabel, “Train–Track–Bridge Dynamic Interaction on a Bowstring-Arch Railway Bridge: Advanced Modeling and Experimental Validation,” Sensors, vol. 23, no. 1, p. 171, Dec. 2022, doi: 10.3390/s23010171.

[36] M. Abdulkarem, K. Samsudin, F. Z. Rokhani, and M. F. A. Rasid, “Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction,” *Struct Health Monit*, vol. 19, no. 3, pp. 693–735, 2020, doi:10.1177/1475921719854528.

[37] S. Mustapha, Y. Lu, C.-T. Ng, and P. Malinowski, “Sensor Networks for Structures Health Monitoring: Placement, Implementations, and Challenges—A Review,” *Vibration*, vol. 4, no. 3, pp. 551–585, 2021, doi: 10.3390/vibration4030033.

[38] A. Sofi, J. Jane Regita, B. Rane, and H. H. Lau, “Structural health monitoring using wireless smart sensor network – An overview,” *Mech Syst Signal Process*, vol. 163, p. 108113, 2022, doi:10.1016/j.ymssp.2021.108113.

[39] N. Navabian, S. Beskhyroun, and J. Matulich, “Development of wireless smart sensor network for vibration-based structural health monitoring of civil structures,” *Structure and Infrastructure Engineering*, vol. 18, no. 3, pp. 345–361, 2022, doi:10.1080/15732479.2020.1850801.

[40] F. Zanelli, F. Castelli-Dezza, D. Tarsitano, M. Mauri, M. L. Bacci, and G. Diana, “Design and Field Validation of a Low Power Wireless Sensor Node for Structural Health Monitoring,” *Sensors*, vol. 21, no. 4, 2021, doi: 10.3390/s21041050.

[41] M. Karatas and B. S. Onggo, “Optimising the barrier coverage of a wireless sensor network with hub-and-spoke topology using mathematical and simulation models,” *Comput Oper Res*, vol. 106, pp. 36–48, 2019, doi: 10.1016/j.cor.2019.02.007.

[42] F. Zanelli, N. Debattisti, M. Mauri, A. Argentino, and M. Belloli, “Development and Field Validation of Wireless Sensors for Railway Bridge Modal Identification,” *Applied Sciences*, vol. 13, no. 6, 2023, doi: 10.3390/app13063620.

[43] Y. Fu, Y. Zhu, T. Hoang, K. Mechitov, and B. F. Spencer, “xImpact: Intelligent Wireless System for Cost-Effective Rapid Condition Assessment of Bridges under Impacts,” *Sensors*, vol. 22, no. 15, 2022, doi: 10.3390/s22155701.

[44] Y. Fu, T. Hoang, K. Mechitov, J. R. Kim, D. Zhang, and B. F. Spencer, “xShake: Intelligent wireless system for cost-effective real-time seismic monitoring of civil infrastructure,” *Smart Struct Syst*, vol. 28, no. 4, pp. 483–497, Oct. 2021, doi: 10.12989/sss.2021.28.4.483.

[45] S. S. Saidin, A. Jamadin, S. Abdul Kudus, N. Mohd Amin, and M. A. Anuar, “An Overview: The Application of Vibration-Based Techniques in Bridge Structural Health Monitoring,” *Int J Concr Struct Mater*, vol. 16, no. 1, p. 69, 2022, doi: 10.1186/s40069-022-00557-1.

[46] D. M. Siringoringo, Y. Fujino, M. Suzuki, and V. Mehta, “Implementation of Wireless Sensor Network for Continuous Seismic Monitoring of Isolated Cable-Stayed Bridge,” *Journal of Bridge Engineering*, vol. 27, no. 4, p. 4022011, 2022, doi:10.1061/(ASCE)BE.1943-5592.0001813.

[47] Z. Ni, S. Cai, and C. Ni, “Application of Wireless Sensor Network Based on Improved Genetic Algorithm in Bridge Health Monitoring,” *Sensors and Materials*, vol. 35, no. 5, pp. 1659–1670, 2023, doi:10.18494/SAM4309.

[48] D. A. Purnomo, W. A. N. Aspar, W. Barasa, S. M. Harjono, P. Sukamdo, and T. Fiantika, “Initial Implementation of Structural Health Monitoring System of a Railway Bridge,” *IOP Conf Ser Mater Sci Eng*, vol. 1200, no. 1, p. 012019, Nov. 2021, doi: 10.1088/1757-899x/1200/1/012019.

[49] T. Fiantika, W. A. N. Aspar, D. A. Purnomo, W. Barasa, S. M. Harjono, and S. P. Primadiyanti, “A review of structural health monitoring systems and application for railway bridges,” *AIP Conf Proc*, vol. 2646, no. 1, p. 50006, Sep. 2023, doi: 10.1063/5.0115843.

[50] D. M. Siringoringo and Y. Fujino, “Wavelet-Based Analysis for Detection of Isolation Bearing Malfunction in a Continuous Multi-Span Girder Bridge,” *Journal of Earthquake Engineering*, vol. 26, no. 10, pp. 5237–5267, 2022, doi: 10.1080/13632469.2020.1868363.

[51] C. Yang, “An adaptive sensor placement algorithm for structural health monitoring based on multi-objective iterative optimization using weight factor updating,” *Mech Syst Signal Process*, vol. 151, p. 107363, 2021, doi: 10.1016/j.ymssp.2020.107363.

[52] M. Nasir, A. R. Javed, M. A. Tariq, M. Asim, and T. Baker, “Feature engineering and deep learning-based intrusion detection framework for securing edge IoT,” *J Supercomput*, vol. 78, no. 6, pp. 8852–8866, 2022, doi: 10.1007/s11227-021-04250-0.

[53] J. Yang *et al.*, “A Review on Damage Monitoring and Identification Methods for Arch Bridges,” *Buildings*, vol. 13, no. 8, 2023, doi:10.3390/buildings13081975.

[54] E. Yakıcı and M. Karatas, “Solving a multi-objective heterogeneous sensor network location problem with genetic algorithm,” *Computer Networks*, vol. 192, p. 108041, 2021, doi:10.1016/j.comnet.2021.108041.

[55] S. Samudra, M. Barbosh, and A. Sadhu, “Machine Learning-Assisted Improved Anomaly Detection for Structural Health Monitoring,” *Sensors*, vol. 23, no. 7, 2023, doi: 10.3390/s23073365.

[56] *STAAD.Pro V8i (SELECTseries 4) Technical Reference Manual*, Bently Software Inc., Exton, PA, USA, 2012.

[57] *Transportation Minister of the Republic of Indonesia, Regulation no. 60 of 2012: Railroad Technical Requirements*, PM 60 Tahun 2012, Minister of Transportation, Jakarta, Indonesia, 2012. [Online]. Available: https://djka.dephub.go.id/regulasi?lang=en

[58] *Indonesia National Standard: Loads for bridges*, SNI 1725:2016, National Standardization of Indonesia, Jakarta, Indonesia, 2016. [Online]. Available: https://akses-sni.bsn.go.id/sni

[59] *Indonesia National Standard: Specifications for Structural Steel Buildings*, SNI 1729:2020, National Standardization of Indonesia, Jakarta, Indonesia, 2020. [Online]. Available: https://akses-sni.bsn.go.id/sni

[60] *Indonesia National Standard: Bridge design against earthquake loads*, SNI 2833:2016, National Standardization of Indonesia, Jakarta, Indonesia, 2016. [Online]. Available: https://akses-sni.bsn.go.id/sni.

[61] J. Ding, T. Xu, C. Jin, Z. Wang, J. Zhao, and T. Liu, "Impact of Equalization-Enhanced Phase Noise on Digital Nonlinearity Compensation in High-Capacity Optical Communication Systems," *Sensors*, vol. 20, no. 15, 2020, doi: 10.3390/s20154149.

[62] A. Kajmakovic, K. Diwold, K. Römer, J. Pestana, and N. Kajtazovic, "Degradation Detection in a Redundant Sensor Architecture," *Sensors*, vol. 22, no. 12, 2022, doi: 10.3390/s22124649.

[63] R. R. Nigmatullin, E. A. Bataleva, K. S. Nepeina, and V. E. Matiukov, "Quality control of the initial magnetotelluric data: Analysis of calibration curves using a fitting function represented by the ratio of 4th-order polynomials," *Measurement*, vol. 216, p. 112914, 2023, doi:10.1016/j.measurement.2023.112914.

[64] S. Adla, N. K. Rai, S. H. Karumanchi, S. Tripathi, M. Disse, and S. Pande, "Laboratory Calibration and Performance Evaluation of Low-Cost Capacitive and Very Low-Cost Resistive Soil Moisture Sensors," *Sensors*, vol. 20, no. 2, 2020, doi: 10.3390/s20020363.

[65] W. A. N. Aspar et al., "Direct Analysis of a Steel Railway Bridge via Monitoring System of an Instrumented Structure," International Journal on Advanced Science, Engineering and Information Technology, vol. 14, no. 1, pp. 287–298, Feb. 2024, doi:10.18517/ijaseit.14.1.19148.