Piotr Nazarko, PhD, DSc, Eng, Associate Prof.
Faculty of Civil and Environmental Engineering and Architecture
Rzeszow University of Technology, Poland

Rzeszów, 10.11.2025 r.

Review of the doctoral dissertation by Mr **Yang Zhang**, MSc, Eng, entitled

Structural damage diagnosis and remaining useful life assessment model for adhesively bonded composite materials

Formal and legal basis

The basis for the review of the doctoral dissertation mentioned in the title are:

- the letter (dated 28th August 2025, received by the university office on 3rd September 2025, delivered to the reviewer on 4th September 2025) signed by Mr Grzegorz Żywica, PhD, DSc, Eng, Associate Prof., Deputy Director for Scientific Affairs of the Institute of Fluid-Flow Machinery of the Polish Academy of Science in Gdańsk, together with the related agreement,
- Act of 20th July 2018, Law of Higher Education and Science (Journal of Laws of 2024, item 1571, as amended).

Characteristics of the dissertation

The dissertation is concerned with the detection of damage in adhesively bonded composite joints and the estimation of their remaining safe service life. The subject matter is situated within the broader area of structural health monitoring. Although the problem of damage detection has been extensively addressed in the literature, the Author appropriately emphasizes the importance of assessing the **Remaining Useful Life** (RUL) and **End-of-Life** (EoL) in the context of the investigated specimen.

The non-destructive testing method employed in the dissertation is based on the propagation of elastic waves. The analysis of recorded signals and the subsequent estimation of damage extent are supported by a Damage Index defined with respect to the undamaged reference state. Both experimental investigations and numerical simulations were carried out using an adhesively bonded composite bar model. The analysed cases concern cracks of various lengths occurring within the adhesive layer, whereas other types of damage were not considered in this study. The dissertation is distinguished by the fact that, in addition to laboratory experiments, a numerical model - interpreted in this context as a **Digital Twin** (DT) - was utilized to estimate the remaining useful life.

The inference regarding the remaining safe service life is supported by the application of machine learning techniques. The Author analysed several approaches, in particular Convolutional Neural Networks and Bayesian Neural Networks. It is noted, however, that machine learning algorithms generally perform more effectively in interpolating output parameters than in extrapolating them. Therefore, in the context of predicting the remaining

P. Nazarko

service life, the integration of machine learning methods with numerical simulations and fracture mechanics constitutes a key element of the dissertation.

Scientific value of the dissertation

The main objective of the dissertation is to develop a model for damage diagnosis and prediction of the remaining useful life of bonded composite materials. Addressing this topic meets current research needs and contributes to the advancement of knowledge in the areas of structural health monitoring and structural safety.

The Author demonstrates a clear understanding of the limitations of approaches developed to date, including those based on conventional fracture mechanics as well as purely data-driven techniques. This also applies to the existing applications of machine learning algorithms, including Bayesian inference. In response to these limitations, the dissertation introduces the concept of a **Digital Twin Hybrid Model (DTHM)**, which is distinguished by the application of:

- deep learning methods combined with the principles of fracture mechanics,
- the use of elastic wave phenomena for the prediction of damage extent,
- the prediction of remaining useful life and the associated uncertainty through a model employing dropout mechanisms for outlier data.

The novelty of the research lies in the hybridization of physical and data-driven modelling, offering a coherent framework that bridges deterministic fracture mechanics with probabilistic machine learning approaches. This integration represents a meaningful step toward enhancing the accuracy and reliability of structural health monitoring systems. The methodological concept is scientifically sound and demonstrates internal consistency between the adopted models, the analysed phenomena, and the intended diagnostic objectives.

From a practical standpoint, the proposed approach has the potential for broad applicability in engineering disciplines where bonded joints are widely used, such as aerospace, automotive, and civil engineering structures. Considering the subject matter, the scope of the research, and the obtained results, the thesis has been properly defined and convincingly substantiated. The evidence presented allows the conclusion that the dissertation's main hypothesis has been successfully demonstrated.

Methodology and research approach

The research methodology adopted in the dissertation is based on a multidisciplinary model fusion framework that integrates experimental investigations, numerical simulations, and machine learning techniques within a unified diagnostic-prognostic scheme. This hierarchical framework, referred to by the Author as a **diagnostic-prognostic model**, consists of three core components: the damage extent quantification model, the fatigue crack growth calculation module, and the Remaining Useful Life (RUL) prognosis model.

The **crack growth calculation module** combines the principles of fracture mechanics with the extended finite element method (XFEM). Numerical simulations performed in Abaqus,

P. Nazarko

COMSOL, and FE-life provide detailed data on crack propagation under cyclic loading. These data are subsequently incorporated into a DT database, which serves as a foundation for the training and validation of machine learning models.

The **experimental module**, representing the physical system, includes two key elements: damage quantification experiments based on guided wave (GW) propagation and fatigue life characterization tests. This part of the study aims to determine the extent of damage and to obtain experimental datasets corresponding to various stages of degradation, including EoL values. However, the dissertation does not provide a fully convincing justification for the choice of specimen dimensions (Question 1). It may be assumed that the adopted geometry was selected to ensure the initiation and development of fatigue damage within the adhesive layer rather than in the composite bars themselves. It also remains unclear whether the tested specimens represent a fragment of a real structural joint or were designed solely as an experimental model to reproduce the relevant damage mechanisms. Furthermore, how many specimens were tested under fatigue loading and included in the analysis presented in the dissertation (Question 2)?

A valuable part of the dissertation, from the perspective of planning future experiments and assessing the sensitivity of the applied approach, is the presentation of experimental results in the form of the Damage Index (DI) obtained for various excitation frequencies (Figs. 5.11–5.13). These results provide important insights into the influence of excitation frequency on the detectability and quantification of adhesive joint damage. The observed trends can serve as a basis for optimizing future experimental procedures, improving signal selection, and refining the diagnostic sensitivity of the GW–based technique.

The dissertation presents results of damage detection and remaining useful life prediction for a particular specimen with a defined adhesive layer length and thickness. While this approach allows for precise control of boundary conditions and damage evolution, it limits the assessment of the method's general applicability. If the proposed concept has been correctly interpreted, extending it to other bond geometries or dimensions would require developing a new numerical model, validating it experimentally, and retraining the prediction algorithm. This raises an important question about how the approach could be adapted for adhesively bonded composite bars or sheets with different structural configurations (Question 3). Addressing this issue would significantly enhance the methodological robustness and practical value of the presented framework.

The **RUL prognosis model**, built upon the DT concept, integrates information from both the numerical simulations and the experimental data. Deep learning frameworks, implemented using TensorFlow and operated within the Anaconda environment, are employed to process the data and predict the remaining useful life together with the associated uncertainty.

The methodological concept demonstrates a high degree of coherence between the physical, numerical, and computational layers of analysis. The integration of XFEM-based fracture mechanics modelling with guided wave diagnostics and deep learning inference reflects a well-designed and innovative multidisciplinary approach. The adopted research framework

P. Nazarko

allows for both the quantitative assessment of damage and the probabilistic prediction of structural performance, which is fully consistent with the stated research objectives.

Structure and clarity of the dissertation

The dissertation is logically structured and demonstrates a clear progression from the presentation of the research background and objectives to the discussion of the adopted methodology, experimental and numerical investigations, and final conclusions. The declared organization of the document is coherent: Chapter 1 outlines the research motivation, methodological context, and key contributions; Chapter 2 provides a literature review focused on SHM techniques for damage detection and RUL prediction of adhesively bonded composite materials; Chapter 3 discusses data-driven approaches to RUL estimation, including the neural network architectures commonly used for this purpose; Chapter 4 introduces the diagnostic–prognostic framework developed by the Author, based on DT technology; Chapter 5 presents the results of the RUL prediction study using a single-lap joint (SLJ) specimen and compares the proposed DTHM with other approaches, such as Bayesian and Convolutional Neural Networks; finally, Chapter 6 formulates the main conclusions and outlines possible future research directions.

A substantial part of the dissertation - approximately half of its total volume - is devoted to the literature review and theoretical background. The review is divided into three coherent sections addressing damage detection, RUL prognosis, and DT concepts. The number of reviewed publications is appropriate and up to date, and the discussion demonstrates a comprehensive understanding of the state of the art in all three research domains. The reviewed works are accurately summarized and well referenced, giving the reader a solid overview of current advances in the field. However, the synthesis of this material could be strengthened. The literature review, while extensive, does not clearly highlight the specific research gaps or limitations that directly justify the approach developed in the dissertation. A more explicit articulation of these gaps would help clarify the novelty and motivation behind the proposed methodology.

The dissertation lacks a more detailed discussion of the selection of parameters and the architecture of the applied neural networks, as well as their influence on the obtained results. Although Chapters 3.3 and 3.5 describe the general operation of the implemented algorithms, the absence of a deeper analysis of how network configuration, hyperparameter settings, and training strategies affect model performance limits the methodological transparency of the work. A discussion of error metrics and their interpretation would also allow for a more objective assessment of the predictive accuracy and reliability of the proposed models. This aspect is particularly important from the standpoint of reproducibility and the potential implementation of such solutions in other diagnostic and prognostic applications.

An important role in the presented approach is played by the results of numerical simulations, which, together with experimental measurements, form the DT. These data are subsequently used to train machine learning algorithms and to predict the remaining service life of the tested joint (Fig. 4.1). However, this information is missing from the diagram shown in Fig. 2.2, which links the technical levels of SHM with the evaluated dissertation. Although it is implicitly

P. Nazarko

included in stage V, the diagram itself may give the misleading impression that the approach is based solely on experimental measurements (Question 4).

Although laser vibrometer measurements were performed, the final estimation of damage extent and remaining safe service life was based on elastic wave propagation data obtained from piezoelectric transducers. The Author is requested to clarify the rationale for this choice and to discuss the measurement limitations associated with using laser vibrometers in practical applications (Question 5).

With reference to Fig. 5.19, it is not entirely clear whether the crack width in the bonding zone was estimated based solely on the measured elastic wave propagation signals or whether an additional method, such as a crack gauge, was employed (Question 6). Furthermore, were the elastic wave signals recorded while the tested specimen was under load (Question 7)? In the numerical simulation results presented in Fig. 5.19b, the crack length starts at approximately 3 mm, rather than at zero. Was it not possible to detect smaller cracks, e.g., 1 mm, in the numerical simulations (Question 8)?

On page 86, the Author states that "from the comparison between Fig. 5.22b) and f), the overall prediction probability of CNN-LSTM with dropout is significantly higher." Please clarify how this statement should be understood - specifically, how the obtained results were interpreted and how "prediction probability" was defined in this context (Question 9).

The description of the experiments and simulations should enable independent repetition and verification of the results. However, several details require clarification to ensure full reproducibility (Questions 10-14):

- what are the dimensions of the laboratory and numerical models (e.g., the height and width of the bar cross-section);
- how many samples were obtained from numerical simulations and experiments — on page 66, it is stated that "the volume of experimental data is significantly lower than that of simulation data (200,000×200)," whereas on page 85 and in Table 5.2 the value is given as 200,000×100;
- how to interpret the input vector size 200,000×100 (p. 85 and Table 5.2, p. 88) - the model input is described as "fatigue cycles progress" (p. 82) and "labelled damage extent" (p. 85);
- the term α–Nf, probably obvious for the author, is not included in the abbreviation list should be explained for the reader, as well as its distinction from Nf, the "ultimate fatigue damage cycles" (p. 81);
- where the figure containing the "damage–fatigue cycle curve," mentioned on page 69, can be found. It may refer to Figs. 5.18 or 5.19; however, this remark concerns the need for consistent naming of the key components of the proposed approach, which would facilitate a clearer understanding of the overall concept.

The dissertation is generally well written in a clear and formal scientific style; however, a number of editorial and formatting inconsistencies were noted:

P. Nazarko

- the list of abbreviations does not include all acronyms used in the text (e.g., PHM on p. 35; FCP on pp. 58, 79, 82, 91; CZM on pp. 82, 92);
- Figure 5.13 lacks explanation for subfigure references (a) and (b);
- the axes in the charts presented in Fig. 5.19 have different ranges, making comparison of results more difficult;
- citation errors:
  - on p. 14 it should be "Shan and Cheng [32]" instead of "Cheng et al. [32]";
  - on p. 16 "Zheng et al. [48]" instead of "Yuan…";
  - on p. 20 "Vivek et al. [104]" while in the bibliography list the first author is "Nerlikar";
  - on p. 20 "Zhao and Chen [12]" instead of "Zhao et al. [12]";
- several records in the reference list contain "et al." after the first author instead of listing all co-authors (see items 1–8, 15, 17, 20–22, 24–28, and many others).

Despite these issues, the dissertation demonstrates a coherent structure and presents the conducted research in a readable and technically sound manner. Ensuring consistency in data descriptions and improving editorial errors would further enhance the clarity and professional quality of the document.

Originality and contribution to the field

The dissertation presents a comprehensive and original research concept that combines fracture mechanics, experimental and numerical simulation, and machine learning within a unified diagnostic-prognostic framework grounded in the DT paradigm. This interdisciplinary integration constitutes a meaningful scientific contribution to the field of SHM of adhesively bonded composite joints.

The Author's main original contributions can be summarized as follows:

- development of a diagnostic–prognostic framework integrating measured signals, finite element analysis, fracture mechanics, and machine learning, in which multi-model data fusion is achieved through the DT concept;
- introduction of a GW–based Damage Index for quantifying the damage extent in the adhesive layer, improving the precision of damage detection;
- implementation of a hybrid CNN-LSTM model for time-series prediction, combined with an approximate Bayesian inference method based on dropout to RUL prediction and quantify its uncertainty, providing a computationally efficient alternative to classical Bayesian neural networks.

These elements demonstrate a high level of methodological innovation, particularly through the hybrid integration of physics-based and data-driven models, which enhances both the interpretability and predictive capability of the system. The combination of XFEM-based simulation, elastic wave diagnostics, and deep learning–based prognostics represents a coherent and forward-looking approach consistent with current trends in Digital Twin technology.

B. Nazarko

However, the originality of the presented methodology is demonstrated primarily on a single specimen configuration. Therefore, it would be important to discuss to what extent the proposed framework could be generalized to other types of bonded joints or structural elements, such as adhesively bonded composite sheets (Question 15).

The conclusions presented in the dissertation are consistent with the stated objectives and supported by the obtained results. They are logically formulated and demonstrate the Author's understanding of the investigated phenomena and modelling principles. The conclusions correctly summarize the contribution of the developed Digital Twin Hybrid Model (DTHM) to enhancing damage detection and remaining useful life prediction in adhesively bonded composite joints.

The recommendations for future research are well justified and indicate the Author's awareness of the limitations of the current study. The proposed directions of extending the database with additional experimental data, exploring other structural geometries, and optimizing model parameters for real-time implementation are relevant and feasible. The Author also correctly identifies the importance of extending the approach to other failure types, noting that while guided wave- based crack detection is reliable, bonded interfaces may also experience adhesive voids and disbonding, which warrant the development of suitable GW-based quantification techniques. This observation demonstrates a well-founded and forward-looking perspective on future research.

In summary, the dissertation provides a noteworthy contribution to the advancement of DT–based SHM and prognostic modelling, offering conceptual and practical value for fatigue damage diagnosis and remaining life prediction in composite structures.

Conclusions and overall assessment

The dissertation addresses a relevant research problem concerning the diagnosis of damage and prediction of the remaining useful life of adhesively bonded composite joints. The topic lies within the broader field of structural health monitoring and responds to the growing demand for reliable diagnostic–prognostic tools supporting the safety and durability assessment of modern engineering structures.

The Author has demonstrated a solid understanding of the theoretical foundations of fracture mechanics, fatigue behaviour, and elastic wave propagation, as well as a high level of competence in numerical modelling and machine learning. The adopted methodological framework represents an innovative and coherent attempt to integrate physical modelling with data-driven prediction. The hybrid approach proposed in the dissertation constitutes a valuable contribution to the development of intelligent monitoring systems.

The literature review included in the thesis and the introduction to the subject matter confirm that the Candidate possesses a solid theoretical background in the scientific discipline of mechanical engineering. The manner in which the experimental and numerical results are presented and interpreted further demonstrates the Candidate's ability to conduct independent scientific research.

P. Nieczko

Taking into account all the above-mentioned aspects, I conclude that the doctoral dissertation presented for evaluation meets the requirements of the Act on Scientific Degrees and Academic Titles (dated 20 July 2018, Law on Higher Education and Science, Journal of Laws of 2024, item 1571, as amended). On this basis, I request the Scientific Council to admit the doctoral candidate to the next stages of the procedure for awarding the doctoral degree.

Piotr Nowacko