recenzja spełnia wymogi formalne

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Listed among the Top 2% of researchers in the World,
as reported by Stanford University and Elsevier

REVIEW

of PhD dissertation of **Muhammad FAWAD** entitled

BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates

1. Base of elaboration

The review has been prepared for the requirement of the Chairman of the Civil Engineering, Geodesy and Transport Discipline Council of the Silesian University of Technology, Professor Marcin STANIEK (official letter no RDILGT.512..2024 dated 5th of July 2024, received 23rd of July 2024).

The reviewed PhD dissertation was written under the supervision of Professor Marek SALAMAK from the Silesian University of Technology and Professor Kálmán KORIS from the Budapest University of Technology and Economics.

2. General assessment of the PhD dissertation

PhD thesis is written in English on 129 pages, including two-page summaries in Polish and English, lists of abbreviations, figures and tables, as well as three appendixes with elaborated codes. The PhD thesis is also delivered on the CD. The work consists of six chapters and a list of literature covering 243 items. The thesis is theoretical and experimental in nature and concerns interdisciplinary issues related to civil engineering (in particular bridge management), digital technologies, modern and

smart sensors, and structural health monitoring. The subject of the dissertation is very important from a scientific and practical point of view, as it concerns issues of maintenance and monitoring of critical infrastructure such as bridges using a modern approach. For this reason, the choice of topic is appropriate and in line with current trends in civil engineering, especially bridges. In conclusion, the doctoral student's approach to this subject is the most appropriate.

3. Detailed assessment of the PhD dissertation

The reviewed PhD dissertation has a theoretical and experimental character. Chapters 4 and 5 are key to the dissertation due to the research motivations and the thesis formulated in the introduction.

The first part of the work (chapter 1: Introduction) concerns the background of the PhD thesis and the motivation of the doctoral student to take up the subject and scope of the research.

Chapter 2 presents the issues of bridge management systems (BMS) and their applications in the SHM of bridges. It discusses traditional methods such as visual inspections. The chapter also discusses the role of IoT technology in SHM, focusing on smart wireless sensors and components for their development. It also highlights the benefits of integrating SHM with BMS, which can be supplemented with IoT tools to address the shortcomings of traditional inspection methods.

Chapter 3 discusses the application of BIM and digital technologies in bridge engineering, including emerging technologies such as visual programming, artificial intelligence (AI), 3D reconstruction methods, and virtual/augmented/mixed reality (VR/AR/MR) for bridge health assessment and monitoring. It also introduces the concept of the digital twin of bridge, highlighting its advantages and applications in sustainable development.

Chapter 4 presents bridge modelling techniques, focusing on analytical modelling and BIM. Finite element analysis (FEM) was used to assess bridge damage, proposing a SHM system. Two case studies show the practical application of analytical

modelling and bridge load testing methods. This chapter also discusses integrating advanced technologies such as BIM, IoT, and MR into the SHM domain.

Chapter 5 presents a case study of an arch bridge that uses 3D reconstruction techniques, focusing on developing 3D models. Finite element analysis (FEA) is used to simulate the damage condition of the bridge and propose an installed bridge SHM system to monitor the strength parameters of the bridge. Additionally, this chapter discusses the development of a novel approach to infrastructure asset management, focusing on the development of the Immersive Bridget Digital Twin Platform (IBDTP). The platform automates the bridge's SHM system and uses MR devices for immersive decision-making.

Chapter 6 formulates the final conclusions from the PhD thesis, including a discussion of results to achieve research objectives and new scientific achievements. I confirm that the achievements indicated are of great importance from a scientific and practical point of view for the SHM of bridges. Notably, the author also stated the directions for further research in the subject of the dissertation, which testifies to the PhD student's research maturity.

4. Critical and discussion comments

Below, I present critical comments and discussion on particular dissertation chapters.

4.1. Substantive remarks

Chapter 2:

- What are the advantages and disadvantages of the proposed approach to bridge monitoring?
- What is the reliability and accuracy of the proposed SHM method compared to other methods, e.g., satellite techniques?
- Are there any input limitations for the proposed bridge monitoring approach?

- Does the PhD student propose a new approach to bridge management (BMS - Fig. 2.1), or does he modernize its elements? This should be clearly emphasized.
- Bridges are critical infrastructure. How to protect data/system against unauthorized access, which is particularly important during war?
- Please indicate the most important disadvantages of IoT in the context of SHM.

Chapter 3:

- In my opinion, BIM has not changed the approach described in subsection 3.3.3 (page 24) because it only collects and analyzes the data we enter. In most cases, the developed FE model has certain simplifications (depending on the complexity of a given structure). How will BIM consider, for example, the interaction between a reinforced concrete slab and steel girders?
- The digital twin (subsection 3.4, page 28) will depend on the quality of the data entered. How to optimize data reliability so that the results obtained are helpful and do not give the so-called false alarm?
- Subsection 3.5.4 (page 34). What were the criteria for selecting the bridge structure? Personally, I like Concept 1 more.

Chapter 4:

- Page 46: If the technical condition of the bridge is poor (there are cracks) and no repairs are planned, how will the SHM installation improve its safety over the next 15 years?
- Page 46: What material parameters (steel and concrete) were used for FEM modelling? Were these design parameters or actual parameters?
- Page 48: Why is concrete defined as a homogeneous material when, in principle, it is treated as heterogeneous, and in this case, especially since it is cracked? What constitutive model was selected for cracked concrete?
- Subsection 4.3.2: It would be good to show, e.g., on a figure, a comparison of the values obtained from FEM with the experimental ones. Then the correctness of the FEM simulation could be easily demonstrated.

- Subsection 4.3.4, Fig. 4.6: Will making 7-8 mm grooves for the sensors to install not cause too much damage to the already severely degraded girder?

- Subsection 4.3.4: What is the estimated cost of SHM for a bridge in Hungary?

- Subsection 4.4.3: I know that this is not the main element of the PhD thesis, but it would be good to provide more details of the FEM modelling of the analyzed bridges, e.g. what constitutive models were used for concrete, tendons, how the foundations were taken into account, the method of connecting the elements, the number and type of finite elements, boundary conditions, linear-nonlinear analysis, etc. Has a finite element mesh sensitivity analysis been performed?

- Eq. 5.3 (page 61): U_d means calculated (theoretical) displacements, and in table 4.2, U_d means measured displacements. Different markings should be introduced, or there is an error in the description of Eq. 5.3 (??)

- Subsection 4.4.6: As is well known, signals read from sensors are burdened with the so-called "measurement noise". What filters were used to "clean" signals from LVDTs and accelerometers?

- Fig. 4.19(c): Is the PVA course shown after or before signal filtering? How was the signal denoised?

Chapter 5:

- Fig. 5.7, Table 5.2: I understand that the measured values refer to tests of the bridge under actual vehicle traffic (??). And the calculated values concern design displacements or some other (??). Are both loads comparable?

Chapter 6:

- In my opinion, the main limitation in the widespread use of such an innovative approach to monitoring bridges and infrastructure more broadly is the limitations of the managers of these facilities. How can this be overcome?

- Bridges are critical infrastructure, and their monitoring systems should be subject to special protection. Does the developed monitoring system have any protection against "outside interference"?

4.2. Editorial and editorial comments

- Page 6, bottom of the page: there are repeated sentences.
- The way of citation should be in order. Pages 13, 42, 43, 44.
- Page 14: MEMS stands for micro-electromechanical systems, not micro-electrochemical systems.
- Pages 23 and 24: citation method, e.g. [104] has emphasized... Should be: Chase [104] emphasized ... etc.
- Page 48: should be "Poisson ratio" instead of "poison ratio".
- The numbering of formulas in chapter 4 should be 4.1, 4.2, etc., instead of 5.1, 5.2, ...
- List of literature: minor errors and inconsistencies: 1, 29, 38, 56, 138, 153, 185, 186, 198, 207, 2012, 217, 218, 2019, 229, 232.

5. Recapitulation

The PhD student solved the research task himself, analysed the available literature, formulated the scope and purpose, and then consistently aimed to prove it. The aims of the PhD thesis set out in the introduction have been achieved. The proposed SHM of bridges is a new and original approach to the study of these types of structures. The developed SHM, which is equipped with digital technologies, smart sensors, and the Internet of Things, has been tested and validated on selected bridge structures. The critical and discussion remarks mentioned above do not diminish the work's scientific and practical value. I believe there is a good chance that the obtained research results will be published in high-impacted journals, and the elaborated SHM can be widely implemented in bridge practice as a bridge management system.

In my opinion, the reviewed PhD dissertation prepared by Muhammad FAWAD entitled „BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates" presents the candidate's general theoretical knowledge in the discipline of

civil engineering, geodesy and transport, as well as the ability to conduct scientific work independently. In summary, the PhD thesis meets all the requirements of the relevant act (Ustawa Prawo o szkolnictwie wyższym z dnia 20 lipca 2018 roku (Dz.U. 2022 pozycja 574 z późniejszymi zmianami).

Therefore, I am applying to the Discipline Board of Civil Engineering, Geodesy and Transport of the Silesian University of Technology for admission to Muhammad FAWAD for public defence of the reviewed PhD dissertation.

Recenzję podpisał
Damian Bęben