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Review Report on the PhD thesis submitted to the
Scientific Board of the Szewalski Institute of Fluid-Flow Machinery
Polish Academy of Sciences

to attain the
Degree of Doctor of Philosophy (Ph.D.)
(w dziedzinie nauk inżynieryjno-technicznych w dyscyplinie inżynieria mechaniczna)

entitled

"Structural Damage Diagnosis and Remaining Useful Life Assessment Model for Adhesively Bonded Composite Materials"

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The review report was prepared on the basis of a decision of the Scientific Board of the Szewalski Institute of Fluid-Flow Machinery Polish Academy of Sciences dated 23.06.2025.

1) General characteristics of dissertation

The thesis deals with development of a new diagnostic-prognostic methodology in the context of structural health monitoring (SHM) and non-destructive testing (NDT) of adhesively bonded composite structures with the aid of ultrasonic guided waves. The development is based on recent progress in deep learning techniques such as convolutional neural networks (CNN) and long-short term memory networks (LSTM) and predictive uncertainty quantification approaches such as Bayesian neural networks and Monte Carlo dropout. This development can be also attributed to the current limitations of classical methods of signal processing in the context of extraction of damage-related features from signals propagating in structural elements.

Thus, the subject of the dissertation "Structural Damage Diagnosis and Remaining Useful Life Assessment Model for Adhesively Bonded Composite Materials" by Mr Yang Zhang is closely related to the studies of whether deep learning methods can be effectively used as tools for monitoring and prognosis the technical condition of an adhesively bonded thin structural components. For this purpose, propagating guided waves in thin-walled elements of the structure are used and the deep learning methods are aimed at processing propagating waves caused by structural damage and predicting the remaining useful life of the monitored composite element. This dissertation makes a major contribution in the probabilistic damage diagnosis and prognosis tasks and in proposing a novel methodology based on the digital twin hybrid model.

The dissertation consists of 6 chapters, and it comprises 105 pages, 5 tables, 49 figures and 123 cited publications. It begins with Chapter 1 which presents a problem statement, purpose of the study, objectives and motivation, dissertation contribution and dissertation organization. Chapter 2 gives a comprehensive literature review of both experimental and numerical studies related to adhesively bonded composite materials. It contains the review of three research directions: guided waves (GW) based structural health monitoring (SHM) techniques applied for damage detection and diagnosis, remaining useful life (RUL) prognosis methods and the application of digital twin (DT) technology in this context. Additionally, this chapter also critically examines the limitations and research gaps within existing studies. Chapter 3 introduces a RUL prediction process based on data-driven methods with a particular emphasis on the description of deep neural networks commonly employed for the RUL prediction process. Chapter 4 presents the methodology of this dissertation by describing a diagnosis-prognosis framework based on a digital twin (DT) technology. Chapter 5 demonstrates the RUL prediction results using a single lap joint (SLJ) specimen and comparison with published methods, including Bayesian neural networks (BNN) and convolutional neural networks (CNN) to show the advantages of the proposed digital twin hybrid model (DTHM). Chapter 6 summarizes and concludes the original contributions of the research and presents potential future research that stem from the findings presented in this work.

The main thesis of this dissertation is as follows: combining fracture mechanics (FM) with machine learning (ML) methods via digital twin (DT) technology enables damage diagnosis and remaining useful life (RUL) prognosis with uncertainty quantification for the bonding zones of adhesively bonded composite structures. In this study, a digital twin hybrid model (DTHM) was built as a diagnostic-prognostic system for diagnosis and remaining useful life (RUL) prognosis with uncertainty quantification for the bonding zones of adhesively bonded composite structures.

2) Overall evaluation of dissertation

The research methodology of this dissertation is focused on development of a multidisciplinary diagnostic-prognostic model using digital twin technology. Such a research topic fits well to the current research directions related to structural health monitoring. The scope and presented results prove the doctoral candidate’s proficiency in theoretical and practical research works. This dissertation has a structure of basic research but the developed methodology relates directly to real structural health monitoring problems and its application should be assessed as an important step towards solutions of the diagnosis-prognosis problems using digital twin technology with predictive uncertainty quantification.

More specifically, the developed methodology comprises three main components: fatigue crack growth calculation, damage extent quantification and remaining useful life prognosis. It should be considered interesting and significant original elements of this dissertation. What is particularly noteworthy is the wide scope of the presented research conducted in three different stages. These stages required use of various methods of numerical analysis and experimental techniques.The assessment of the components development and application is given below.

Fatigue crack growth calculation

In the dissertation, the doctoral candidate developed the crack growth calculation module that combines fracture mechanics (FM) and extended finite element method (XFEM) cohesive theory to simulate crack propagation in the bonded zone. This module calculates the damage evolution across fatigue cycles. It also generates key fracture mechanics parameters which are employed in the subsequent analyses. The module is applied mainly for data generation using Abaqus, COMSOL and FE-life software. The generated data are incorporated into a digital twin database to support training of machine learning models for fatigue crack growth prediction. In my opinion, the numerical experiments were carried out with care, and the results were presented in a clear manner. Moreover, it should be noted that the scope and diversity of the conducted simulations expanded the Candidate's competence, enriching his numerical analysis background.

Damage extent quantification

In the second research task, the Candidate developed the damage extent quantification module which constitutes the real world system which consists of two parts: experimental damage extent quantification based on guided waves (GW) and fatigue life characterization. The purpose of this module is to obtain experimental datasets about damage extent and corresponding end-of-life (EoL) values. The fatigue testing data used in this dissertation is referenced from the validated experimental framework proposed in cited papers [73, 121]. The experiments were conducted on the single lap joint (SLJ) specimens. Due to limitations in the available experimental data, the dataset was extended by introducing additive Gaussian noise.

Remaining useful life prognosis model

The remaining useful life (RUL) prognosis model is built using the digital twin technology. This model integrates and processes data from both simulations and experiments. It predicts RUL using convolutional neural networks (CNN) and long-short term memory networks (LSTM) with predictive uncertainty quantification. A CNN-LSTM architecture integrated with dropout method and Monte Carlo sampling is implemented in TensorFlow via the Anaconda environment. This research shows a new approach centered on application of CNN-LSTM-based model to predict RUL with predictive uncertainty quantification. The Author achieved his goal by testing the suitability of the model against experimental data using digital twin technology.

3) General comments and questions

The reviewer did not notice any major omissions and/or errors in the dissertation. The dissertation is well-written. There are few typographic errors. The diagrams are drawn properly. Few comments and questions are as follows:

1. It would be very beneficial to include a list of ALL abbreviations used in the dissertation at the beginning of the thesis, there are some abbreviations not included, for example FCP is not explained.
2. There are some ambiguous statements in the text, for example: "The dissertation is implemented in Abaqus by developing user materials UMAT …".
3. The order of the presentation of the material is suboptimal and as a result it is difficult to follow, the 3rd chapter and the 4th chapter should be presented in the reversed order.
4. On page 63 in Eq. 4.16 is presented a linear regression model for RUL prediction, what is the goal of this model in this context?
5. Question relating to the uncertainty quantification (UQ). Has the Author considered other methods of UQ than Bayesian neural networks before finally using the Monte Carlo dropout method?

4) Typographical errors

1. Page 41, subsection title, "... remianing useful life" should be corrected.
2. There are some errors and missed information in the references, for example in [119] and [122].

5) Final evaluation statement

The manuscript prepared by Mr Yang Zhang presents an original research program that fully contributes to the application of deep learning methods for effective signal processing in the context of diagnosis and remaining useful life (RUL) prognosis with uncertainty quantification for the bonding zones of adhesively bonded composite structures. The comprehensive research program conducted by the Candidate and the diversity of the research tasks significantly expanded the Candidate's research competences, enriching his research skills.

The Author achieved all three goals of the doctoral dissertation by exploring the diagnosis-prognosis methodology for assessing the health status of composite structures based on fracture mechanics, guided waves propagation and digital twin technology with predictive uncertainty quantification. He also proved the thesis of this dissertation which stated that: combining fracture mechanics (FM) with machine learning (ML) methods via digital twin (DT) technology enables damage diagnosis and remaining useful life (RUL) prognosis with uncertainty quantification for the bonding zones of adhesively bonded composite structures.

As the Candidate mentioned it in perspectives, further experimental studies would be necessary to identify other types of bonded composite materials and failure modes. Many questions remained unanswered regarding the performance of the developed model in comparison with other hybrid models that could enhance robustness and generalisability of the findings.

In my opinion, Mr Yang Zhang, the Author of the thesis entitled: "Structural Damage Diagnosis and Remaining Useful Life Assessment Model for Adhesively Bonded Composite Materials" proved to have an ability to perform research and to achieve results of a scientific value. Moreover, the Candidate presented the capacity to implement scientific results in engineering practice.

The thesis demonstrates that Mr Yang Zhang meets the requirements laid down by the Polish law (Prawo o szkolnictwie wyższym i nauce, Dz. U. z 2020 r. poz. 85 z późniejszymi zmianami) for candidates for the degree of Doctor of Philosophy in the field of engineering and technical sciences in mechanical engineering (tytuł doktora nauk technicznych w dziedzinie nauk inżynieryjno-technicznych w dyscyplinie inżynieria mechaniczna). Taking into account the above, I am applying to the Scientific Board for admission of the Candidate to the next stages of the procedure of awarding the doctoral degree.