Silesian University of Technology
Faculty of Civil Engineering
Department of Mechanics and Bridges

DOCTORAL DISSERTATION

Bridge health monitoring using automated FE model updating, signal processing, and machine learning

NGUYEN CONG DUC

Dissertation supervisor: Marek Salamak
Full Professor, Ph.D., D.Sc. Eng.
Silesian University of Technology, Gliwice
Faculty of Civil Engineering
Department of Mechanics and Bridges

Dissertation supervisor: Andrzej Katunin
Associate Professor, Ph.D., D.Sc. Eng.
Silesian University of Technology, Gliwice
Faculty of Mechanical Engineering
Department of Fundamentals of Machinery Design

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PhD student: Nguyen Cong Duc

Extended Abstract in English

1. Motivations and Aims

1.1. Motivations for undertaking research

The motivations for engaging in research studies on bridge health monitoring approaches can be either one or more of the following reasons:

- Why the structural diagnostic load test need to be performed? Why the SHM of the existing heavy bridge is needed?
- There are many structural health monitoring systems on the market. What is an appropriate technology for bridge health monitoring?
- There are numerous structural members and numerous sensors. Why collect structural parameters?
- How to reduce the duration and costs of monitoring maintaining high detectability level of possible events?
- What are the best technologies and algorithms for field bridge data processing and management? How to acquire and process data effectively?

1.2. Aim and scope of the current work

The performed research studies within this thesis allowed providing some answers to above questions and formulate the aims of the study on their basis. The objective of the research topic is to propose the automated FE model updating, signal processing, and machine learning approaches that can be used for bridge health monitoring. The topic covers issues related to automated bridge FE model calibration using field testing, advanced signal processing for vibration signals collected from a long-term vibration-based SHM system of railway steel arch bridge, and machine learning techniques to predict railway bridge health conditions.

The bridge diagnostic load test consists of the load evaluation and the load test (or proof-load test). The purpose is to use field data to calibrate the FE model for load rating. The final calibrated FE model is proposed to integrate into the SHM system of the existing bridge.

Bridge SHM is used to track changes over time under the various load events and weather conditions. The vibration-based SHM system installed on the railway steel arch bridge is to record the dynamic behavior of the hangers and the spans under train events. The vibration measurement is useful to analyze the experimental natural frequencies of hangers, and then determine tension forces and stresses. The objective of the development of the long-term SHM system is proposed to monitor on-line and remote alarms.

The structural parameters collected in the field tests are the strains, deflections and natural frequencies of the real bridges. These measured parameters can be used for the FE model updating to calibrate the material and stiffness properties. The right technology for bridge testing and monitoring is the innovative solution which makes it possible to connect the experimental parameters with the current bridge design guide specifications and standards.

The duration and costs of bridge testing and monitoring depend more on data processing and management than the use of many sensors in the field. Sensors can be reused in the various bridge structures, while the data processing needs and requirements may vary depending on the behavior of each bridge under load events.

The data processing approaches comprise FFT algorithms, wavelet transforms and machine learning, including deep learning. The advanced signal processing technologies are implemented for the vibration signals recorded from the SHM system to analyze the field data patterns as well as to predict the structural behavior under the different load events.

The primary contributions of the study can be summarized as the following main issues:

- Automated FE model calibrations were proposed to update the stiffness and material properties of bridge structures using measured static strains and natural frequencies. Case studies consist of the highway bridges in Vietnam to demonstrate the applicability and effectiveness of the proposed FE model updating algorithms.
- Machine learning-assisted regression models were performed to predict the dynamic behavior of the railway bridge span under various train events. Data sets used in prediction models that were collected from the vibration-based SHM system of the Dębica railway steel arch bridge in Poland over a period of nine months from December 2019 to September 2020.
- GoogLeNet CNN classification models were developed to predict the hanger health conditions of the existing railway bridge using wavelet-based and orbit-shaped signal images.

2. Current status and development trends of bridge health monitoring systems

This chapter provides an overview of the current status and development trends of state-of-the-art bridge health monitoring systems. In Poland and Vietnam, where the civil infrastructure has developed rapidly, the demands and needs of the SHM market are expected to grow significantly. All-in-one comprehensive solutions for intelligent data processing and management of data-driven SHM systems are to implement machine learning techniques designed with the smart alert system in real time to ensure the safety, reliability, and integrity of bridge structures during major load events, natural hazards, and weather change risks. Bridge SHM data management is not only intelligent data processing, but also integrating bridge information management, referred to as virtual digital twins. Furthermore, national guidelines and regulations for SHM of civil structures and bridges could be continuously updated to meet international standards, codes, and specifications.

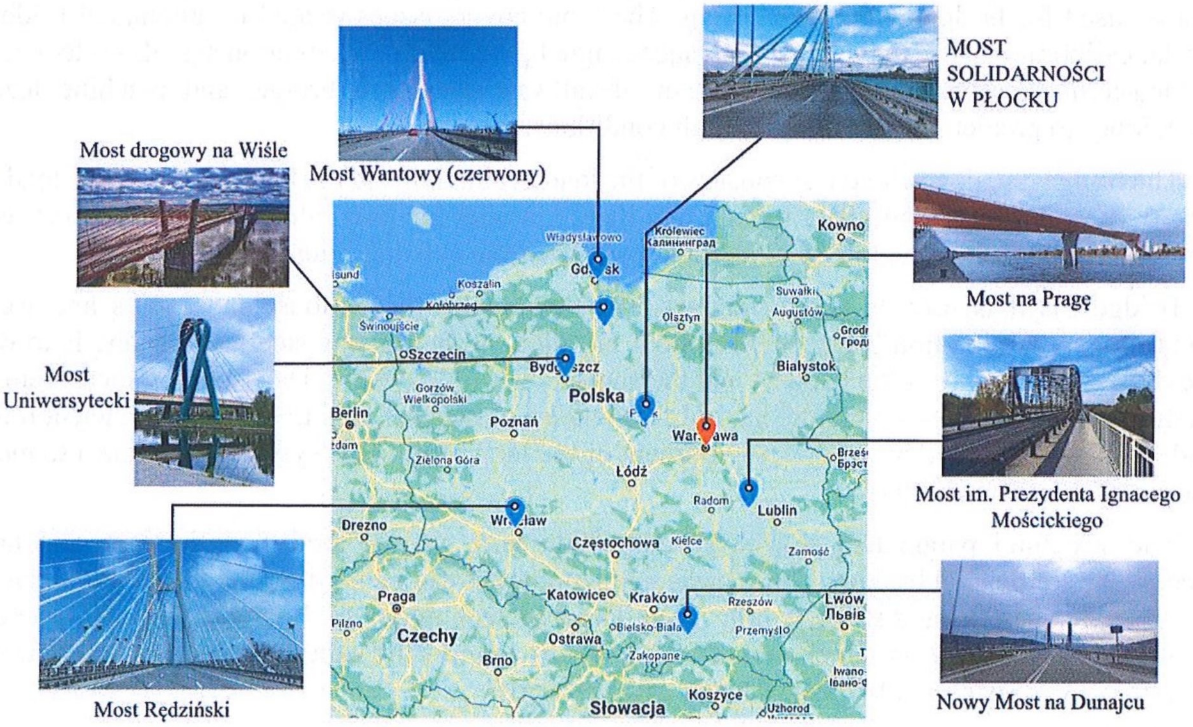

Fig. 1. SHM systems for bridges in Poland.

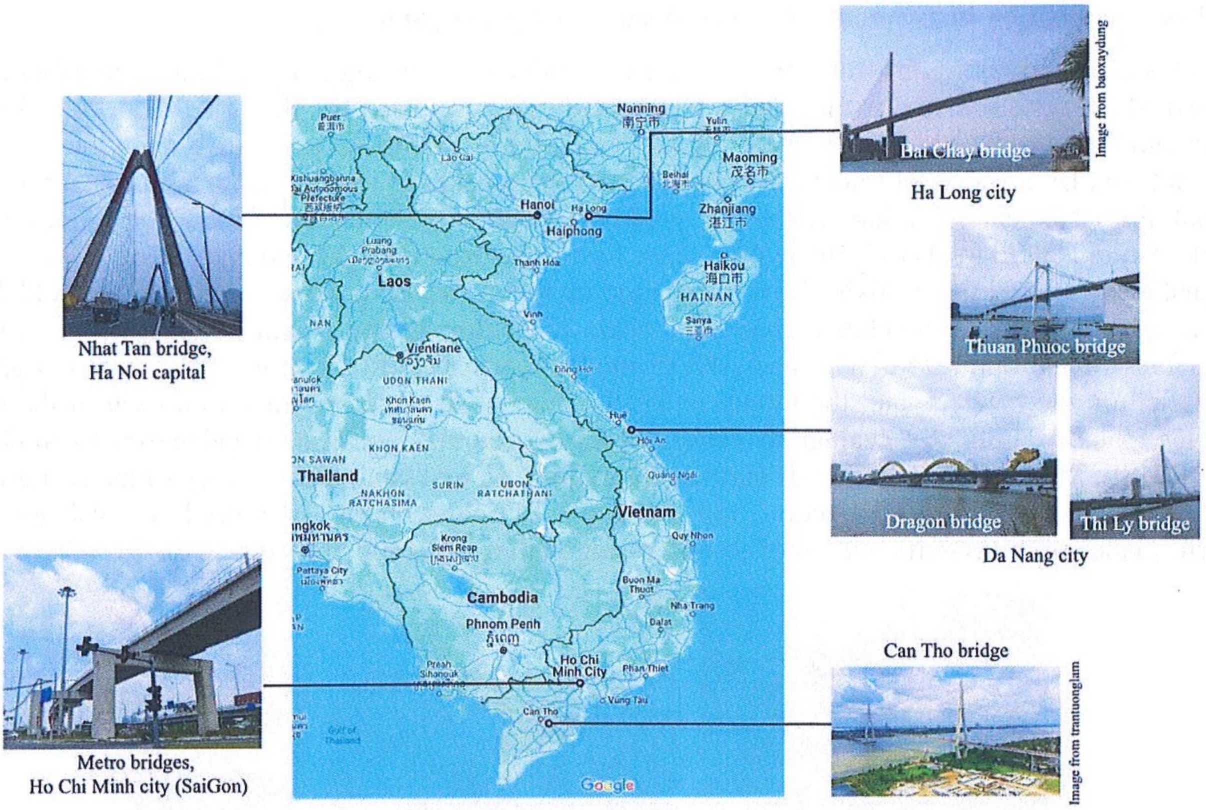

Fig. 2. SHM systems for bridges in Vietnam.

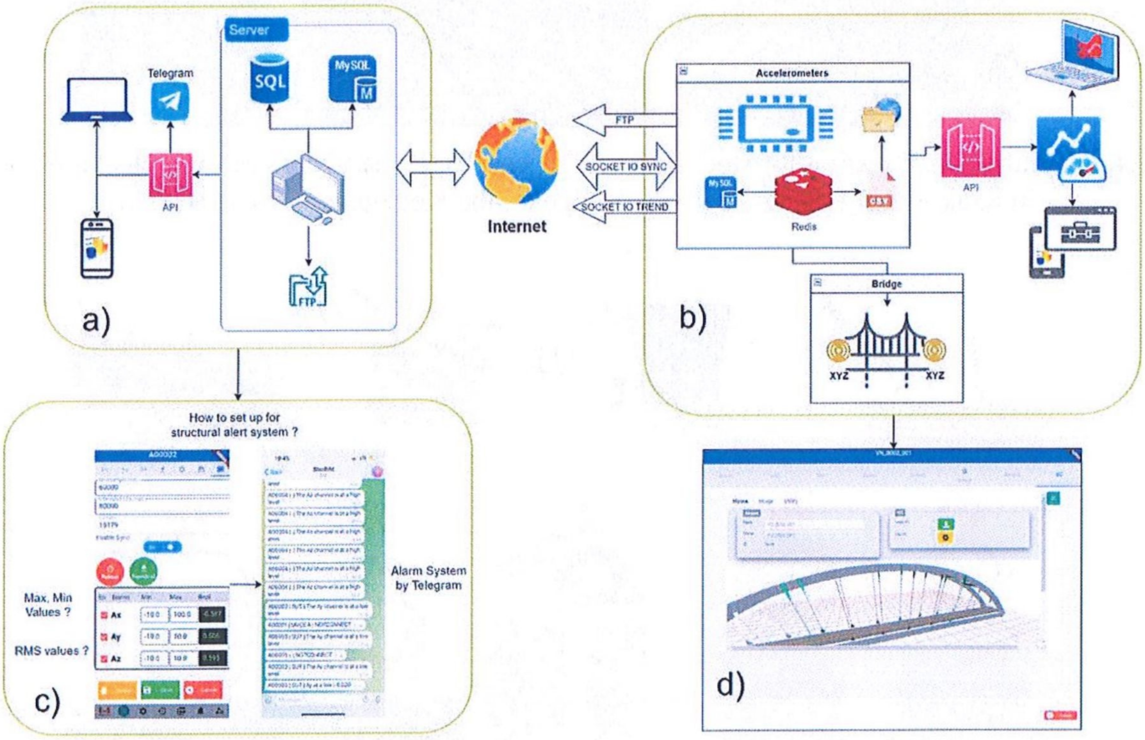

Fig. 3. Digital twin-based intelligent SHM data management: a) Integration of machine learning algorithms for SHM system; b) Vibration-based SHM system; c) Smart alert system using Telegram; d) BrIM data management.

3. Data acquisition instruments and advanced signal processing

This chapter presents instruments for the field bridge load testing and the long-term vibration-based SHM system used for this study. Diagnostic load tests used for the bridges in Poland and Vietnam are introduced. The advanced signal processing methods are performed using the Morse, Morlet, and Bump wavelet transforms to convert vibration signals into 2D scalogram images as the input for CNN classification models to predict structural potential problems. The GoogLeNet architecture is used to classify the feature maps for recognizing the analyzed and collected vibration signal images. In addition, ANN, ANFIS, and random forest are also proposed to extract the field data feature, as well as to develop regression models to predict bridge health conditions. The input variables of the optimized ANN and ANFIS models consist of RMS values of vibration signals installed on the hangers, and the output is RMS values of dynamic responses on each of the two bridge spans. Additionally, evaluation metrics are introduced for classification and regression models. R^2, RMSE, MAE, MAPE, and NSE metrics are utilized for assessing the accuracy of the regression models. F1-score, macro F1-score, and weighted F1-score metrics are used to evaluate the performance of the classification models addressing with imbalanced data sets.

Fig. 4. Diagnostic load testing for steel arch bridges: a), b), c), d) Vistula railway steel arch bridge in Kraków city; e), f) Steel arch bridge on the Kędzierzyn-Koźle (DK40).

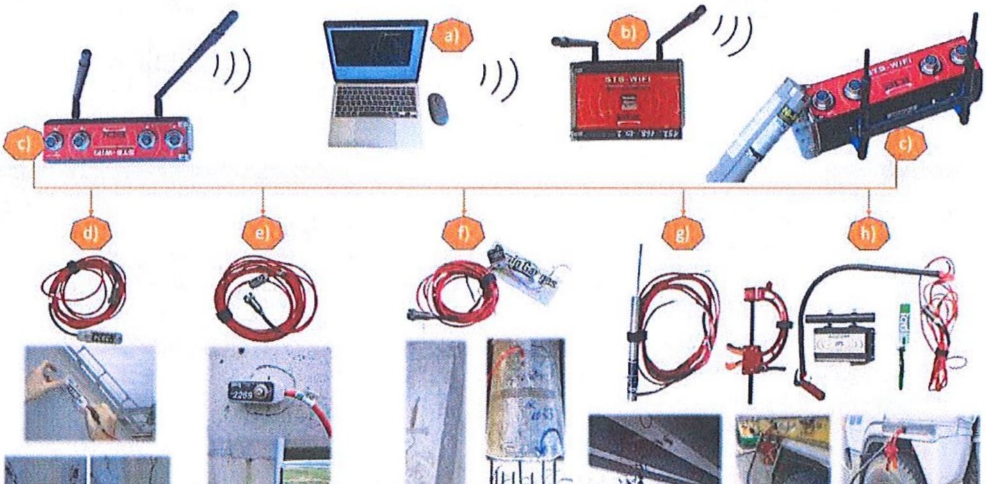

Fig. 5. The wireless structural testing system (STS-WiFi) for diagnostic load testing of existing bridge structures.

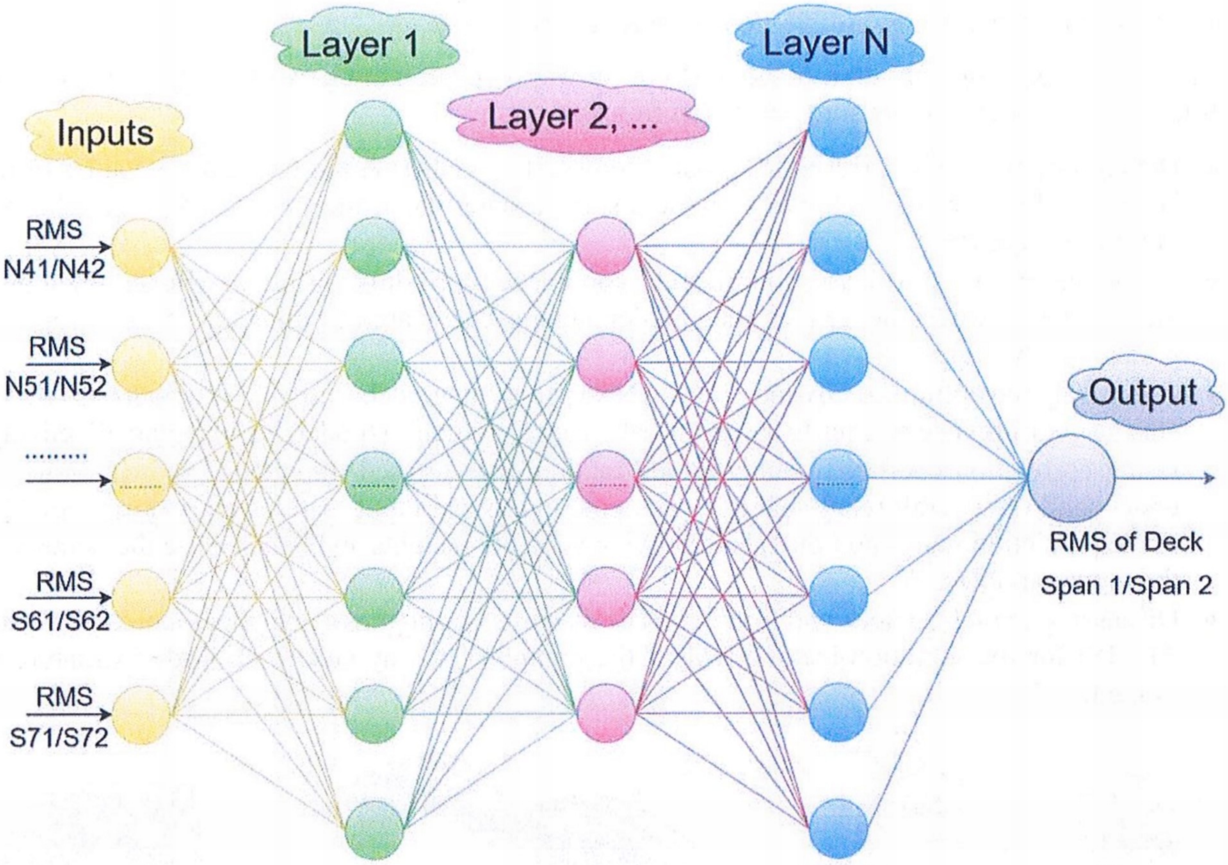

Fig. 6. ANN architecture with RMS input and output variables.

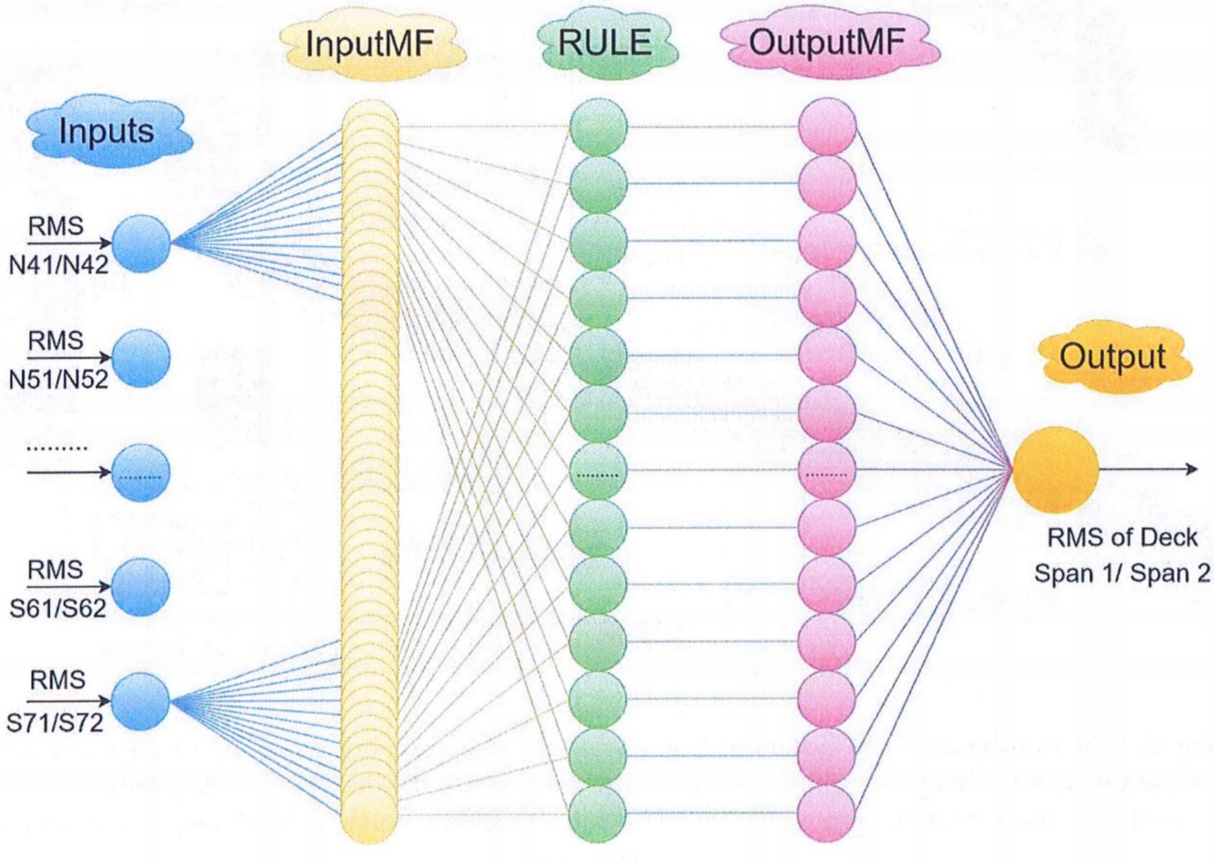

Fig. 7. The architecture of ANFIS model.

4. Railway bridge health monitoring using machine learning

This chapter presents vibration-based SHM of railway steel arch bridge with optimized ANN and ANFIS regression models that summarized as follows:

- Developing the ANN and ANFIS-assisted models for predicting the future RMS values of the behavior of the bridge deck based on the historical data sets of the RMS values of the hanger vibration responses;
- Implementing the GA-based optimization approaches for adjusting the parameters including the number of hidden neurons in each hidden layer of ANN architectures for various proposed prediction strategies;
- Comparing the optimized GA-integrated ANN regression models with ANFIS models using the various performance metrics to assess the ML-based prediction models reliably and effectively;
- Using correlation coefficient analysis and random forest-based importance scores aiming to understand the overall relationship between the individual input features and output variables in the prediction regression models to provide valuable insights and help reduce the number of the input variables;
- Discussing the advantages and limitations of machine learning assisted approaches (ANN and ANFIS) for the vibration-based SHM of the complex railway steel arch bridge structure in Poland.

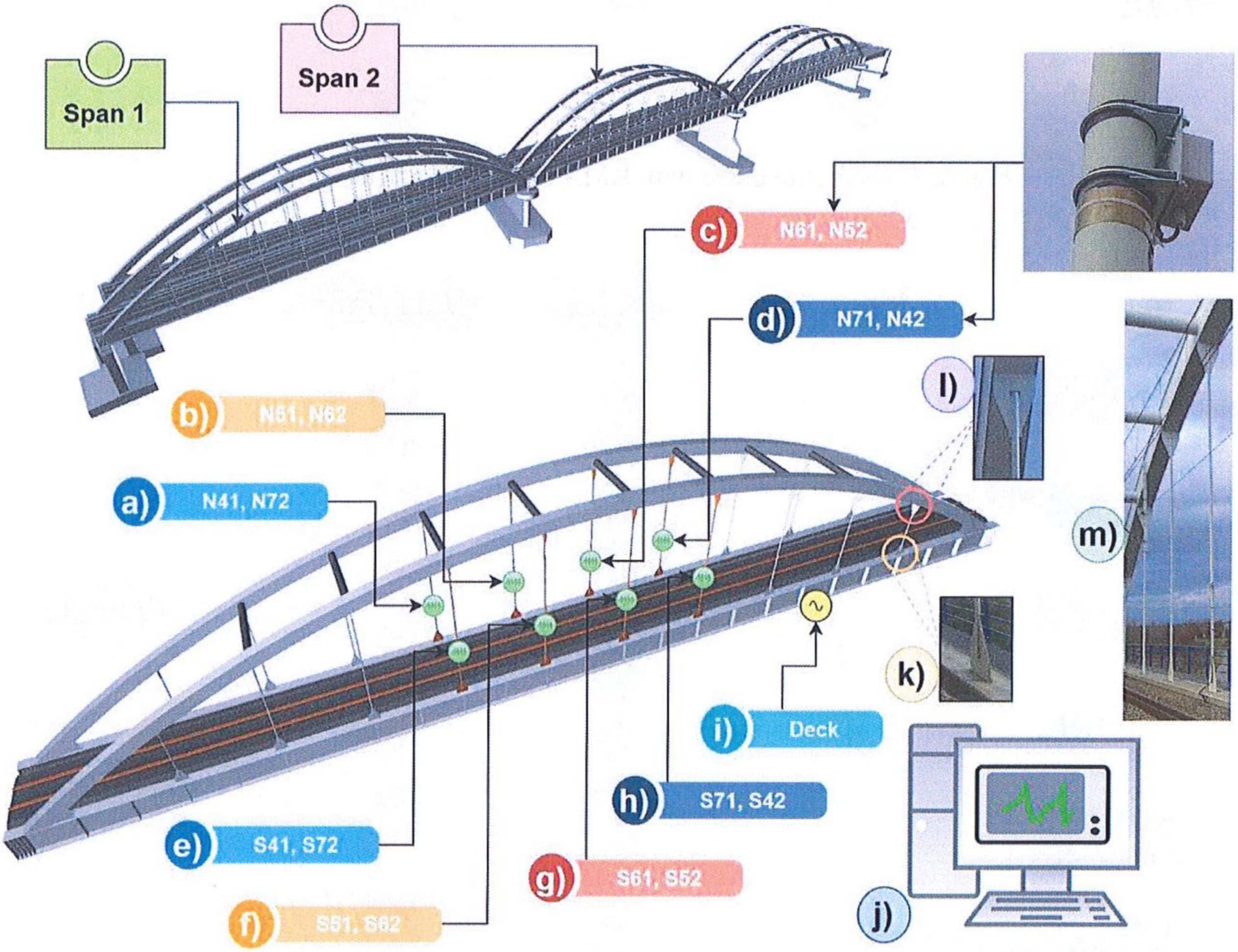

Fig. 8. Vibration-based SHM system of Dębica railway steel arch bridge: a), b), c), d), e), f), g), h) accelerometers for hangers; i) piezoelectric accelerometer for the deck; j) data acquisition system; k) welded connection of hanger with I-shaped beam; l) welding connection of hanger with arch rib; m) hangers.

5. Railway bridge health diagnosis using wavelet analysis and deep learning

In this chapter, deep learning approaches for data-driven SHM for Dębica railway arch bridge are proposed. In Fig. 9, GoogLeNet CNN classification models are employed to classify hanger health conditions under train load events and weather changes over a nine-month period.

First, wavelet-based scalograms of vibration signals recorded on the deck are used as the image input of CNN models, whereas the output is the hanger states based on the tension force extracted from the experimental natural frequencies of hangers. The FE model calibration of the railway steel arch bridge is developed to reproduce the tension force values of the hangers using the bridge design standards.

Second, orbit-shaped CNN models are developed for the dynamic behavior of each hanger recorded in the longitudinal and transverse directions. FFT techniques of hanger vibration signals in the discrete frequency domain are performed to convert two-axis accelerometers of each hanger into displacement-based orbit-shaped images.

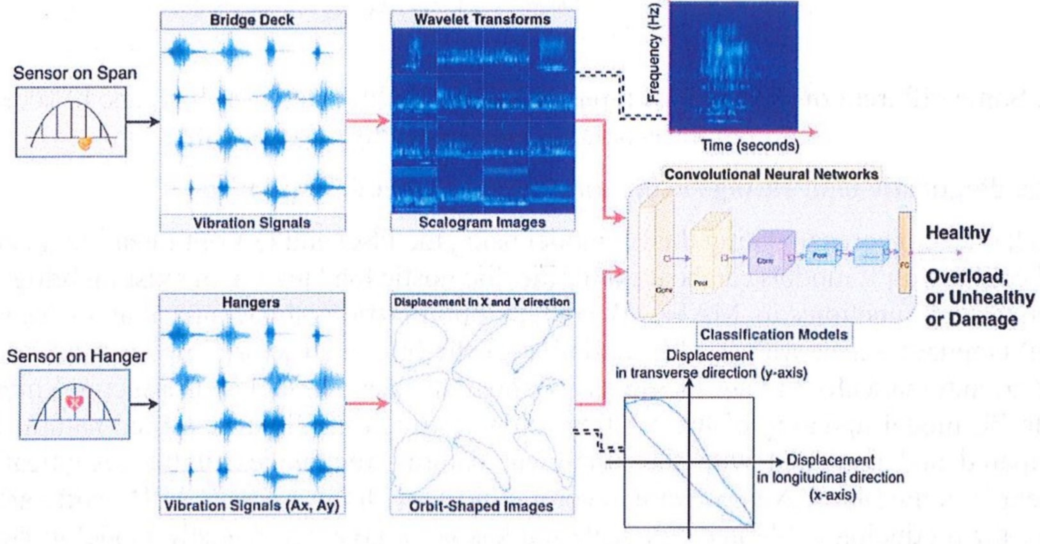

Fig. 9. Wavelet-based CNN-assisted SHM and vibration orbit-based image diagnostic.

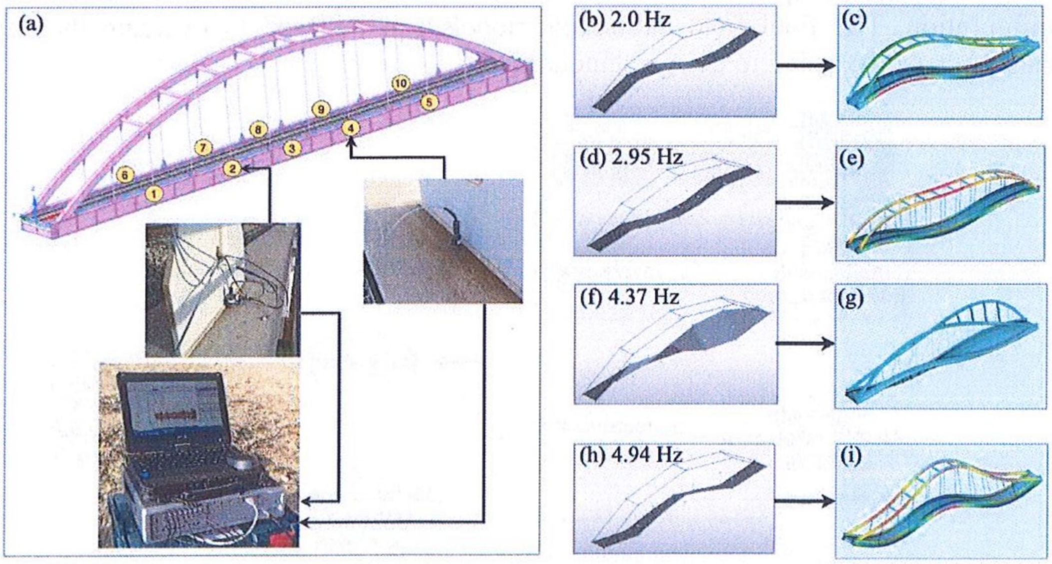

Fig. 10. Vibration-based diagnostic testing for bridge span 1: a) field vibration measurement using single-axis accelerometers (PCB Piezotronics) installed at 10 positions along the two main girders; b), d), f), h) operational modal analysis using Siemens LMS TestLab software; c), e), g), i) FE model updating.

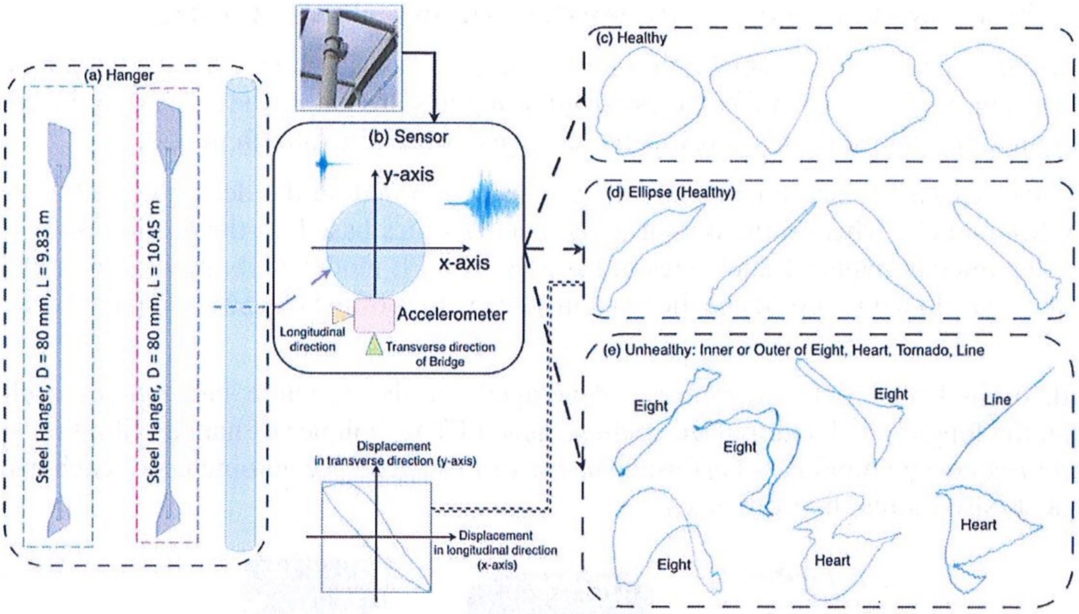

Fig. 11. Some different orbit shapes of types of hanger healthy states: a) hangers; b) accelerometers or vibration sensors; c) and d) healthy; e) unhealthy.

6. Bridge diagnostic load ratings using automated FE model updating

This chapter concerns updating the FE model using the PSO and GA optimization methods so that the final calibrated FE models can be used for the diagnostic load testing of existing bridge structures. The scripts and functions in MATLAB contain optimization algorithms that interface with the CADINP language script with the FE modeling of the bridge structure implemented in SOFISTIK TEDDY to automatically update the cross-sectional stiffness variables of structural members. The full-scale FE model updating of the existing bridge through the field-measured natural frequencies are compared and modified with the numerical natural frequencies of the analytical FE model implemented in the MATLAB software to communicate with the ANSYS APDL software. The main objective for producing calibrated full-scale models is to have one realistic model to compute load rating procedures and predict load limits using the design specifications of the American Association of State Highway and Transportation Officials design specifications, which can be performed for any load configuration. The final field calibrated models can be used to evaluate the capacities of structural members according to design standards.

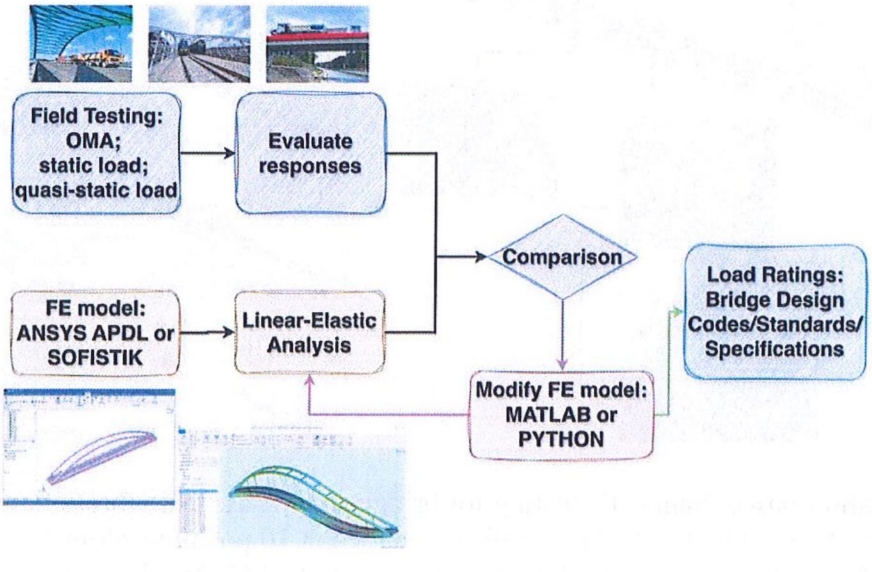

Fig. 12. The wireless structural testing system (STS-WiFi) for diagnostic load testing in existing bridge structures.

7. Conclusion

The purpose of the present work was to study automated FE model updating, advanced signal processing, and machine learning approaches for bridge health monitoring. Field data sets collected from bridge load diagnostic testing and railway bridge health monitoring were analyzed to evaluate bridge health condition through FE model calibration as well as machine learning-assisted structural health assessment. The following conclusions are drawn from the results obtained:

- FE model updating plays a crucial role in reproducing numerical data when comparing measured and computed responses, used for load ratings, load limits or permit loads, and overloads of the existing bridges. The final calibrated FE model could be used to determine the allowable load bearing capacity of structural members for the smart alarm system of long-term bridge health monitoring.
- Deep learning-integrated applications were developed for the vibration-based SHM system of the railway steel arch bridge. Wavelet-assisted CNN classification models were performed to predict hanger health conditions for the Dębica railway bridge located in Poland. The tension force values of the hangers were calculated from experimental vibration responses and the updated FE model of the heavy railway bridge to label the healthy and overload states on each hanger in CNN classification models. Using trained CNN models, it is possibe to predict hanger health status under various dynamic loading effects based on the measurements from a single accelerometer installed on the bridge span.
- Deep learning-based hanger health monitoring using orbit-shaped analysis of the bidirectional vibration sensor was conducted to assess the bending and torsional behavior of hangers under train load events and wind excitation. The use of orbits for hanger condition monitoring could consider the fundamental theory of mechanics and vibration analysis in terms of the similarity of the mechanical behavior of hangers and machinery shafts subject to dynamic loading, including their boundary conditions.
- Data-driven bridge health monitoring using ANN and ANFIS algorithms was performed to predict RMS values of Dębica bridge with various train events over a period of nine months from December 2019 to September 2020. The trained ANN and ANFIS models could be implemented in AI-based sensors to predict potential structural problems in bridge structures.

Summarizing the FE model calibration based on the bridge diagnostic load testing was efficiently proven and also applied for the SHM system. The machine learning-assisted SHM application was demonstrated for the existing railway bridge by integrating the updated FE model for reproducibility. The data-driven SHM using the machine learning and deep learning-attention algorithms was established for the railway steel arch bridge. Finally, the proposed innovative solutions would be cutting-edge technologies when machine learning-based algorithms could be implemented into AI-based vibration sensors for the smart alert system and intelligent data management as developed in this study.

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