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REVIEW

of doctoral dissertation M.Sc. Eng. TORKAN SHAFIGHFARD under the title "DIAGNOSTIC METHODS FOR FIBER REINFORCED COMPOSITE STRUCTURES WITH IMPERFECTIONS",
made under the supervision of Prof. Magdalena Mieloszyk, D.Sc. Ph.D. Eng.,
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Identification description: typescript signed by the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk (September 2023).
Formal and legal basis:
- letter (dated January 18, 2024, sent on January 19 this year; received by the reviewer on January 24 this year) signed by Dr. hab. engineer Grzegorz Żywica, prof. IMP PAN, Deputy Director for Scientific Affairs of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk,
- Act of July 20, 2018, Law on Higher Education and Science (Journal of Laws 2023, item 742, as amended) (Ustawa z dnia 20. lipca 2018 r. Prawo o szkolnictwie wyższym i nauce; Dz.U. 2023, poz. 742 ze zm.).

I. EVALUATION OF DOCTORAL THESIS

A. Introduction

The author's main intention was to investigate the possibility of using selected diagnostic techniques, mainly from the Structural Health Monitoring (SHM) and Non Destructive Technique (NDT) groups, to analyze changes in the mechanical properties of Carbon Fiber-Reinforced Polymer (CFRP), which may lead to material degradation. Attention was focused on the imperfections of fibrous carbon composites, both resulting from the applied manufacturing technology (e.g. voids, gaps, inclusions, delaminations, embedded FBG sensors) and resulting from the geometry of the object (e.g. holes intentionally introduced into the structure). The object of the research were composite samples produced by two technologies, namely: Additive Manufacturing (AM) and a plain weave composite produced by autoclave technology.

A variety of procedures, both experimental and modeling, have been used to study the composite process, including: Infrared Thermography (IRT), Digital Image Correlation (DIC) and Finite Element Method (FEM). Point Stress Criterion (PSC) and Extended Point Stress Criterion (EPSC) were used to predict the strength of woven composite structures. In addition, a fractographic method was also used to analyze damage initiation and damage propagation for different samples. In the final section, the possibility of using Machine Learning (ML) to reduce the time and cost of experimental and numerical work was presented. A new ML model using a large dataset was also applied, which was made possible by combining numerical simulation and Python Macro code.

The topic of the dissertation is closely related to the issue of composites, which is an area of intense scientific development, both in basic and applied research. The literature on the subject mentions three main types of modern composite materials, namely: polymer matrix composites, metallic matrix composites and ceramic matrix composites. The variety of matrix and reinforcement materials allows for a large number of possible combinations, and therefore types of materials. Modern polymer composite research generally covers a wide spectrum of aspects related to new matrix and reinforcement types, manufacturing technologies, processing, testing and characterization methods and applications. The number of publications in this field, found using, for example, the keywords "Recent research and developments in Polymer Matrix Composites" and for the years 2019-2023 alone, includes more than 15,000 items.

Synthetic and natural fibrous materials are widely used today as reinforcements for polymer composites to provide desired properties such as stiffness, static and fatigue strength, including for various loading conditions (e.g., torsional, axial and impact) found in structural components.

The dissertation under evaluation uses carbon fiber, which among many reinforcing fibers provides maximum specific strength and high stiffness. In addition, carbon fiber has high tensile strength over a wide temperature range. Carbon fiber also provides high thermal and electrical conductivity with a relatively low coefficient of expansion. Carbon fiber provides a tensile strength of 7GPa, and the axial compression strength is 15-60% of its tensile strength. In addition, they are difficult to melt, conduct electricity and are chemically inert. The stiffness and elastic modulus of carbon fiber are also much higher. These properties make it widely used in the automotive, electronics and aerospace industries and in many areas of the military sector.

The subject of resins is also richly represented in the literature. Resins are dense, viscous compounds that harden under heat to form a polymer matrix. Although resins represent naturally occurring substances, they are now mostly synthesized. In the dissertation, two types of resins were used to create composites, namely: Polylactic Acid (PLA) and epoxy resin (OM10).

Some of the results presented in the dissertation were obtained in cooperation with Kaunas University of Technology (Lithuania) and with the participation of the composite technologies center of excellence in Istanbul, Türkiye (KORDSA). It should further be noted that the research was supported by funds from the M-ERA.NET 2 Call 2019 project and a grant funded by the scientific and technological research council of Türkiye (TÜBİTAK).

It should be stated that the subject matter of the issue undertaken is interdisciplinary in nature and is located in the area of mainly Mechanical Engineering and partly Materials Engineering.

The author succinctly presented the current state of knowledge in the field of the subject matter covered in the dissertation, quoting representative and well-chosen works for this purpose. On this basis, the Doctoral Student formulated the thesis, objectives and main tasks to be undertaken in the dissertation. He then described the methodology of his own research, as well as the results obtained. The dissertation was concluded with a summary and conclusions of the research.

Summarizing at the outset the intentions of the author of the paper and taking into account the state of knowledge, it should be assumed that the issue of the possibility of using selected diagnostic techniques to analyze the change in mechanical properties of Carbon Fiber-Reinforced Polymer (CFRP) is a current and important issue in the field of basic and applied research. This is due to the complexity of the phenomena occurring during the technological process and the need for an interdisciplinary research workshop to learn and interpret these processes. Taken together, this allows us to conclude that the choice of research topics contained in the submitted dissertation is fully scientifically and applicationally valid.

B. Characteristics of the work

The dissertation submitted for evaluation is divided into 6 chapters and 62 sub-chapters, which also includes a summary and discussion with final conclusions. In addition, the work includes an abstract, acknowledgments, a list of papers co-authored by the doctoral student, a list of abbreviations, tables and figures or photos, and a list of cited literature on the subject. The monograph includes 109 pages, 57 figures or photos and 16 tables. The list of cited literature includes 124 items. The publication output co-authored by the doctoral student includes 12 journal papers, 7 of which are on other topics (reinforced cementitious composites), 1 book chapter and 2 conference papers.

The submitted dissertation is briefly characterized below.

The first chapter (Introduction) highlights the roles and advantages of laminated fiber-reinforced composite con- structions, their areas of application, and challenges in technology and manufacturing costs. It was emphasized that understanding the degradation pro-cesses under different loading conditions of composites requires further scientific efforts in the fields of materials, technology and design. In doing so, work in the area of predictive models was considered particularly important.

The extensive second chapter (State Of The Art) characterizes the state of current knowledge in the field of composites and exposes new trends, including the possibility of manufacturing composite products using Additive Manufacturing (AM) technology in combination with Structural Health Monitoring (SHM) through the use of Fiber Bragg Grating (FBG) fiber optic sensors. It was recognized that in this way it is possible, on the one hand, to take advantage of the strengths of AM (fabrication of objects layer by layer from a digital model, minimization of waste, easy fabrication of complex shapes), and at the same time, using SHM - to eliminate process limitations (e.g., structural defects) and monitor degradation processes (e.g., change of physical properties, cracking, etc.).

The state of AM development was briefly characterized, highlighting the existence of more than 30 detailed technologies in this field. The drawbacks of existing AM technologies and ways to overcome them were also highlighted. Fused Deposition Modeling (FDM) was considered a particularly promising technology for CFRP composites, and numerous works in this field, including those from the Gdansk center, were cited.

The strengths of fiber-optic sensors as well-known SHM tools for measuring strain and temperature, including in composites, are outlined. The sensors' resistance to various disturbances was highlighted. The work of the Gdansk team in this area was highlighted. Attention was drawn to the various possible ways of embedding FBG sensors in composite structures fabricated by FDM technology and the resulting post-measurement limitations.

Next, canvas-weave composites with two interacting notches were characterized. This is because the case with holes is characterized by a decrease in strength due to stress concentration around the notches. The role of numerical modeling techniques in understanding the stress state and degradation processes in such objects is highlighted. Anticipated advances in numerical modeling in this area will be associated in the near future with the increase in computational power of compu-rters and with sophisticated new algorithms. On the other hand, the vast amount of digital data will prompt the use of Machine Learning (ML) and Artificial Intelligence (AI) in the modeling process. The state of the art in the application of ML in the field of composites is also characterized.

The final section formulates the purpose of the work, assuming that it is to investigate the applicability of diagnostic techniques (SHM and NDT) for FRP components manufactured by standard and incremental methods. The occurrence of imperfections (voids, gaps between fiber bundles, delamination, holes, etc. or inclusions in the form of embedded optical fibers with FBG sensors) was taken into account.

and the following thesis:

It is possible to continuously monitor the loading and degradation processes of FRP composites using SHM and NDT diagnostic methods.

The specific challenges addressed in the thesis and the questions that need to be answered, which are related both to the consequences of embedding FBG in a composite manufactured with FBG technology and to a number of aspects concerning the modeling and sy-mulation of so-called AM smart composites, are also summarized.

The third chapter (AM for CFRP embedded FBG) presents an AM method for fabricating CFRP samples with embedded FBG sensors, followed by a discussion of the thermal loading test and numerical simulation using ABAQUS. The FDM method was modified by replacing two separate heads (for polymer and fiber) with one designed for pre-impregnated fiber.

The fabricated CFRP samples consisted of four layers of polylactic acid (PLA) matrix and continuous carbon fiber reinforcement. To determine the effect of the embedded FBG sensor on the durability of the material, five different samples were produced without optical sensors, while five contained them. The number of samples was selected to meet the requirements of statistical testing. The primary axis of the samples was parallel to the orientation of the FBG sensor, and the polymer sample was reinforced with carbon fibers (Toray T300B-1000). A 25% volume fraction of carbon fiber was used in all fabricated samples. The study of the effect of temperature was divided into two parts: elevated temperature increasing from 10 ◦C to 50 ◦C and sub-zero temperature decreasing from 10 ◦C to -50 ◦C. FEA using ABAQUS CAE software was used to describe the thermal properties of the CFRP samples and compare them with experimental results. The specimens (without heat treatment and after heat treatment) were subjected to tensile testing. The tensile test was carried out on groups of specimens of five from each case. Its purpose was to determine the effect of embedded optical fiber on the durability of the FRP material. It was observed that FBG sensors have no effect on mechanical strength and fracture mechanism.

The fourth chapter (Application of multi-instrument techniques) discusses the application of various NDT methods for evaluating the tensile strength of canvas weave composites. Numerical tests were also conducted and the possibility of using PSC (Point Stress Criterion) and EPSC (Extended Point Stress Criterion) criteria was explained. The object of the research was impregnated carbon cloth with a canvas weave, which was purchased from KORDSA in Türkiye. Samples were produced by curing the composite in an autoclave. For the two-notched specimens, three hole configurations were considered, while maintaining, however, the diameter and distance between holes. An Instron 8853 universal testing machine was used to test all specimens, and a passive infrared camera (FLIR) IRT system was used to record specimen temperature. As a supplement, macroscopic fracture morphology was examined. In addition, DIC was used to analyze the strain field. In addition, the fracture surfaces were also examined under a stereoscopic microscope. Commercial Abaqus/CAE software was used to perform the numerical analysis. The FEA simulation results were compared with the experimental results of the tensile test for five specimens for each hole configuration.

The fifth chapter (Stacked Machine Learning model) presents the possibility of using ML to predict maximum stresses in composite structures with a canvas weave, especially where holes occur. It was assumed that a correctly selected ML model would enable a reduction in the cost of experiments and the time required for numerical simulations. At the outset, the ML technologies currently in use were reviewed. Then the necessary dataset was generated using numerical simulations and Python Macro code. Simulations were carried out for different hole configurations in the composite specimen. Three ML models were analyzed in detail. One of them (labeled Model II) was found to be the best.

In the sixth chapter (Summary and Conclusion), the author's summary of the dissertation was made and it was concluded that the dissertation's goal had been achieved and the thesis proven. In the conclusions, detailed reference was made to the possibility of using Additive Manufacturing (AM) technology to produce CFRP composites with embedded FBG sensors, plain-weave composites with two interacting holes, as well as Machine Learning (ML) methods on composites with holes. In addition, further scientific work was suggested that could enrich the results achieved by the PhD student.

C. Critical remarks, questions and suggestions

While generally sharing the opinion that the thesis adopted in the dissertation has been proven and the stated goal achieved, the following critical remarks, questions and suggestions are summarized below:

1. The composite produced in the thesis by Additive Manufacturing (AM) technology, despite its innovation, was characterized by a very low proportion of fiber in the composite. Indeed, the Fiber Volume Fraction (FVF) was only 25%. Typical CFRP composites produced by technology such as Filament Winding allow FVF in the range of 40% to more than 60%, depending, for example, on the strength of the fiber tension. What, then, are the real possibilities of application of the composite obtained by the doctoral student, in which the share of resin is dominant?
2. The FBG sensor placed during the manufacturing of the composite by printing method shrank along with the composite after the printing was completed and the temperature was lowered. This may have affected the correctness of subsequent

measurements when the samples were stretched. So how was the initial shrinkage of the FBG sensor compensated for?

3. The use of linear FBG sensors to study the planar or triaxial strain field in composites, especially in specimens where one size (length) dominates the width and thickness has rather limited possibilities. It seems that it would be more pertinent to use highly-birefringent optical fibers (HB FBG) sensors. What is the Doctoral student's opinion on this issue?

An example of a publication in this area below.

- *Wachtarczyk, K., Gąsior, P., Kaleta, J., Anuszkiewicz, A., Bender, M., Schledjewski, R., ... & Osuch, T. (2021). In-Plane strain measurement in composite structures with fiber Bragg grating written in side-hole elliptical core optical fiber. Materials, 15(1), 77.*

4. Table 4.2 (Average mechanical properties of the manufactured specimens) summarizes the stiffness matrix parameters for composite specimens manufactured at KORDSA in Türkiye. Experimental determination of the directional moduli Eij, Gij and νij for the composite is a complex issue. Hence the questions:

- were the E, G and ν moduli determined by the sample manufacturer?
- if, on the other hand, they were determined by the PhD student himself, how were the E22, G12, G23 and ν12 moduli determined ? This is because the limitations of the measurement capabilities of methods such as FBG or DIC are known. Was any material model used to determine the moduli ?

5. The dissertation largely deals with the issue of digital modeling of the mechanical properties of fiber-reinforced composites. One of the intensively developing approaches in this area is the so-called homogenization and determination of the composite stiffness matrix on this way. This approach was not mentioned in the dissertation in the literature review. What is the doctoral student's attitude to such procedures?

Below are only selected examples of the very extensive literature in the field of analytical and computational homogenization of composites (including co-authors from Türkiye):

- *Firooz, S., Steinmann, P., & Javili, A. (2021). Homogenization of composites with extended general interfaces: comprehensive review and unified modeling. Applied Mechanics Reviews, 73(4), 040802.*
- *Hashin, Z. (1983). Analysis of composite materials—a survey.*
- *Kanouté, P., Boso, D. P., Chaboche, J. L., & Schrefler, B. (2009). Multiscale methods for composites: a review. Archives of Computational Methods in Engineering, 16, 31-75.*
- *Matouš, K., Geers, M. G., Kouznetsova, V. G., & Gillman, A. (2017). A review of predictive nonlinear theories for multiscale modeling of heterogeneous materials. Journal of Computational Physics, 330, 192-220.*
- *Błachut, A., Wollmann, T., Panek, M., Vater, M., Kaleta, J., Detyna, J., ... & Gude, M. (2023). Influence of fiber tension during filament winding on the mechanical properties of composite pressure vessels. Composite Structures, 304, 116337.*

6. The reviewer read with great interest and appreciation the section of the monograph on the possibility of using ML to predict stresses in composite structures. The topic is the subject of many contemporary scientific works. Since this scope of the study does not coincide with the reviewer's core competencies, neither did he make any comments or suggestions. However, bearing in mind that the doctoral student's achievements in this area have been published in reputable journals with a high Impact Factor (IF) - the reviewer considers this aspect of the dissertation to be well documented and subject to solid scientific discussion.

II. EVALUATION OF THE TOTAL SCIENTIFIC ACHIEVEMENTS OF THE DOCTORAL STUDENT

The publication output co-authored by the Doctoral Student includes 12 journal papers, 7 of which deal with other topics (reinforced cementitious composites), 1 book chapter and 2 conference papers. Particularly noteworthy is the fact that the total Impact Factor (ΣIF) of all published or peer-reviewed papers is almost 90, and for papers in the field covered by the subject of the doctoral dissertation, more than 23. Such output in Poland corresponds to scientists with a status much higher than that of a doctoral student. This allows us to unequivocally state that the total output, in comparison with the achievements of other doctoral students known to the reviewer, is very large and distinguished - with respect to candidates for the doctoral degree in the discipline of Mechanical Engineering.

III. CONCLUSION

The presented thesis with the title "Diagnostic Methods for Fiber Reinforced Composite Structures with Imperfections", taking into account the comments made previously, I evaluate unequivocally positively. The thesis set forth in the dissertation has been proven and the goal has been achieved. The topic of the dissertation is scientifically and applicationally up-to-date. In turn, the doctoral student's scientific achievements meet the requirements for doctoral theses in the discipline of Mechanical Engineering.

Taking into account all the above-mentioned aspects, I conclude that the work presented for evaluation meets the requirements of the Act on Scientific Degrees and Academic Title, dated 20. July 2018. (Law on Higher Education and Science, Journal of Laws 2023, item 742, as amended; in Polish: Ustawa z dnia 20. lipca 2018 r. Prawo o szkolnictwie wyższym i nauce; Dz.U. 2023, poz. 742 ze zm.) and may be the basis for the award of the degree of Doctor of Technical Sciences in the discipline of Mechanical Engineering. At the same time, I request that the reviewed dissertation be admitted to public defense.

In addition, taking into account the particularly rich publication output of the Doctoral Student, including and in the area closely related to the dissertation – I request that the dissertation be awarded.

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