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REVIEW

of PhD dissertation of MSc. Eng., Jafar Amraei, entitled „Thermomechanical fatigue life assessment of polymer-matrix composites under temperature control and different loading regimes".

Legal basis:

The review has been prepared for the requirement of Chairman of the Discipline Council of Mechanical Engineering of the Silesian University of Technology, Prof. Alicja Piasecka-Belkhayat – official letter no RDIMe.512.69.2025 from the 27th of March 2025.

1. General and formal characteristics of dissertation

The doctoral dissertation entitled "Thermomechanical fatigue life assessment of polymer-matrix composites under temperature control and different loading regimes" by Mr. Jafar Amraei addresses a highly relevant and timely topic within the field of structural materials engineering. Polymer-matrix composites (PMCs), including carbon fiber-reinforced polymers (CFRPs) and glass fiber-reinforced polymers (GFRPs), are increasingly utilized in the energy sector (e.g., wind turbines) and various transportation domains (e.g., automotive, aerospace, railway, and marine) due to their favorable combination of high strength-to-weight ratio, durability, environmental resistance, and design flexibility.

Despite these advantages, the widespread adoption of PMCs is hindered by the limited understanding of their fatigue behavior under cyclic loading conditions. This lack of knowledge often leads to overly conservative design practices, resulting in unnecessarily heavy and costly structures, which in turn constrain performance optimization. A key challenge lies in capturing the fatigue performance of PMCs across different regimes, ranging from low-cycle to very-high-cycle fatigue.

One of the fundamental bottlenecks in this area is the excessive time required for conventional fatigue testing, particularly in the very-high-cycle domain ($\geq 10^9$ cycles), where tests conducted at typical loading frequencies (≤ 5 Hz) may take several years. High-frequency fatigue testing offers a practical solution by significantly reducing test durations. However, due to the viscoelastic nature of PMCs, such loading regimes induce self-heating effects that create complex thermomechanical interactions. These interactions can lead either to stable operation or to substantial material degradation, depending on the severity of the temperature rise, thus complicating the analysis and modeling of fatigue-induced damage.

The dissertation under review aims to address this multifaceted challenge by developing a physics-informed framework to understand and model the self-heating behavior in PMCs subjected to cyclic loading. It further introduces innovative methodologies to assess and mitigate the detrimental effects of self-heating and explores the possibility of harnessing this phenomenon as a diagnostic tool for structural integrity evaluation. Given the increasing industrial reliance on PMCs and the urgent need for reliable, time-efficient fatigue assessment techniques, this work presents a significant and timely contribution to both academic research and engineering practice.

This PhD thesis is a compilation of research articles published in scientific journals that are thematically related. Based on their subject relevance, the eight research papers that make up this collection are divided into seven chapters. The Appendices provide the full texts of these papers.

The dissertation under evaluation is 81 pages long and includes a bibliography with 126 references. It is structured into seven chapters that present the discussion and results, preceded by a preface, a list of figures, a list of tables, a list of abbreviations, and acknowledgements.

The presented work includes the following content of the work:

Chapter 1 provides a well-structured and comprehensive introduction to the topic, effectively contextualizing the self-heating phenomenon within the broader field of fatigue analysis of polymer-matrix composites (PMCs). The chapter logically progresses from the fundamental description of self-heating (Section 1.1) through its impact on fatigue behavior (Section 1.2), current modeling strategies and their limitations (Section 1.3), and practical approaches for accelerated fatigue assessment (Section 1.4). The inclusion of mitigation strategies (Section 1.5) and the potential of thermography-based non-destructive testing (Section 1.6) demonstrates the author's awareness of both theoretical and applied dimensions. The final sections (1.7 and 1.8) clearly define the research objectives and methodological framework, setting a solid foundation for the remainder of the thesis.

Chapter 2 focuses on the modeling of the self-heating phenomenon in fatigue-loaded polymer-matrix composites (PMCs), offering both theoretical and numerical insights. It begins with an overview of the underlying thermomechanical principles (Section 2.1), followed by the development of a thermoviscoelastic model using a comprehensive 44-term Prony series representation (Section 2.2), which accounts for both temperature and frequency dependence. The simulation results are presented and validated in Section 2.3, demonstrating good agreement with experimental data. A particularly important contribution is the identification of radiative heat flux as a significant factor affecting the thermal response, which must be included for accurate modeling. Additionally, the analysis confirms that, for thin PMCs, through-thickness temperature gradients remain negligible, validating the use of surface temperature measurements by infrared thermography. The chapter concludes with a clear summary (Section 2.4) that reinforces the relevance and robustness of the proposed modeling approach.

Chapter 3 presents an in-depth thermomechanical fatigue analysis of carbon fiber-reinforced PEKK (CF/PEKK) composites under different loading regimes, specifically low-frequency fatigue testing (LFFT) and ultrasonic fatigue testing (UFFT). The chapter explores the limitations of traditional S–N curves in capturing the material response across the full fatigue spectrum, particularly in the transition zone between LCF and VHCF. To address this challenge, the author introduces an innovative approach based on the heat dissipation rate, which enables the integration of data from both LFFT and UFFT regimes. This approach also facilitates the identification of a critical self-heating temperature range (50–65 °C), providing a practical failure criterion for high-frequency fatigue experiments. Overall, the chapter demonstrates a strong combination of experimental insight and methodological innovation.

Chapter 4 offers a multifaceted assessment of thermomechanical fatigue life in PMCs by introducing and comparing several innovative methodologies. Central to the chapter is the application of entropy-based analysis, which is explored through heat dissipation rate modeling, acoustic emission monitoring, and stiffness degradation tracking. The chapter demonstrates that standard S–N curves alone are insufficient for capturing damage evolution across varying loading frequencies. In response, the author presents refined fatigue life estimation techniques using fracture fatigue entropy (FFE), entropy-based damage index (EDI), and stiffness degradation (SD). These approaches allow for a more nuanced evaluation of fatigue behavior across different regimes and damage stages, offering practical alternatives for fatigue life prediction and testing termination criteria. The integration of thermographic and acoustic emission data adds robustness to the analysis, and the proposed trilinear $\dot{q} - \sigma$ model represents a notable advancement in entropy-informed fatigue modeling.

Chapter 5 investigates the role of nanocarbon-based fillers—specifically graphene nanoplatelets (GNPs) and carbon nanofibers (CNFs)—in enhancing the fatigue performance of modified GFRP composites. The findings indicate a nuanced interaction: while GNPs may degrade fatigue strength, hybrid nanoparticle (HNP) systems offer measurable improvements across fatigue regimes. Thermographic and mechanical analyses reveal that incorporating thermally conductive nanofillers helps mitigate self-heating effects, thus reducing thermal degradation and extending service life. The chapter also introduces the MPD-based $\Delta T - \sigma$ and $\dot{q} - \sigma$ approaches as more accurate alternatives to traditional MCR-based methods for fatigue strength estimation. These results support the use of tailored nanofiller systems as a passive strategy to control temperature rise—especially valuable where active cooling is infeasible.

Chapter 6 focuses on extending the self-heating-based approach toward non-destructive damage evaluation of PMCs. By utilizing self-heating vibrothermography (SHVT), the study confirms that minor temperature increases (below 2 °C) do not affect the material integrity, validating the method's non-destructive character. A key contribution of this chapter is the development of an effective selection strategy for raw thermograms, allowing clear visualization of damage from large datasets. This is further enhanced through a dedicated post-processing algorithm that significantly improves damage identification and localization. The presented methodology broadens the practical utility of SHVT, particularly in applications with limited accessibility such as aircraft component inspections.

The final chapter summarizes the key findings of the dissertation, emphasizing advancements in modeling self-heating, fatigue life assessment, and damage detection in PMCs. It highlights the successful fulfillment of research objectives and outlines future research directions focused on complex loading scenarios, advanced damage quantification, optimized material systems, effective cooling strategies, and further development of SHVT for realistic and 3D composite structures.

2. Assessment of the topic and purpose of the scope of dissertation

The dissertation addresses an innovative and highly relevant topic focused on the thermomechanical fatigue behavior and damage assessment of polymer matrix composites (PMCs), with particular attention to the self-heating phenomenon. The work is strongly motivated by key limitations in current fatigue life prediction and non-destructive evaluation methods. The stated hypothesis is clear, well-justified, and directly targets the central challenge: improving fatigue assessment by accounting for and mitigating the self-heating effect.

The research objectives are logically derived from the identified knowledge gaps and comprehensively cover both modeling and experimental aspects, including fatigue modeling, cross-regime transferability, fatigue life estimation via novel indicators, material design via nanofiller hybridization, and the extension of SHVT to plate-like composite structures. These objectives are well-structured and correspond to clearly defined milestones, each of which is directly addressed in the dissertation chapters.

The scope is ambitious yet realistic and well-aligned with the overall research hypothesis. The milestones reflect a rigorous and methodical approach to validating the hypothesis and fulfilling the research aims, confirming the dissertation's strong conceptual foundation and high relevance for both academic and applied materials research.

Considering the above, it can be concluded that the selected dissertation topic is timely, well-defined, and highly relevant to the field of fatigue life assessment of polymer matrix composites. The objectives are sufficiently ambitious while remaining realistically achievable within the scope of doctoral research. The dissertation stands out for its interdisciplinary approach, which integrates material characterization, mechanical modeling, advanced experimental techniques (including LFFT, UFFT, and SHVT), signal processing, and the development of novel evaluation methodologies. As a result, the work contributes both to a deeper understanding of underlying physical phenomena and to the creation of practical tools and methods with strong application potential in aerospace, automotive, and structural health monitoring domains.

3. Dissertation evaluation

The commentary accompanying the individual papers is generally well written and succeeds in connecting the articles into a coherent narrative. However, from a reader's perspective, it was somewhat challenging to clearly identify which article is being discussed at a given point in the main text. Frequent reference to the initial sections — particularly the Author Contribution Statement and the List of Publications — was necessary in order to match each commentary with the corresponding publication. A more explicit referencing system (e.g., by numbering the articles and referring to them consistently throughout the commentary) would have significantly improved the readability and clarity of the dissertation.

A minor but noticeable formal issue concerns the use of abbreviations throughout the main text. It is customary in academic writing to introduce each abbreviation by first stating the full term followed by the abbreviation in parentheses upon its first occurrence (e.g., carbon fiber-reinforced polymer (CFRP)). In this thesis, the author frequently uses abbreviations without prior definition in the main text, assuming the reader's familiarity or requiring them to consult the List of Abbreviations. While the abbreviations are indeed listed, this practice can disrupt the reading flow and reduce accessibility, particularly for interdisciplinary audiences. A more reader-friendly approach would have been to define all abbreviations in-line at their first mention. For example, the abbreviation *SD* is not included in the list of abbreviations, although it is properly introduced in the main text.

Despite these minor issues, the overall quality and relevance of the dissertation remain exceptionally high. The candidate has demonstrated a deep understanding of the topic, evidenced by the authorship of two comprehensive review articles — one is already highly cited in the field. The experimental design is well thought out and includes appropriate methodologies that combine low- and high-frequency fatigue testing with advanced thermographic techniques. Moreover, the dissertation employs a rigorous numerical framework supported by physics-based modeling and damage quantification approaches. The interdisciplinary nature of the work — encompassing materials science, mechanical engineering, thermal analysis, and signal processing — strengthens both its scientific contribution and its practical applicability.

In summary, the minor formal shortcomings do not diminish the high scientific merit of the work. The dissertation represents a significant and original contribution to the field of fatigue characterization and non-destructive evaluation of polymer-matrix composites. Its findings have a direct relevance to technical practice, particularly in aerospace and structural applications where predictive durability and advanced diagnostics are critical.

Questions:

1) In the commentary accompanying Figure 4.8, it is stated that *"the FFE-based S–N curves slightly underestimate the number of cycles in the LCF regime (below 10^5 cycles)."* However, according to the figure, this statement appears accurate for the 40 Hz case, but not for the 50 Hz case, where the FFE-based curve seems to overestimate the fatigue life in the LCF regime. Could the author clarify this apparent discrepancy and elaborate on the possible reasons for the differing behavior at 50 Hz?

2) The dissertation presents promising results for fatigue life prediction using the Maximum Cumulative Rate (MCR) and Maximum Fatigue Damage (MFD) approaches, particularly under fixed loading conditions with the lower bound of maximum stress set at 50 MPa (Fig. 5.1). However, for practical application in engineering design or structural health monitoring, it is essential to understand the robustness of these approaches across a broader range of loading conditions. Could the author elaborate on the sensitivity of the MCR and MFD models to variations in the maximum stress level? Specifically, how would the predicted fatigue life be affected if the maximum stress were significantly higher (or lower) than 50 MPa? Addressing this question could provide important insights into the generalizability and real-world applicability of the proposed approaches.

4. Final conclusion

Despite the drawbacks mentioned above, the content and format of Mr. Jafar Amraei's PhD thesis clearly demonstrate his expertise in thermography and fatigue of composite materials. The way the work is structured and presented confirms that the candidate is capable of independently planning, conducting, and completing advanced scientific research using contemporary scientific and engineering methods.

The dissertation provides original solutions to well-formulated scientific problems, supported by a solid theoretical background and interdisciplinary methodology. All the stated objectives of the dissertation have been met in full, and the hypothesis has been adequately verified by both experimental and modeling results. According to my evaluation, the thesis satisfies the criteria for a doctoral dissertation and demonstrates the candidate's ability to conduct scientific work independently. It therefore meets the requirements of the Act of July 20, 2018, Law on Higher Education and Science (Journal of Laws of 2024, item 1571) Article 187. I recommend that the dissertation be accepted and allowed for public defense.

Provided that Mr. Jafar Amraei successfully defends his dissertation before the examination committee, I recommend that he be awarded the academic degree of Doctor (Ph.D.).