Recenzja spełnia wymogi formalne
Przewodniczący Rady Dyscypliny
Inżynieria Lądowa, geodezja i Transport

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REVIEW

OF THE DOCTORAL DISSERTATION OF MR. NGUYEN CONG DUC M.Sc., ENG., ENTITLED *„BRIDGE HEALTH MONITORING USING AUTOMATED FE MODEL UPDATING, SIGNAL PROCESSING, AND MACHINE LEARNING"*

Field: engineering and technical sciences
Scientific discipline: civil engineering, geodesy and transport

1. Formal basis and subject of the review

I have prepared this review based on a civil law contract with the Silesian University of Technology No. UMC/2507/2024 of July 15, 2024, signed on behalf of the University by the Dean of the Faculty of Civil Engineering, Ms. Prof. Joanna Bzówka DSc, PhD, Eng.

The subject of the review is the doctoral dissertation of Mr. Nguyen Cong Duc, M.Sc., Eng., entitled "Bridge health monitoring using automated FE model updating, signal processing, and machine learning", developed at the Faculty of Civil Engineering of the Silesian University of Technology, under the supervision of Prof. Marek Salamak DSc, PhD, Eng. – as the supervisor and Andrzej Katunin DSc, PhD, Eng., prof. of the Silesian University of Technology – as the auxiliary supervisor.

The doctoral dissertation was presented in the form of a compact A4 printout, signed by the Department of Mechanics and Bridges of the Faculty of Civil Engineering of the Silesian University of Technology. The doctoral dissertation was prepared in the *scientific discipline* of *civil engineering, geodesy and transport* in the *field* of *engineering and technical sciences.* The work is dated May 2024.

The legal basis for the review is the Law on Higher Education and Science (Journal of Laws of 2018, item 1668, as amended).

2. Subject, title, layout and form of the dissertation

The subject of the reviewed dissertation is related to the Structural Health Monitoring (SHM) procedures applied in bridge engineering based on the advanced processing of measurement data recorded by sensory monitoring systems. This class of monitoring strategy is focused on identification of negative phenomena in the bridge construction on the basis of

the physical and possibly also chemical response of the object to various types of loads and impacts, measured by means of an electronic control system. The monitoring system usually consists of: sensors, measuring devices, data transmission systems as well as entities that record, process and provide real-time information on the structure in operating conditions.

Structural Health Monitoring can be accomplished by systematically assessing changes in damage-sensitive structural performance indicators, determined from measurement data during the monitoring process. The current assessment and forecasting of the condition of the facility are performed based on computational algorithms (the subject of this dissertation) individually designed for a given structure, which, based on the history of information collected by the system, will allow for the identification of possible changes in the characteristics of the structural system. Permanent changes in the above parameters, with unchanged environmental conditions, are usually associated with damage and may cause immediate or future changes in operating parameters.

The performance characteristics of structures determined as a result of processing data obtained from monitoring systems are very valuable information that can – and should – be used to assess changes in the condition of structures as a result of degradation processes and, consequently, to effectively manage the maintenance and operation of bridge infrastructure.

Generally, the scope of application of sensory monitoring systems in relation to bridge structures includes mainly:

- new facilities with spans of considerable spans, innovative construction and material solutions and special importance for the transport system,
- selected types of structures of typical objects, representative of significant groups of bridge structures, which are the subject of research studies related to the identification of actual loads and impacts, detection of structural damage, modelling of degradation processes, durability forecasting, etc.,
- facilities in poor technical condition, with advanced degradation or at risk of rapid development of degradation processes, which, however, cannot be taken out of operation for various reasons – until they are repaired or replaced.

The importance of the problem under consideration is growing with the increase in traffic intensity and speed of vehicles passing over bridges and the resulting intensification of degradation processes of the material structure. The procedures currently standardly used for inspections of bridge structures required by regulations may not guarantee a sufficiently precise determination of the structure's condition in the case of more complex structures. Therefore, there is a need to use more advanced diagnostic methods.

I consider the PhD student's attempt to solve the complex issue presented above using advanced measurement data processing methods and simulation analyses to be important both from a cognitive and technical point of view. In light of the above comments, I state that the topic of the reviewed doctoral dissertation was aptly selected, the scientific problem considered is interesting from the cognitive side, and at the same time has direct practical references.

The reviewed doctoral thesis consists of 109 numbered pages of A4 format text - divided into 7 chapters. The main text is preceded by: a title page, a page of acknowledgments, a 2-page abstract, a 3-page table of contents, a 7-page list of figures, a 1-page list of tables and a 2-page list of acronyms and their explanations. The dissertation is supplemented by: a bibliography (184 items, 22 pages), an index of selected terms (1 page), appendices A, B and C (26 pages in total) and a list of the author's scientific achievements (4 pages).

The 4-page Chapter 1 entitled "Introduction" presents the general characteristics of the undertaken scientific task. The basic goals and scope of the work are formulated, and the layout of the dissertation is presented.

Chapter 2 (8 pages) briefly presents the current status, needs and development trends in bridge health monitoring.

Chapter 3 (17 pages) describes the data acquisition instruments and advanced signal processing algorithms used during the preparation of the dissertation.

The next three chapters (4-6) present the author's scientific achievements, including his original solutions for assessing the condition of existing bridge structures based on advanced processing of data obtained from electronic sensory monitoring systems.

The 34-page Chapter 4 entitled "Railway bridge health monitoring using machine learning" presents an intelligent data processing algorithm based on artificial neural networks (ANN) and adaptive neuro-fuzzy inference systems (ANFIS) to predict the dynamic behaviour of the railway steel arch bridge in Dębica based on dynamic responses of steel hangers during the passage of trains. Field data were collected from the vibration-based electronic monitoring system of the bridge over a nine-month period from December 2019 to September 2020. The input variables of the ANN and ANFIS models consist of RMS (Root Mean Square) values of vibration signals recorded on hangers, and the output are RMS values of dynamic responses of bridge spans. The ANN and ANFIS architectures were optimized using a genetic algorithm (GA).

The 19-page Chapter 5 entitled "Railway bridge health diagnosis using wavelet analysis and deep learning" presents developed deep learning approach (a subcategory of machine learning that involves creating deep neural networks) for health evaluation of above-mentioned railway steel arch bridge in Dębica. Convolutional neural network (CNN) classification models are employed to assess hanger health in operating conditions, i.e. under train load events and weather changes over the nine-month period of continuous monitoring of railway bridge. The developed diagnostic procedure based on CNN models, using measurement data from the monitoring system of the bridge in question, includes also the use of the wavelet-based scalograms of vibration signals as well as the FFT based integration and differentiation techniques of the vibration signal.

The 22-page Chapter 6 entitled "Bridge diagnostic load ratings using automated FE model updating" presents the author's achievements in the field of calibration of FEM numerical models of bridge structures based on a comparison of the results of theoretical analyses and the results of tests of the actual object under the loads of heavy vehicles with known parameters. The proposed methodology for updating bridge models is based on the interaction between the ANSYS (or SOFISTIK) software and the MATLAB functions utilizing optimisation algorithms (including genetic algorithm, GA) for determination of the values of parameters finally applied in the FE model. The optimisation variables include: the cross-sectional properties and the young modulus of concrete material. The proposed procedures for the calibration of FEM models are presented on the example of spans of two road bridge structures located in Vietnam: reinforced concrete bridge (case study 1) and steel-concrete composite bridge (case study 2). This is an important part of the dissertation because it is of great importance to use appropriate, reliable models for condition assessment of existing bridge structures. In particular, this applies to the diagnosis of bridges with damage that reduces its load capacity.

The last chapter – Chapter 7, entitled "Conclusion and future work" – on 2 pages, presents a synthetic summary of the results of the work carried out by the PhD student and conclusions resulting from the performed analyses. The last page of the dissertation outlines proposed directions for further scientific and research work related to the analyzed problem.

The programming scripts developed by the author for analyses in MATLAB, SOFISTIK and ANSYS software are well documented in the appendices A, B and C.

The dissertation ends with a Bibliography comprising 184 items. The selection of literature sources demonstrates good orientation of the PhD student in the issues that are the subject of the dissertation.

To sum up, it should be stated that the division of the dissertation into chapters and their order are logically justified and consistently document the achievement of the assumed goals. From an editorial perspective, the dissertation is well-developed. The technical terminology used does not raise significant objections. The numerous graphic illustrations and tables provided are generally legible and communicative.

A good idea is to have short summaries at the beginning of each chapter, which facilitate understanding of the concept and structure of the work, as well as summaries at the ends of the chapters, containing the PhD student's conclusions and opinions.

I have included more important detailed comments regarding the form of the study in point 4 of the review.

3. Substantive evaluation of the dissertation

In terms of its substantive content, I generally assess the reviewed doctoral thesis by Mr. Nguyen Cong Duc, M.Sc., Eng. very positively. Its significant substantive value is determined by the following features:

- The topic of the dissertation has been properly selected – it is interesting from a cognitive point of view, requires a comprehensive approach, and the scientific issue being solved is related to the needs of engineering practice.
- The doctoral student demonstrated a good understanding of the state of knowledge in the area covered by the dissertation, demonstrated great creativity and proficiency in advanced data processing, as well as in modelling and numerical analysis of bridge structures.
- All objectives of the doctoral thesis formulated in chapter 1.3 have been achieved.
- I consider the most important original element of the doctoral dissertation of Mr. Nguyen Cong Duc, MSc. Eng. to be: **Development and implementation into research practice of comprehensive procedures for advanced data processing, enabling the identification of selected features characterizing the technical condition of bridge structures.**
- Developed original, advanced processing procedures of measurement data recorded by sensory monitoring systems are based on interfacing various hard and soft computing techniques, including ANN and optimisation algorithms. The proposed solutions may constitute the basis for further research in the field of electronic sensor monitoring systems supporting the management of operation and maintenance of bridge structures.

It is worth emphasizing and praising that the fragments of the dissertation presented in chapters 4 and 6 were previously published by the author in renowned international journals. This proves the high substantive value of the proposed solutions by the author, constituting his individual and original scientific achievement.

The bibliography of the dissertation lists 7 publications co-authored by the PhD student, including: 3 publications in renowned international journals and 4 in international conference materials. The remaining publications co-authored by of the PhD student (papers not cited in

the text of the dissertation), referred to in the list of scientific achievements at the end of the study, include 11 publications.

I submit the following general comments and remarks on the reviewed doctoral dissertation:

1. The objectives and scope of the work formulated in Chapter 1 are clearly defined and logically result from the state of research on diagnostics of bridge structures in the sensory monitoring strategy.
2. I highly appreciate the research methods used in this dissertation for advanced processing of data obtained from monitoring systems in order to transform them into domain knowledge characterizing the health of bridge structure.
3. The doctoral student has demonstrated that various techniques of symbolic and non-symbolic knowledge representation, including computational intelligence methods, are highly effective and should be used in SHM of bridge structures. However, it should be remembered that each sensory monitoring system of bridge structure must be designed individually, taking into account the specific problems of the tested structure. The types of measured values, the location of measurement points, the types of sensors and the data acquisition and processing strategy should be determined individually for each structure, in a way that allows its assessment based on the established criteria.
4. Any changes in the characteristics of the structural system should be analyzed – in each case – together with changes in the environmental conditions surrounding the object, occurring during its use. The issue of the influence of changes in the temperature on the behaviour of the structure has been omitted in the presented dissertation.
5. Acquisition of good quality data during the entire monitoring process is absolutely crucial. The selection of technical solutions in the measurement system has the greatest impact on the generally understood effectiveness of sensory monitoring systems in achieving the assumed goals. Hardware issues, which are of great importance in practice, were presented in the dissertation to a very limited extent.
6. Very specialized terms are used in the work without providing their definition. In the case of scientific theses on interdisciplinary issues, the creation of a glossary of terms by the author would be an additional advantage.
7. Sensory monitoring of bridge structures is a very complex, interdisciplinary scientific and technical issue that requires specialist knowledge from various fields: bridge engineering, measurement systems, computer science, structural mechanics, as well as knowledge of numerical calculation methods and computational intelligence methods. In my opinion the author of the dissertation demonstrated extensive theoretical and practical knowledge in the above-mentioned fields.

4. Detailed comments

I am presenting detailed comments in the order in which they were formulated while studying the work; they are not arranged according to their substantive or editorial importance:

a) Pages 29, 30 and some others – preferably a colon instead of dots should be used before listing the various items.

b) Page 29, point 3.4. The listed sentences in my opinion do not best summarize the content of Chapter 3, which only briefly presents the tools used latter in the dissertation. Some formulations seem imprecise or untrue to me: "wavelet transforms were proposed", "FFT algorithms were discussed", "Differentiation algorithms were performed".

c) Page 66, point 5.1. The block diagram (Fig. 5.1) of the proposed procedure for assessing the condition of hangers in an arch bridge does not contain elements concerning the estimation of forces in the hangers.

d) Page 29, point 5.2.2. What types of actions on structure could be considered when the forces in the hangers are to be determined according to the given formula (5.1)? Only half a page is devoted to this very important issue (in the case of monitoring tension objects). No results of analyses in this area were presented.

e) Page 69, Table 5.2. The final values of the steel and concrete parameters used in the analyses raise considerable doubts because they are unusually low. Little is known about the structural system of the bridge itself. Are the bridge spans made entirely of steel, or are they composite steel-concrete structures? If these are composite spans, then in my opinion the solution to the problem of "excessive stiffness" of the original model should be sought elsewhere.

f) Page 69. Imprecise caption under Figure 5.4.

g) Page 71. Imprecise caption under Figure 5.6, as well as imprecise explanation in the text of the analytical results shown in this graph.

h) Page 72, point 5.2.5. If I understand correctly, the classes of the force level in the hangers are determined based on vibration measurements at one point on the bridge deck only. This is a very valuable observation from the point of view of designing monitoring systems. How was the location of this point established?

i) Page 83, point 6.1. Unclear text fragment: „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".

j) Page 84, point 6.2. Incorrect caption under Figure 6.1, as well as imprecise explanation of the calibration procedure for numerical models in the text.

k) Page 85, point 6.3. The formulas (6.2) and (6.3) can only be applied to some simple structural systems. There is no comment on this topic in the text. To assess the load-bearing capacity of a composite structure, even in a simply supported static system (as in case study No. 2), these formulas are not applicable.

l) Page 86. The text preceding formula (6.4) is unclear, as is the wording of that formula.

m) Page 88, point 6.4.2. In the process of calibrating the numerical model of the ThiThac bridge spans, the reference physical quantity is the measured strain at mid-span in the fibers of the lower reinforced concrete girders. Whether, and if so, how, was the issue of cracking of reinforced concrete girders and the effects of thermal impact on the values of the measured quantities taken into account? The text states that the deflections of the girders were also measured, which in this case could be a more reliable parameter characterizing the behavior of this structure under the vehicles loads.

n) Page 91, point 6.4.3. The final values of the moments of inertia of reinforced concrete girders obtained as a result of the model calibration according to the

procedure developed by the author are unusually low. It is possible that in this case there may be a problem of so-called keyboard effect performed by prefabricated girders due to progressive damage to the mutual connections between the beams and/or the thin concrete slab as a result of cyclic loads (a problem occurring in bridge spans built from prefabricated elements, mainly in the 1970s). Then, in this particular case – during calibration process of FE model – it would be reasonable to modify also locally the stiffness of the mutual beam connections in the FEM model.

o) Pages 92-93. Imprecise captions under Figures 6.7 to 6.10, as well as imprecise explanations in the text of the analysis results shown in the graphs. What exactly is shown in these graphs?

The few comments presented above do not significantly lower the overall high assessment of the reviewed doctoral dissertation.

5. Summary and final conclusion

In conclusion, I state that the doctoral dissertation of Mr. Nguyen Cong Duc, M.Sc., Eng. entitled "Bridge health monitoring using automated FE model updating, signal processing, and machine learning" is a work of significant substantive value - both scientific and practical, contains an original solution to the investigated scientific problem and demonstrates the ability of the PhD student to appropriately conduct scientific research.

In the reviewed work, the main attention was focused on the methodology of processing measurement data from sensory monitoring systems in order to identify the condition of bridge structure. For the purposes of this work, original experimental studies of 3 bridge structures were performed. Numerical models of the tested structures were developed and the methodology for their calibration and verification was presented.

The author of the dissertation demonstrated extensive theoretical and practical knowledge in the field of experimental research of engineering structures and their numerical analyses. He also presented the ability to solve scientific problems with the harmonious use of theoretical and experimental analysis tools, which deserves special emphasis.

The few critical remarks presented in the review concern mainly the editorial and linguistic aspects and do not have a significant impact on the overall high assessment of the :d dissertation. It is worth emphasizing the rich and carefully prepared illustrative .....l, ensuring a high communicativeness of the dissertation.

The main objective of the work was achieved using scientific methods. Recommendations regarding various aspects of the presented methodology are included in the appropriate parts of the work. Technical details regarding the analysis procedures conducted using specialized computer programs are described in the appendices placed at the end of the thesis.

The reviewed work, in my opinion, meets the requirements for doctoral dissertation... accordance with the Act of July 20, 2018, Law on Higher Education and Science (Journal of Laws of 2018, item 1668, as amended). I therefore request that it be accepted and admitted to public defense.

Mieszko Kużawa

Wrocław, September 12, 2024.

* wyłączenie jawności w zakresie danych osobowych oraz prywatności osoby fizycznej na podstawie art. 5 ust. 2 ustawy z dnia 6 września 2001 r. o dostępie do informacji publicznej (tj. Dz. U. z 2026 r. poz. 1764)

Marzena Gaura