Fatigue Testing of the Small Wind Turbine Blade

Karol Zawadzki, Anna Baszczyńska, Angela Fliszewska, Szymon Molenda, Jakub Bobrowski, and Michał Sikorski
Institute of Turbomachinery, Lodz University of Technology, Lodz, Poland
Email: 211043@edu.p.lodz.pl, {222627, 222640, 208727, 223903, 222567}@edu.p.lodz.pl

Abstract—**Blades are the elements of a wind turbine which are the most vulnerable to destruction. Facing the unstable wind (one that changes its speed and direction), they are subjected to cyclic and fluctuating loads. This problem is particularly pronounced in case of small wind turbine (SWT) blades or blades for wind tunnel tests in scale, which are oftentimes made of anisotropic materials or manufactured in a way leading to anisotropy, like 3D-printing. SWT blades have to be designed in a way which will allow them to operate for a long time without any fracture. Hence, the fatigue strength is a key parameter, which determines their operation time and should be tested before putting a wind turbine into operation.**
The aim of this paper is to describe the methodology of fatigue tests of the small wind turbine blades. Next, the construction of the fatigue test stand and results of the experiment will be examined.

Index Terms— **mechanical testing, fatigue strength, wind turbine blade, 3D printing, S-N curve, materials science**

I. Introduction

Wind turbine blades, subject to strong winds, lightning strikes, foreign object impacts, may experience different modes of failure. In this paper, the procedure of wind turbine blade fatigue testing is described. Fatigue is a localised material damage process caused by cyclic loading. This process comprises cha nucleation, crack propagation and final fracture of a specimen [1].

The crack nucleation is initiated at stress concentrations, such as material discontinuities, pores, inclusions, notches, and grain boundaries. 3D-printed structures are among those particularly prone to cracking. Specimens manufactured via the procedure of filament deposition are characterised by high porosity and significant surface roughness. These features favour crack initiation [1].

An increasing presence of 3D printing techniques in fabrication of wind turbine components increases the proneness to this kind of fracture, as they result in creation of highly anisotropic structures. Once crack nucleation has occurred, cyclic stresses stimulate further crack growth. In the second stage, crack propagation is governed by the microscopic material properties, since the crack size is comparable to the material microstructure. In 3D-printed specimens, the crack grows in the interlaminar plane, since the strength of the specimen is compromised at the junction of two adjacent laminae. Eventually, long crack causes structural failure [1].

There have been several studies on fatigue testing of 3D-printed specimens. Padzi et al. [2] indicated that 3D-printed ABS specimens exhibit vastly inferior mechanical properties (both in terms of fatigue and mechanical strength) compared to their moulded counterparts. Ezeh and Susmel [3] showed that 3D-prints made of PLA may achieve similar performance compared to the traditional moulds, however it is highly dependent on the manufacturing angle (angle between the filaments and the axis of the specimen in tension) and on the infill percentage.

To the best knowledge of the authors, fatigue testing of 3D-printed wind turbine blades has not yet been described in the literature. This may be due to several reasons. Firstly, the technology of 3D printing has gained popularity only in the last few years. Secondly, wind turbine blades are usually made of fibre reinforced polymers (FRP), compared to which 3D-prints show inferior mechanical properties. However, authors assume that the procedure of fatigue testing of 3D-printed wind turbine blades is similar to the methodology of the fatigue examination of FRP blades.

Greaves et al. [4] defined two main directions of wind turbine blade bending – flapwise (excited by lift and drag) and edgewise (excited by non-aerodynamic forces, e.g. centrifugal force or gravity). Moreover, they performed a numerical fatigue test (simulation of cyclic bending in two aforementioned directions simultaneously, with the use of the finite element method) to assess the magnitude and location of structure damage after service life. Al-Khudairi et al. [5] examined experimentally the fatigue strength of a full-scale glass fibre reinforced polymer wind turbine blade. The test consisted of the static flapwise bending (for calibration), modal testing and finally, cyclic flapwise bending (fatigue testing). This was performed by application of the load to two saddles located on the blade. The visual and acoustic emission (AE) damage inspection allowed to assess the crack propagation in the structure. For the purpose of the fatigue analysis simulation, the dedicated software can be applied as well, which was done by Teixeira et al. [6]. The special MATLAB application was used to emulate the cyclic blade loading and basing on obtained results, create the S-N curve (see Section 2).

Wind turbine blades can be made of glass/carbon/aramid fibre reinforced polymer [5] or with

Manuscript received October 21, 2021; revised January 24, 2022.

doi: 10.18178/ijmerr.11.4.269-274

the use of 3D print technology. Creating blades with the use of a 3D printing technique has a big potential in terms of sustainability [7]. 3D printers are devices that can be easily transported to any region. Moreover, they allow to create scaled models for tests in a relatively easy way and short time [8]. In order for wind turbine to be profitable, blades need to last over 20 years without any major failure [4]. At the same time, it is impossible for the wind to blow continuously in the same manner. Hence, the wind turbine blades need to withstand cyclic and fluctuating loadings of the wind [6]. Hence, every blade of a wind turbine ought to be tested for fatigue strength before putting them into operation. This requires a specially designed device, allowing to estimate, with an adequate accuracy and low time-to-results, the fatigue strength of the examined blade [9].

At the Lodz University of Technology, the student's Project GUST also decided to address the issue. The main intention for conducting the research was to develop a method for the stress-deflection curve determination for 3D printed blade to define fatigue strength during the flapwise bending (see Section 2). A special test stand was designed, which can emulate blade deflection under different wind conditions. This makes it possible to count the number of cycles until blade failure, a fundamental parameter when it comes to fatigue strength. The aforementioned blade is the part of the horizontal axis small wind turbine (SWT) built by GUST for the purpose of tests at the International Small Wind Turbine Contest (ISWTC) in the Netherlands. The GUST small wind turbine is aimed to be used by individual consumers (prosumers) – therefore, comparing to commercial wind turbines, the GUST SWT dimensions are relatively small (rotor diameter: 1.6 m, maximum power: 460 W [10]).

II. METHODOLOGY

According to the European standard on the full-scale structural testing of wind turbine rotor blades [11], the test procedure should be composed of the following measures:

- Mass, centre of gravity and natural frequencies determination,
- Static tests,
- Fatigue load tests,
- Post-fatigue static tests.

The main topic of this paper is the fatigue load tests, therefore this issue will be examined in detail. All remaining measures listed above will be discussed as well, but in the brief and concise way.

A. Blade Geometry Description

The aerodynamic design of the blade plays a crucial role in the operation of a wind turbine. The geometry of the GUST wind turbine blade is based on two NREL aerofoils (Fig. 1): S834 in the sections directly connected to the hub and S826 along the blade span.

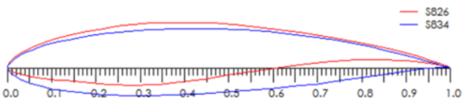

Figure 1. GUST SWT aerofoils.

The blade is the element of a wind turbine most challenging to manufacture. It is the most heavily loaded and most prone to failure, so it is crucial for the whole system to ensure it works properly. The selected material should be lightweight to reduce the moment of inertia and centrifugal forces during operation of the rotor. However, when selecting a technology, several additional factors had been taken into account by the Team: durability, the possibility to produce large-sized components (GUST SWT blade length with mounting part is 770 mm), adequate accuracy, surface quality and low price. Finally, Protogen White was used to produce full-scaled blades [12]. This is a liquid, ABS-like, white coloured photopolymer that is suitable for general purpose applications. It may be characterized with high toughness and durability, together with good surface quality and thermal properties. Blades for ISWTC editions 2017 to 2019 model were manufactured from this material.

The blade investigated during the experiment is the scaled (1:4) model of the abovementioned existing blade and is equipped with a winglet to enhance its aerodynamic properties [13].

The length of the blade is equal to 195 mm and its centre of gravity is at the distance 54 mm from the rotor axis of rotation. The model of investigated blade is presented in Fig. 2.

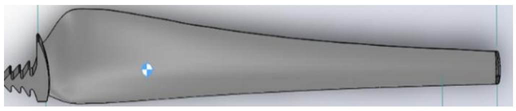

Figure 2. 3D model of the investigated blade, dot marks the centre of gravity location.

The design process of scaled blades consisted of creating a model in the Solidworks 2018 software. After that, the geometry was processed using the Z-suite 2.4.0.0 software for 3D printing of the blade models. FDM (Fused Deposition Modelling) technique was used, employing a Zortrax M300 filament printer (filament diameter: 1.75 mm ± 0.05 mm). The time of printing of the set of three blades was equal to approximately 11h – 12h. The used material was ABS plastic. The anisotropy of the blade comes from the fact that the model consists of layers of plastic that were applied in parallel one on another, thus the blade does not have a uniform structure. As a rule of the thumb, the consecutive layers should not be added in the radial direction, so as to avoid the destructive action of centrifugal forces.

B. Natural Frequency Determination

In the experiment, the natural frequency of the blade subjected to deflections in two bending directions (flapwise and edgewise, Fig. 3) was determined.

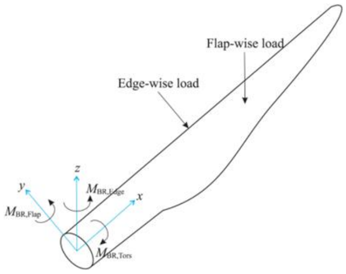

Figure 3. Flapwise and edgewise bending of the blade [14].

For the purpose of natural frequencies determination, a special force acquisition system, composed of two parts, was adapted. The first part contains an adaptor, used to set and fix the blade (Fig. 4).

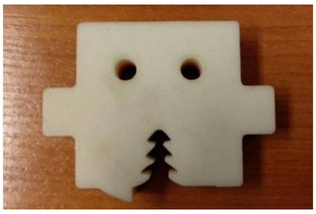

Figure 4. Adaptor fixing the blade.

The second part is high-frequency force acquisition system connected to PC, which is used to record the signal. The system used Daqview software to acquire all three force components.

In order to diminish the acquisition system's error, the forces under different sampling frequency (4000 Hz, 5000 Hz, 8000 Hz, 10000 Hz) and different sampling time (5 s, 10 s, 20 s) were recorded. Using the FFT (Fast Fourier Transform) algorithm in MATLAB, the natural frequencies in aforementioned directions were determined. Results are presented in Fig. 5 (4000 Hz sampling frequency and 10 seconds sampling time). As shown in the frequency domain graph, the first natural frequency is equal to 41.8 Hz, while the second – 115.4 Hz. It turns out that these values are similar to the outcomes obtained from analogous analyses performed for another wind turbine blade [15].

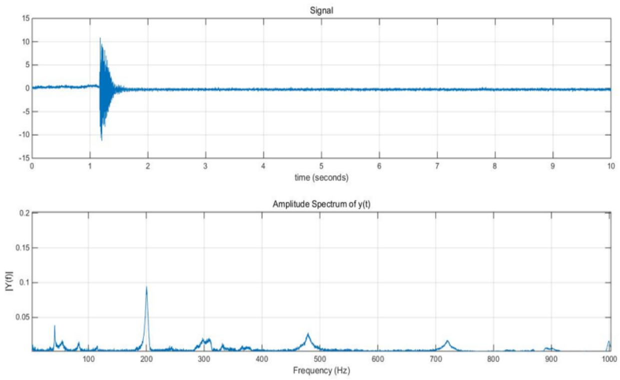

Figure 5. Natural frequencies determination.

C. Static Tests

In order to perform simplified static load tests, the single-point load was applied to the tip of the blade, to produce the biggest bending moment at the root of the blade.

One of the most important outcomes of the static tests is the value of the limit load that can be applied to the blade, which in the tested case is equal to 5 N. It produces the ultimate stress Rm equal to around 50 MPa, causing the damage of the blade. The investigated specimen has been broken down in its weakest cross-section, which is located near the root of the blade and is shown in Fig. 6.

Figure 6. GUST SWT scaled blade after static tests.

For the purpose of the test bench for fatigue testing (for more details see Section 2.4), deflections at different loads (starting from 0 N, up to the aforementioned limit load, equal to 5 N) have been measured. Outcomes are presented in Table I and will be used for the purpose of the test bench design.

TABLE I. TYPE SIZES FOR CAMERA-READY PAPERS

Load [N]	Blade deflection [mm]
0.2	10
0.6	20
0.8	25
1.0	30
1.2	35
1.4	40
1.8	45
2.0	50
2.8	60
3.4	70
5.0	80

D. Fatigue Tests and Experimental Bench

The method of the fatigue strength examination is based on the following procedure:

- a certain load is applied to the blade (by imposing the blade deflection),
- the blade is bent a certain number of cycles until the fracture occurs.

Higher load applied (and, consequently, higher stress amplitude) decreases the number of cycles necessary to destroy the specimen. Having several values of ultimate stress amplitudes and numbers of cycles corresponding to them, the global dependence between different loads values and number of cycles can be determined. This correlation is logarithmic and is called S-N curve (sometimes also Wöhler curve). Starting from the ultimate stress Rm (which will cause the failure immediately), the loads are gradually decreased until the appropriate shape of the graph is obtained, which will allow to determine the horizontal asymptote. Stress amplitude marked by this asymptote is the fatigue strength. The exemplary S-N curve is shown in Fig. 7.

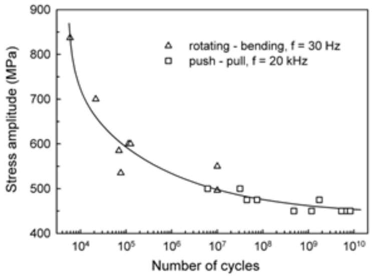

Figure 7. An exemplary S-N curve [16].

The experimental stand (Fig. 8) was constructed in a way that allowed to impose and count the number of cyclic loadings bending the blade flapwise. It consists of:

- Motor and housing,
- Fly-line and pulleys,
- Jaw,
- 2-phase stepper motor,
- Arduino board connected to the motor and computer.

The part which is directly responsible for setting the load and displacement is the motor (2-Phase Hybrid Stepper Motor – model 17HS4401). Rotation movement of the motor is translated by the beam – roller system (1) into linear movement of the beam and fly line attached to it. The latter goes along the pulleys (2) and is attached to the jaw (3). This part is put directly on the blade so that displacement given by the motor and transported by the fly line to the jaw results in the deflection of blade (4).

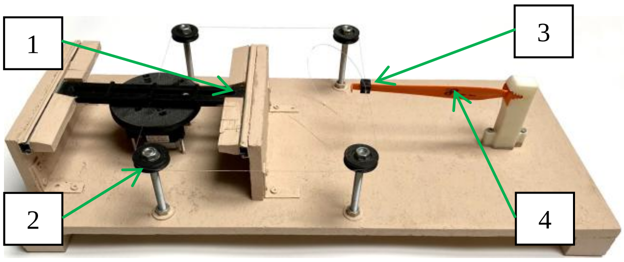

Figure 8. General view of the fatigue test stand.

The base of the stand is a plywood board with dimensions 624 x 268 x 90 mm (Fig. 9). In between walls (5), in the centre, the stepper motor (6) is attached to the board. On top of the motor sits a rotating disc (7) and a beam (8).

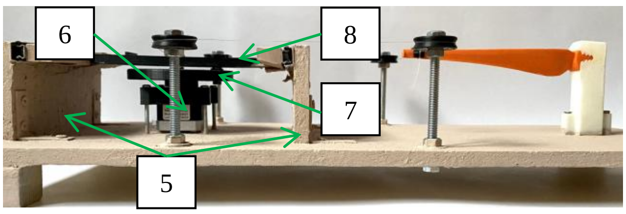

Figure 9. Side view of the test stand.

The rotating disc is linked to the beam by a screw connection (marked by a blue arrow in Fig. 10) through one of the 6 holes (9). The holes are located at different distances from the centre and allow to set different blade deflections (20, 25, 30, 35, 40 and 45 mm; red arrows in Fig. 10), which correspond to particular bending forces presented in Table I. Underneath the beam (8), the fly line (10) is led, which later goes through 4 pulleys that are mounted on the base.

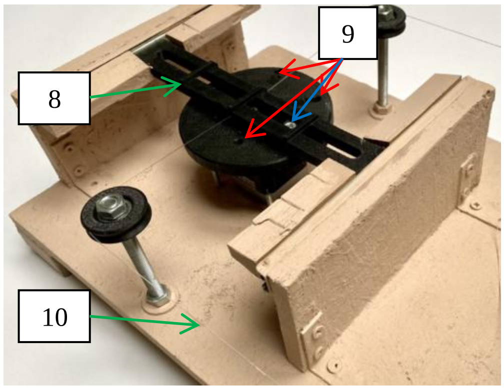

Figure 10. Part of the test stand with the motor and the disc

The fly line (10) is connected to the jaw (3) from both sides (Fig. 11). On the other side of the base there is a holder (11). Blade (4) is put into it with a jaw on the tip of it. Rotating disc, the beam and pulleys are all printed in 3D (manufactured by means of FDM method using ABS material), alike the blade.

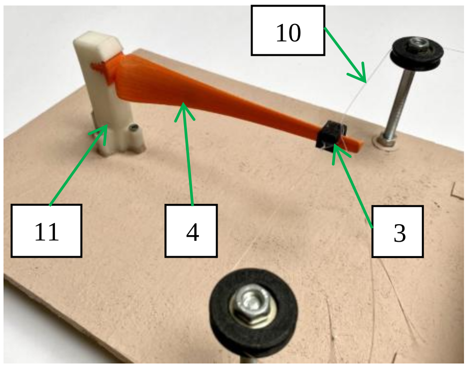

Figure 11. Jaw and pulleys.

The jaw is a part of the system that is in the direct contact with the investigated blade. The basic goal of this component is to impose the load directly on the blade to cause the deformation. The jaw allows to avoid undesirable dissipations of the force set by the motor, produced for instance by the friction. The jaw was designed in such a way that it could be easily put at the tip of the blade. Its model is shown in Fig. 12.

Figure 12. CAD model of the blade and the jaw.

The flapwise direction of blade bending is considered as the one, which has the biggest influence on the fatigue strength of the structure. The test (i.e. the deformation) was performed in the horizontal plane – to avoid the influence of gravity force and weight of the jaw on blade deformation in the flapwise direction.

III. Results and Discussion

According to the abovementioned assumptions and the original project, the motor–powered device, performing bending of the blade in the flapwise direction was constructed. The presented conclusions arise basing on achieved results. All blades used in both test series (see Table II) were assumed to be identical – the same printing time, printing settings, as well as identical materials were used. The direction of the applied bending forces was the only difference.

TABLE II. Description of the Performed Test Series

	Displacement [mm]	Time until fracture occurence	Cycles
1.	35	53h 39min	241,425
2.	35	116h 52min	525,900

In the first test series, the fly line attached to the jaw and blade did not lie ideally in a horizontal surface. It was influenced by the fact that the blade was located approximately 2 centimetres higher in the holder, than the blocks on which the wire was mounted. Thus, there appeared two force components: vertical and horizontal one. This resulted in destruction of the specimen after 241,425 cycles. The number of cycles was approximately 2 times smaller compared to the second test series (blade positioned horizontally with respect to the fly line mounting). It means that thus applied force (at an angle to the horizontal direction) causes greater fatigue and stress compared to the force applied exactly in the horizontal plane. In the latter case, corresponding to the second test, the fracture occurred after 525,900 cycles. Since the initial assumptions stated that the bending force generated by the wind should lie in a horizontal direction, it was expected that the biggest bending moment would appear at such conditions (i.e. the flapwise direction, which is said to be the most significant regarding the fatigue of the wind turbine blade).

The above remarks impose an important conclusion: force put in the horizontal direction does not generate the biggest fatigue and the original conjecture may be imperfect. To assess fairly the fatigue strength of a blade, the fatigue test should be conducted, when in each cycle the maximal equivalent stress will be produced. Such specification requires to put a cyclic bending force not in a flapwise direction, but rather in the combination of flapwise and edgewise directions – in such a way that the maximal equivalent stress will occur during each single cycle. This approach can actually potentially also lead to determination of the fatigue strength of the blade and will make the experiment more realistic, since the wind can blow in any direction, causing many combined stresses in the blade. The biggest equivalent stress should be firstly determined analytically, to obtain the direction of force causing it. Then, in the future steps, the stand could be modified in a way, which will allow to attach fly lines to the blade in a determined direction. This could establish the potential ways of improvement of the measurement stand, as well as the methodology of the experiment itself.

To compare and analyse the obtained results further, they were compared with the experimental data presented in [17]. Destruction of the tested blade occurred in the similar location compared to the blade described in the cited article – at its root (Fig. 13). Damage in this location was adversely affected by a much smaller blade thickness compared to the rest of the geometry. In order to increase the strength of the blade in this area, the proposed solution is to change the geometry of the blade's base so the place where the damage has occurred would be thicker.

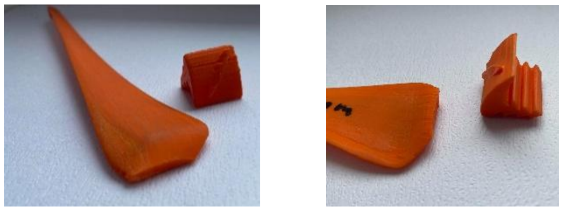

Figure 13. Fracture of the tested model.

Another thing that may have a positive influence on extending the life of the blade is to change the material used in production. The device used in the conducted experiment is suitable for testing blades made of any material. The material used during the 3D printing process is ABS filament, though the use of a composite structure could potentially result in increasing the durability of the element [17,18].

IV. Summary

The purpose of the research was to design an effective procedure for testing the fatigue strength of the wind turbine blade, as well as to simplify the mechanism to allow to test a blade model and assess the collected results. These requirements were satisfied, due to the simplicity of controlling the amount of cycles executed, as well as the deflection from the initial position. Also, the conducted tests are relatively easy to carry out, and the stand itself is quite easy to construct.

Conducting fatigue tests of wind turbine blade is crucial due to the need to withstand changing wind forces and directions during their lifecycle, which affects their fatigue character. Therefore, an important conclusion has arised – force applied at an angle to the horizontal direction causes greater fatigue and stress compared to the force applied exactly in the horizontal plane. In other words, force put in the horizontal direction does not generate the biggest fatigue and the original conjecture may be imperfect. In order to produce the maximal equivalent stress, putting a cyclic bending force not in a flapwise direction, but rather in the combination of flapwise and edgewise directions are required during each single cycle.

The experimental setup has an additional potential for scaling-up, so the regular-sized SWT blades can be tested. This may result in collecting data needed to assess the lifespan of different types of blades, vital for the eventual future commercialisation of the prototype.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed to the research and article. In particular, Karol Zawadzki was responsible for the development of the test procedure and methodology, as well as for the general outline of the article. Anna Baszczyńska was responsible for the mechanical design of the test stand and determination of the blade natural frequencies. Angela Fliszewska and Szymon Molenda conducted the experiments (static and fatigue), collected results and formulated conclusions. Michał Sikorski and Jakub Bobrowski were engaged in the theoretical background and research gathering.

Acknowledgment

The authors wish to thank the GUST Team supervisors: Michał Lipian, PhD and Michał Kulak, PhD for their support in conducting the research and writing the article.

References

[1] Y. Lee, J. Pan, R. Hathaway, and M. Barkey, *Fatigue Testing and Analysis, 1st ed., Theory and Practice*, Butterworth-Heinemann, 2004.

[2] M. M. Padzi, M. M. Bazin, and W. M. W. Muhamad, "Fatigue characteristics of 3D printed acrylonitrile butadiene styrene (ABS)," in *Proc. IOP Conference Series: Materials Science and Engineering* vol. 269, 1, IOP Publishing, 2017.

[3] O. H. Ezeh and L. Susmel, "On the fatigue strength of 3D-printed polylactide (PLA)," *Procedia Structural Integrity*, vol. 9, pp. 29-36, 2018.

[4] P. R. Greaves, R. G. Dominy, G. L. Ingram, H. Long, and R. Court, "Evaluation of dual-axis fatigue testing of large wind turbine blades," in *Proc. the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* vol. 226, no. 7, pp. 1693-1704, 2011.

[5] O. Al-Khudairi, H. Hadavinia, C. Little, G, Gillomore, P. Greaves, and K. Dyer, "Full-scale fatigue testing of a wind turbine blade in flapwise direction and examining the effect of crack propagation on the blade performance," *Materials* vol. 10, no. 1152, 2017.

[6] R. Teixeira, P. Moreira, P. Tavares, J. Correia, M. M. Calvente, A. M. P. de Jesus, and A. F. Canteli, "Fatigue analysis of wind turbine blades," in *Proc. 2nd International TU1304 Winercost Conference*, 2017

[7] M. Lipian, M. Kulak, and M. Stepien, "Fast track integration of computational methods with experiments in small wind turbine development," *Energies*, vol. 12, no. 9, p. 1625, 2019.

[8] M. Lipian, I. Dobrev, M. Karczewski, F. Massouh, and K. Jozwik, "Small wind turbine augmentation: Experimental investigations of shrouded- and twin-rotor wind turbine systems," *Energy*, vol. 186, 2019.

[9] S. V. Tawade, S. B. Todkar, and A. S. Hade, "Fatigue life optimization of wind turbine blade," *Int. J. of Research in Eng. and Tech.*, vol. 03, 2014.

[10] M. Stepien, M. Kulak, and K. Jozwik, "Fast track analysis of small wind turbine blade performance," *Energies*, vol. 13, no. 21, 2020.

[11] European Committee for Electrotechnical Standardization, *BS Standards Part 23: Full-scale structural testing of rotor blades*, 2014

[12] Materialize. [Online]. Available: http://www.materialise.com/en/manufacturing/materials/protogen-white

[13] M. Kulak, M. Lipian, and K. Zawadzki, "Investigation of performance of small wind turbine blades with winglets," *Int. J. of Num. Methods for Heat & Fluid Flow* vol. 31, no. 2, pp. 629-640, 2020.

[14] S. Cho, E. E. Bachynski, A. R. Nejad, Z. Gao, and T. Moan, "Numerical modeling of the hydraulic blade pitch actuator in a spar‐type floating wind turbine considering fault conditions and their effects on global dynamic responses," *Wind Energy*, vol. 23, no. 2, pp. 370-390, 2020.

[15] L. K. Tartibu, M. Kilfoil, A. J. van der Merwe, "Vibration analysis of a variable length blade wind turbine," *Int. J. of Advances in Eng. & Tech.*, vol. 4, no. 1, pp. 630-639, 2012.

[16] M. Janecek, F. Novy, P. Harcuba, J. Strasky, L. Trsko, M. Mhaede, and L. Wagner, "The very high cycle fatigue behaviour of Ti-6Al-4V alloy," *Acta Physica Polonica*, vol. 128, no. 4, pp. 497-503.

[17] F. M. Lai, S. H. Yang, J. H. Wu, C. H. Hsueh, C. C. Yang, B. H. Wang, and C. H. Lan, "Development of fatigue test system for small composite wind turbine blades," *Procedia Eng*. vol. 14, pp. 2003-13, 2011.

[18] S. S. P. Reddy, R. Suresh, M. B. Hanamantraygouda, and B. P. Shivakumar, "Use of composite materials and hybrid composites in wind turbine blades," *Materials Today: Proceedings*, 2021.

Karol Zawadzki was born in Lodz, Poland in 1997. He received B.S. degree in Mechanical Engineeging from Lodz University of Technology, Lodz, Poland, in 2020.
Since 2016, he has been a member of the GUST Team at the Institute of Turbomachinery. Moreover, he is an author of many research articles from the field of wind energy and wind turbines design.
Karol Zawadzki works as a trainee in the P&G Gilette factory (Process Engineering Value Stream).

Anna Baszczyńska is a fourth-year student of Biomedical Engineering. She is a leader of student's project Generative Small Urban Turbine (GUST).
She is interested in Computational Fluid Dynamics and Computer Aided Design used in biomedicine and in the design of small wind turbines.
Anna Baszczyńska works as a Biomedical Engineer at PROTEO.

Angela Fliszewska is a fourth-year student of Biomedical Engineering. She is interested in Medical Imaging and Human-Computer Interfaces. Privately Angela Fliszewska is a volleyball and literature enthusiast. She works as an Order Management Specialist at Philips.

Szymon Molenda is a M.Eng. of Automatic Control and Robotics.
He is interested in modern mechanics and robotics usage in manufacturing processes. In free time enthusiast of volleyball and video games. Currently Szymon Molenda works as a Process Engineer in Procter & Gamble Gillette.

Jakub Bobrowski is a fourth-year student of Mechanical Engineering (B. Eng.).
In 2020, he worked as a CAD Engineer at Hitachi ABB Power Grids. Now, Jakub Bobrowski works as a Stress Engineer at Airbus Helicopters. He is passionate about compressible and incompressible aerodynamics, solid mechanics and motorsports.

Michał Sikorski is a third-year student of Management and Production Engineering. He is interested in renewable and alternative sources of energy.