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**Review of the doctoral dissertation of Mr. Jafar Amraea, M.Sc.**
**„Thermo-mechanical fatigue life assessment of polymer-matrix composites under temperature control and different loading regimes"**

## 1. *Basis for the preparation of the review and the candidate's profile*

The subject of this opinion is a review of the doctoral dissertation of Mr. Jafar Amraei, M.Sc., Eng., a PhD student at the Faculty of Mechanical Engineering of the Silesian University of Technology, entitled "Thermo-mechanical fatigue life assessment of polymer-matrix composites under temperature control and different loading regimes". This dissertation was written under the supervision of Professor Andrzej Katunin, PhD, DSc, Eng., and the assistant supervisor was Dominik Wachla, PhD, Eng. This review was commissioned by the Chairperson of the Mechanical Engineering Discipline Council of the Silesian University of Technology, Alicja Piasecka-Belkhayat, PhD, DSc, Eng., Professor of the Silesian University of Technology, based on the Resolution of the relevant Discipline Council adopted on March 26, 2025. The legal basis for the review is the Legal *Act on Higher Education and Science* of 20.07.2018, Article 187 (Journal of Laws of 2024, item 1571).

Mr. Jafar Amraei, M.Sc., Eng., completed a three-year master's degree in composite materials engineering in 2016 at the Malek-Ashtar University of Technology in Tehran, specializing in Composite Structures Design. He presented his master's thesis on "Micromechanics-Based Multiscale Modeling of Polymer Nano-composites Reinforced with Carbon Nanotubes". From 2017 to 2021, he worked as a researcher in composite materials at the Sharif University of Technology in Tehran. Subsequently, in the years 2021-2024, he was a student of the Joint Doctoral School of the Silesian University of Technology in the discipline of Mechanical Engineering and at the same time was employed as an assistant at the Department of Fundamentals of Machine Design at the same university. In the materials from the doctoral dissertation, we can find information that the Scopus database displays 14 of his publications with 151 citations, which gives him a total Hirsch index of 5 and a cumulative IF of 60.58. For comparison, the Promoter's Hirsch index is currently 26 according to the same database.

## 2. *Subject and scope of the dissertation*

The dissertation was presented in English, in the form of a thematic series of co-authored publications with an appropriate introduction, description, and summary of the most important results. Its content consists of acknowledgments, introduction, list of publications with a declaration of the PhD student's participation in their writing, table of contents, list of figures, tables, and markings, as well as a description of the adopted markings. The further, substantive part of the dissertation, written on 86 pages, consists of seven chapters, bibliography, and abstracts in Polish and English, so the presented dissertation meets the statutory formal requirement for doctoral dissertations. For the brief description of the publication cycle, 126 literature items are cited. Next, appendices are presented, in which the PhD student has compiled the publications that make up the series constituting his dissertation, followed by declarations by co-authors. Appendices constitute the largest part of the work – 250 pages.

The subject of the dissertation concerns the fatigue issues of polymer matrix composites, often used in various engineering solutions on an industrial and individual scale. These composites were analyzed under different load cycles, so the results of the analysis are quite general. These composites also take into account the phenomenon of self-heating, which significantly hinders mathematical and numerical modeling; Experimental research is also much more complex. This aspect proves the originality of the research carried out, as thermo-mechanical tests and fatigue simulations of polymer-based composite materials are no longer a novelty in themselves. The subject of composite materials, their design, and the phenomena occurring from them is still very popular despite many publications and mathematical and numerical models, and its technical importance does not wane. Certainly, the analysis of such issues requires good preparation of the PhD student and deep knowledge, primarily in the field of mechanics of composite materials.

The series of publications constituting the dissertation here consists of the following articles, seven of which have been published, and one is at the stage of review:

[1] J. Amraei, A. Katunin, Recent advances in limiting fatigue damage accumulation induced by self-heating in polymer matrix composites, published in Polymers in the year 2022 (70% contribution, 100 points, Scimago H-index=167);

[2] P.N.B. Reis, A. Katunin, J. Amraei, Critical analysis of the systems used to reduce self-heating in polymer composites subjected to very high cycle fatigue regimes, contained in Fatigue and Fracture of Engineering Materials and Structures 2025 (15% contribution, 100 points, Scimago H-index=104);

[3] J. Amraei, A. Katunin, M. Lipińska, Numerical simulation and experimental validation of self-heating of polymer-matrix composites during low-cycle fatigue loading, published in the International Journal of Fatigue (65% contribution, 140 points, Scimago H-index=163);

[4] J. Amraei, T. Rogala, A. Katunin and others, Thermomechanical fatigue behavior of CF/PEKK composite under low and ultrasonic frequencies presented in Composites Part B, an issue from 2024 (25% contribution, 200 points, Scimago H-index=227);

[5] A. Premanand, T. Rogala, D. Wachla, J. Amraei and others, Fatigue strength estimation of a CF/PEKK composite through self-heating temperature analysis using cyclic bending tests at 20 kHz, published in Composites Science & Technology, volume 243 from the year 2023 (10% contribution, 200 points, Scimago H-index=259);

[6] J. Amraei, A. Katunin, Thermomechanical fatigue life assessment of polymer-matrix composites via entropy-based damage evolution and stiffness degradation under different frequencies, Composites Part B: Engineering, volume 298 from the year 2025 (80% contribution, 200 points, Scimago H-index=227);

[7] J. Amraei, T. Rogala, A. Katunin and others, Synergistic effects of graphene nanoplatelets and carbon nanofibers on thermomechanical fatigue response of modified glass/epoxy composites, submitted to the International Journal of Fatigue (35% contribution, 140 points, Scimago H-index=163);

[8] J. Amraei, A. Katunin, D. Wachla, K. Lis, Damage assessment in composite plates using extended non-destructive self-heating based vibrothermography technique, which was published in the journal Measurement in issue 241 of the current year (50% contribution, 200 points, Scimago H-index=146).

The reference [1] is an article by a PhD student, written together with the Supervisor, and it defines and characterizes the phenomenon of self-heating of composite materials with polymer matrices. The paper discusses recent experimental studies and theoretical models in this field, taking into account S-N curves and hysteresis obtained at different ambient temperatures, examples of failure of composite machine elements caused by this phenomenon, phenomenological analysis of the self-heating taking into account changes in energy dissipation during the fatigue cycle, as well as methods of protecting polymer composites. From a practical point of view, the diagrams of failure of polymer fibrous composites presented in the paper, including polymer chains, and interesting photographic documentation of fatigue cracks in these composites, are important. A very important for engineering applications is the discussion of environmental aspects in practical operating conditions of composites, taking into account humidity and ambient temperature. Then, the authors present various literature positions and experimental research methods for fatigue analysis of polymer composites, discussing the

influence of different material and geometric design parameters on their fatigue life. This publication is extremely long (88 pages and 285 literature sources) and is a very good starting point for further experimental research. It testifies to the in-depth research of the literature on the subject, which the PhD student did before commencing his analyses.

The second three-author study contains a critical study of systems used in engineering practice to reduce the self-heating of polymer composites subjected to high-cycle fatigue loads. The leading topic in this work is the previously signaled selection of the component constituting the filling of such a polymer composite and its impact on the self-heating phenomenon. The tabular list of various solutions in this area stretches for almost 5 pages of text, and it includes glass and carbon fibers, but also currently developed carbon nanotubes. This publication also reports the relationship between the number of fatigue cycles and changes in the maximum temperature, as well as the dependence of the generated heat on the observed amplitude of maximum loads. This work, although extensive and insightful, does not present any original research of the PhD student in this area, but only a discussion of available models and composite solutions.

In the publication [3], created together with the Supervisor and Ms. Magdalena Lipińska from the Lodz University of Technology, the PhD student presents experimental research, as well as a numerical model of the fatigue failure phenomenon of a polymer composite subjected to low-cycle loading. A thermo-viscoelastic-elastic constitutive compound of such a material is formulated and used for this purpose using Prona series parameterized by frequency and temperature. With the use of such a mathematical apparatus, the amount of heat generated by the cyclic load of this composite is determined. Next, a three-dimensional numerical model is proposed by the formulation of the Finite Difference Method, in which the most important problem was to properly define realistic thermal boundary conditions. Next, an experimental stand for the study of the shear modulus of the composite and a procedure for processing the results created in the MATLAB computer algebra system, which was used to visualize the results and to regress the results of the experiments, were presented. The work is richly illustrated, e.g., by the dependence of temperature on fatigue cycles, which clearly shows the good correspondence of the created numerical model with the experiment carried out.

The book [4] was written by ten co-authors and is the fruit of international Polish-German cooperation. It deals with the thermomechanical fatigue of polymer composites reinforced with carbon fibers, in which the authors analyze the influence of low and ultrasonic frequencies. The polymer under analysis has a semi-crystalline structure. The analysis aimed to create a numerical model and conduct appropriate experimental studies. The computer simulation was performed using the ANSYS program, implementing the Finite Element Method, in which modal and

harmonic analyses were performed. The experimental tests carried out in this case were aimed at determining the emissivity of the tested composite and were carried out for about one million cycles. The attached photos show a three-point bending station with the use of a thermal imaging camera on a composite sample. Among the many valuable results, temperature-to-fatigue cycles dependencies, as well as various regression methods and results, from linear to double exponential. These approximations were aimed at determining the critical self-heating temperature of the composite as a function of fatigue cycles. These analyses were accompanied by images of the composite microstructure illustrating interlayer delamination in the tested samples. The conclusions show that the pattern of destruction of different samples showed significant similarities in the case of low and ultrasonic frequencies.

The next article [5] included in the series of publications was devoted to the issue of determining the fatigue resistance of the previously analyzed polymer composite with carbon fibers. The work was written with the participation of eight co-authors, and the research was sponsored as part of a research project with DFG. This model takes into account the self-heating of the material during cyclic loading, and the analysis was carried out using a 20 kHz bending test. This time, research analyses were purely experimental and were carried out using ultrasonic methods. As in the case of the previous work, a rectangular composite sample was tested, in which the initiation of the failure took place in the middle of the lower part of the material. Tests were performed with a constant load amplitude as well as with an increasing amplitude. A clear increase in the intensity of composite self-heating was noted with the additional increase in the number of fatigue cycles. A statistical analysis based on the existing experimental data series was a novelty in this work, but its relevance for statistical inference is limited due to the small number of samples. In the description of the research, you can find interesting information that the temperature to which the sample was heated up during the tests was about 80°C, which is a significant value. The remaining part of the work is devoted to the analysis of the effect of the interruption time of cyclic loads on the fatigue strength of the composite, as well as to the theoretical analysis of energy dissipation and its changes in order to determine the critical temperature of self-heating in this composite.

The thesis [6] written by the PhD student, together with the Supervisor, was devoted to the issue of thermomechanical fatigue life of polymer composites using the evolution of failure and reduction of stiffness caused by different vibration frequencies. An approach based on thermodynamic entropy was used, and a glass-epoxy composite of Polish production was analyzed. As in many other works, an analytical formula describing bending stresses in a composite sample was used to determine the S-N curves. The thermographic method already known from the previous works was used in order to determine the fatigue strength. The results

combining the increase in temperature and the increase in heat dissipation with the maximum stresses in the sample were subjected to bilinear regression analysis; In the further part of the work, regression was even carried out using three different tangent lines. Ultimately, a standard S-N diagram was developed in a statistical form, showing the permissible intervals of variation of the corresponding logarithmic functions for two selected frequencies of 40 and 50 Hz. In addition to various types of approximations, this work also includes thermographic analyses performed for different numbers of fatigue cycles. The thermodynamic entropy relationships shown for different levels of maximum stress as a function of fatigue cycles should be considered as unique results on the scale of the entire publication cycle. A clear monotonic increase in this entropy is presented, which increases exponentially at the end of the fatigue loading process. The last group of results shows the reduction of stiffness obtained as a function of fatigue cycles, and the relations describing the dynamic Young's modulus of the tested composite as a function of maximum stresses show a rapid decrease of this modulus at the end of the fatigue process. The results for the increase in entropy and decrease in the modulus of elasticity are consistent with the engineering intuition in this regard. This publication shows the PhD student's significant contribution to fatigue research, and also illustrates well his understanding of the experimental methodology used and the mechanism of destruction.

The publication [7] has only been submitted for publication, and its subject matter is related to the use of graphene wafers and nano-fibers and their effect on the thermomechanical fatigue life of modified glass-polymer composites. Since the work has neither been published nor has any review been attached, it will not be evaluated by the reviewer as its substantive content. Nevertheless, the subject matter seems extremely current and interesting, while the tools and methods used are known from previous research of the team to which the PhD student belongs.

In the last of this series of papers [8], the PhD student and three other co-authors analysed the process of destruction of composite panels using a non-destructive technique based on vibro-thermographic examination. This work contains both numerical and, above all, experimental aspects. In the field of computer simulation, a modal analysis was performed using the ANSYS Finite Element Method program, in which a rectangular plate with holes was modeled at several different thicknesses and different densities of meshes prepared using triangular finite elements. Further experimental analysis consisted of two stages, which included: (1) determination of the natural frequency of the plate vibrations and subsequently (2) analysis of the vibrations of the composite element subjected to excitation close to natural vibrations. The second stage was aimed at inducing the phenomenon of the self-heating of the composite and further analysis of the damage - for this purpose, thermograms were made, m.in, at different times of the tested process; As expected, the location of the damage occurred in the middle of the

tested plate. The graphs also show the temperature increments to which the composite element has heated up at a given time. In contrast to previous work, no analytical approximation of the experimental data obtained was proposed.

In summary, in the reviewer's opinion, the most important item should be considered the article [3] from this list, published in a well-known international journal, which presents only articles related to the issues of fatigue of engineering materials, whose editorial board gathers outstanding experts in this field of mechanics of materials.

### 3. *Assessment of the presented dissertation*

The presented dissertation is undoubtedly extremely extensive and richly illustrated both with its results and many available in the literature on the subject, as well as well embedded in the literature devoted to the subject of fatigue of composite materials. The reviewer, on the other hand, did not refer to the results discussed in the works of K. Reifsnider (e.g., W.W. Stinchcomb, K.L. Reifsnider, *Fatigue damage mechanisms in composite materials: a review*) and T. Yokobori, whose works are considered classical. However, the article [5] does not review probabilistic and stochastic methods in fatigue analysis, although this topic is well documented in the literature, even in Polish (cf. K. Sobczyk, B. Spencer, *Stochastic models of fatigue of materials*).

All the presented publications, as well as their description made by the PhD student himself, were written correctly from the linguistic and editing side, communicatively and clearly. Although a certain number of publications have many authors, the PhD student's contribution to each of them turned out to be significant. The editing errors of the dissertation undoubtedly include placing the table of contents in the middle of the initial part of the entire text, which makes it difficult to search the text. In addition, declarations regarding the quantitative contribution of the PhD student to individual articles that make up the presented publication cycle were included both at the beginning and the end of the dissertation. In the introduction, there is no research thesis that the phenomenon of self-heating in polymer composites subjected to cyclic fatigue loads can lead to a significant reduction in their stiffness and fatigue strength. Certain editorial defects, most likely resulting from the limited time for preparing the dissertation, do not have any significant impact on its overall assessment.

The presented series of publications with an introduction reflects the topic of the dissertation very well and is completely monothematic. The selection of publications that make up the dissertation was made distinctly, because according to the Google Scholar database, the PhD student had already co-authored seventeen articles (index *H*=6), *of which less than half of*

*the best papers well suited to the subject were selected. Looking at the entire output of the Candidate, it is difficult to resist the impression that a separate subject could be chosen from the other works, so he could be suitable for a habilitation dissertation. Undoubtedly, the substantive contribution to each of the publications presented in the series was relatively large, except for item no. 5, but this does not have a significant impact on the overall picture of* the Candidate's doctoral achievements and scientific effort.

It should be stated that the presented dissertation presents solid theoretical and experimental knowledge of the PhD student in the field of fatigue phenomena of polymer composites, taking into account the phenomenon of the self-heating. The method of determining stresses in the tested samples remains to be discussed during the public defense – the simple analytical estimation used has its limitations, which may partially affect the analyses carried out here. The scientific problem under consideration has been solved originally, and the results of the dissertation can be applied in the economic sphere, also on an international scale. This is evidenced by the high rank of each of the journals in which the subsequent results of the dissertation were published – half of the series was published in the highest-scoring journals in the selected discipline, which is rare. The attached publications and the PhD student's contribution to each of them indicate the ability to independently conduct scientific work in the discipline of Mechanical Engineering. An important aspect of this dissertation is the significant international cooperation, e.g., with the German research center in Freiburg, the Polytechnic University of Milan, and the University of Coimbra, which resulted in several interesting and important results. It proves the novelty and originality of the conducted and documented research.

During the completion of the dissertation, the Candidate demonstrated significant knowledge in the field of experimental research and techniques of their development, but also some preparation for numerical modeling. However, there is a certain shortage in the description of numerical analyses due to the lack of computational details – it is difficult to find specific information on the method of discretization, detailed parameters of computational processes, etc., but the high agreement with experimental models excludes substantive doubts. The PhD student uses the Finite Element Method and the Finite Difference Method interchangeably, but the main emphasis is on the experiment rather than on the calibration of the computer model. Unfortunately, the qualitative agreement between numerical modeling and experimental analysis without providing a detailed description of this modeling may be accidental and requires more detail. Numerical models show a certain sensitivity to computational parameters that the PhD student did not cite. However, this does not change the overall assessment of the presented doctoral dissertation, which is very good.

## 4. *Conclusion*

The presented dissertation by J. Amraei, M.Sc., in the form of a series of publications with an appropriately extensive description and abstract, meets the statutory criteria for doctoral dissertations listed in the Law on Higher Education and Science. In the Reviewer's opinion, it should be allowed for public defense. In addition, due to the nature and number of publications, as well as the PhD student's large contribution to their creation, as well as the prestigious nature of the journals in which they appeared, the reviewer applies for a distinction in the doctoral dissertation.

*Marcin Kamiński, Łódź, 15.05.2025*