Warsaw, 9 September 2025

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Review of the PhD thesis
MSc. Eng. Yang Zhang
„Structural damage diagnosis and remaining useful life assessment model for adhesively bonded composite materials"

1. Base of eleboration

The basis for the review is the letter of Professor Grzegorz Żywica, Deputy Director for Scientific Issues at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, dated June, 25, 2025, and the attached doctoral dissertation of Mr. M.Sc. Eng. Yang Zhang entitled "*Structural damage diagnosis and remaining useful life assessment model for adhesively bonded composite materials*".

The work was created at Mechanics of Intelligent Structures Department of IMP PAN. The PhD student's supervisors are Prof. D.Sc. Ph.D. Eng. Wiesław Ostachowicz and D.Sc. Ph.D. Eng. Maciej Radzeński from Mechanics of Intelligent Structures Department.

2. Topics of work

The aim of this doctoral dissertation is to develop a model for diagnosing damage and predicting the remaining service life of structural components made of bonded composite materials. The proposed model is characterized by the following key features:

- the use of guided waves to assess damage extent,
- the integration of fracture mechanics with deep learning techniques,
- the prediction of the remaining service life of a component using a neural network with a dropout function to replace Bayesian networks.

This model, combining fracture mechanics with machine learning through digital twin technology, enables the identification of damage and the prediction of the remaining service life of bonded zones in adhesively bonded composite structures. The proposed methodology was experimentally verified on a bonded component consisting of two carbon fiber composites. Therefore, the topic of this dissertation has significant potential for engineering practice, and undertaking such research should be considered fully justified.

3. Scope and content of the thesis

The dissertation has 105 pages and it was written in English. It is divided into 6 chapters, ending with a list of literature. The bibliography contains 123 items, including 4 items co-authored by the PhD candidate, which are indexed in the Scopus database. Additionally, the PhD candidate published his works in renowned journals from the current list of MNiSW (*Journal of Sound and Vibration, International Journal of Mechanical Sciences, Structural Health Monitoring, NDT & E International Journals* and *Sensors*). He also published three conference papers in the prestiguous conferences devoted to SHM.

Chapter 1, which provides an introduction to bond zone damage identification and composite structure remaining service life prediction, presents the key modules of the methodology used in this dissertation. The methodology proposed in this thesis is divided into three functional modules: 1) a simulation module for calculating crack growth based on fracture mechanics and the extended finite element method; 2) an experimental module for quantitatively investigating damage using guided waves; and 3) a deep learning module for integrating simulation and experimental modules to predict the remaining service life of a structure.

Chapter 2 is devoted to a brief literature review of guided waves and their application in SHM systems. This chapter also discusses other aspects of the proposed methodology described in the literature, such as remaining service life prediction models. Finally, the fourth part of Chapter 2 provides information on existing approaches to structural health monitoring based on digital twin technology.

Existing neural network models in the deep learning literature, such as recurrent and convolutional neural networks, long short-term memory networks, and probabilistic Bayesian networks, are discussed in Chapter 3. Additionally, potential improvements in adapting these approaches to damage detection and life prediction in composite structures are analyzed. Furthermore, the autoencoder architecture is presented as a means of reducing high-dimensional input data. Digital twin technology is also discussed, including its application in this study for both damage detection and remaining service life prediction. The chapter is concluded with a presentation of evaluation metrics for machine learning-based predictions and uncertainty quantification methods.

An integrated digital twin-based framework for damage diagnosis and remaining service life prediction of bonded composite structures is proposed in Chapter 4. For remaining service life prediction, a hybrid model methodology is utilized, and an innovative digital twin model that integrates the extended finite element method with fracture mechanics is introduced. Furthermore, to reduce the uncertainty of remaining service life prediction in a hybrid digital twin model, a CNN-LSTM architecture with a dropout method is proposed. This approximately replaces traditional Bayesian uncertainty quantification techniques, thereby increasing the reliability of predictions.

The results obtained from the diagnostic-prognostic framework presented in Chapter 4 are analyzed and discussed in Chapter 5. The content is divided into three sections. First, a guided wave approach is used to assess the damage severity in the bond zone of single-layer lap structures composed of a carbon fiber-reinforced polymer adhesive and a two-component epoxy adhesive. Second, a damage-fatigue cycle curve is generated, and the crack growth rate is simulated using a fatigue crack propagation model. For this purpose, the remaining service life is predicted, and uncertainty is quantified using a hybrid digital twin model, which was presented in Chapter 4. Finally, the predicted remaining service life outcomes are compared with experimental results and existing models in the literature to demonstrate the effectiveness of the proposed method.

In Chapter 6, which concludes the dissertation, the doctoral candidate briefly summarizes the research findings. He highlights the original contribution of the work, draws conclusions, and describes potential directions for further research.

4. Evaluation of the thesis

The dissertation is devoted to the *deep learning-based framework for damage diagnosis and remaining useful life prognosis of adhesively bonded composite structures*. This research topic requires knowledge of numerous issues related to numerical simulations and experimental research. Furthermore, this topic clearly aligns with the research being conducted at many leading academic centers.

The doctoral candidate proficiently uses the methodology of conducting scientific research in the discipline of mechanical engineering, in particular structural health monitoring i.e.:
1) beginning his research by discussing the broad topic of using ultra-light composite structures in many industries, such as aerospace, automotive, wind turbines, and marine sector;
2) analytically formulating and analyzing individual tasks, decomposing a complex problem into individual functional modules;
3) developing numerical solution methods and experimental testing on a representative case;
4) proposing and analyzing the effectiveness of the proposed framework;
5) discussing the literature and situating his results within it;
6) outlining further possible research directions.
This research plan, reflected in the structure of the dissertation, confirms the doctoral student's scientific maturity.

The following should be considered interesting and significantly original elements of the dissertation:

• Development of the novel deep learning-based methodology for identifying cracks and predicting remaining useful life of bonded connections in composite structures with aid of ultrasonic guided wave technology.
• Selection of an appriopriate neural architectures, including Convolutional Neural Network combined with Long Short-Term Memory (CNN-LSTM) network allowing for precise identification of crack propagation.
• Generation of sofisticated dataset composed of synthetic and physical data used for training of the proposed neural network architectures.
• Verification of proposed methodology on a realistic scenario of bonded connection consisting of carbon fiber composites.

What is particularly noteworthy is the wide scope of the research conducted, which covers three different stages of Structural Health Monitoring including early stages starting at damage detection and quantification going to remaining life prognosis. These topics requiring the use of various methods of numerical analysis and experimental techniques. The thematic scope and structure of the work prove the PhD student's proficiency in theoretical and experimental research work.

This dissertation is fundamental research in nature, but the developed methods directly address real-world engineering problems, and their application potential is significant. This applies to the possibility of using the proposed diagnostic and forecasting methodology to test the reliability and effectiveness of various types of adhesive joints in composite structures.

5. General comments and questions

The reviewer did not notice any major errors or omissions in the dissertation. The following comments and questions are of a debatable nature and are intended to contribute to increasing the transparency and cognitive value of the dissertation.

- As can be seen from Figure 5.11, for the proposed diagnostic-prognostic framework to operate effectively, the guided waves used in the first stage of the system's operation must be appropriately tuned depending on the size of the damage (not only the sensor location is important, but also the frequency of the excitation). The question then arises: at what early stage of the crack can it be detected? Can cracks smaller than 10 mm be detected, and if so, what frequency should be used? In other words, is there an explicit relationship between the size of the damage and the guided wave frequency?

- The second question concerns the accuracy of the framework's estimated service life under varying load conditions. It seems that the proposed system will only correctly predict the service life of the adhesive joint under constant fatigue load amplitudes. Please comment on this issue.

- On page 84, one can find information that due to limited experimental data availability, the existing dataset was augmented by adding Gaussian noise to the existing dataset. The question naturally arises as to how much actual experimental data can be replaced by adding noise? What is the expected impact of such a procedure on the accuracy of the prediction results?

- On page 3 it was written "*DT predicts RUL using DL frameworks and platforms (TensorFlow and Anaconda environment)*". Wouldn't it be worth posting the source code on GitHub repository?

- Finally, since the proposed in the disertation *digital twin hybrid model* resembles *physics-informed neural networks (PINN)* the question arises: why the loss function is the proposed approach is a mixture of simulation and experimental data? In *classical PINN* the loss function is a weighted sum of a supervised loss of data measurements and an unsupervised loss of simulation model. Whould it be possible to apply similar approach in the proposed framework?

6. Typographical errors

The dissertation is prepared in English. Its English language and composition are clear and do not require any corrections. Further comments are not of a substantive nature, but only of a technical and editorial nature:

- Page 46: The scoring function definition includes parameter values 10 and 13. What do these numbers mean?
- Page 48: The acronym FCP was not included in the *Nomenclature*; it was defined from the text as Fatigue Crack Propagation.
- Page 49: The phrase "*preceding four chapters*" is incorrect; only three chapters are listed up to page 49.
- Page 50: As above, the acronym FDG was not defined in the *Nomenclature* section, probably "*fatigue damage growth*".
- Page 57: Stylistically awkward phrase "*another important experiment in this experiment*".
- Page 59: Term *URL prognosis* in scheme description should probably be *RUL prognosis*.
- Page 60: In formula (4.10), "k_i" stands for initial contact stiffness, not "k_n".
- Page 62: The iterator ($i = i + 1$) placed inside the `for` loop on line 47 seems redundant.
- Page 84: The graphs in Figure 19a) and b) are mutually uncalibrated.

7. Conclusions

MSc. Eng. Yang Zhang's doctoral dissertation, which addresses the contemporary field of structural health monitoring and damage identification with guided waves, is an original and significant contribution to the scientific community. It demonstrates his independent research skills and problem-solving abilities. The dissertation's value is not diminished by the technical criticisms raised in its review, and it effectively opens new paths for further research.

The reviewed dissertation is an original solution to a scientific problem and meets all the requirements for doctoral theses by the applicable Law on Higher Education and Science of July 20, 2018 (Journal of Laws 2018, item 1668).
I declare the scientific work of MSc. Eng. Yang Zhang is suitable for the open discussion and after a successful defense I suggest giving the PhD title.