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Static and Fatigue Analysis of A Small Wind Turbine Blade

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Abstract

This research work is carried out to confirm the safe fatigue life of 20 years (10^6 cycles) for a newly developed 1.5 m long small wind turbine blades without failure using both, static and fatigue tests. The results of extended static test experiments on glass fiber reinforced plastic blades are obtained using six strain gauges mounted at distances of 0.375, 0.750 and 1.125 m from the blade root on upper and lower surfaces at four different loads 0.5 (equivalent to 60 m/s wind speed), 1, 1.5 and 2 kN. This blade was also tested for the completely reversed amplitude of 100 mm at the 8 Hz frequency to study the fatigue behavior using computational software FEMFAT (Finite Element Method Fatigue) and a dedicated experimental setup developed in the laboratory. The static stresses induced in the blade are found at considerably lower than the permissible limit. The fatigue damage and life results obtained through FEMFAT also indicate the expected reliability and safe design life of developed new blade. This is also confirmed through the experimental test carried out for 1.6×10^7 cycles.

Keywords: Fatigue, small wind turbine, static strength, wind turbine, wind turbine blade

1. Introduction

Small wind turbines have a huge energy potential and capability to fulfill the energy requirement of many rural and isolated homes and systems [1, 2]. The research on small wind turbines (SWT) is still limited to blade airfoils, aerodynamics, generators and power control [3]. Cost, performance, storage, reliability, maintenance and spare parts availability are the major barriers in the acceptability of the small wind turbines by the individuals and community [4]. The fatigue failure of a small wind turbine blade is the most probable incident among all parts [5, 6]. Small wind turbine blades are rotating at higher speed compared to large wind turbine blades and facing continuously changing, unpredictable wind speeds and subjected to more fatigue [7-9]. Author[1] also experienced the fatigue failure of a small wind turbine blade subjected to fatigue, mounted at his research centre. Additionally, he observed the blade fatigue failure of small wind turbine blades at many sites after a few years of working. Figure 1. shows an illustrative example of two broken blades of a small wind turbine. The expected small wind turbine life is about 20 years [10]. Both, full scale static and fatigue tests are recommended for wind turbine blades [11]. To serve this long period without breaking, the fatigue life of a small wind turbine blade is very important in addition to static tests [12-15].

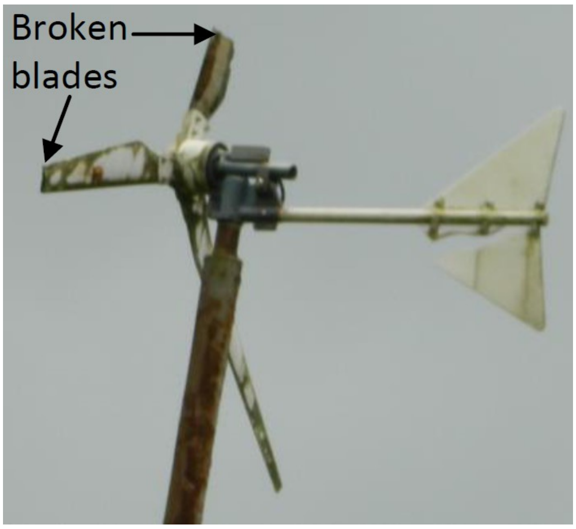


Fig. 1: SWT with two broken blades [Photo by Author[1]]

Following paragraphs discuss the different types of research works carried out by various researchers on small wind turbine blade strengths including static tests, fatigue tests and proposed materials tests.

Muyan and Coker carried out the computational analysis for a 5 m long blade to study the static strength using ANSYS [16]. Rady et al. presented a computational research on effect of blade root dimensions on static stresses and deflection of small wind turbine blades of 2.5 m length using ANSYS [17]. The scope of these two research works was constrained to computational analysis using ANSYS. Zawadzki et al. studied the static strength of 3D printed blade prototype of 0.16 m length and the main focus was to study the integrity of 3D printed material for blade [18]. Dong-Kuk Choi et al. performed a computational and experimental static test of a real fabric covered, 3.55 m long carbon composite blade consisting of multiple spars to measure the strength of covered fiber [19]. Kale and Hugar have conducted a static test on a real 1.5 m long blade and measured local stresses near the blade root at 0.35, 0.45 and 0.55 m from the rotor axis. In this research the stresses were measured near to the root portion only which covers around 1/3rd length of the blade [20]. A research on static strength evaluation of specific full scale small wind turbine blades made from Glass Fiber Reinforced Plastic (GFRP) can be a significant study.

In addition to the static test, Muyan and Coker carried out a fatigue loading test using ANSYS [16]. Choi H et al. compared the fatigue life using the results obtained from the open source software QBlade [21]. Castro and Branner have carried out a preliminary fatigue evaluation under various uniaxial and multi-axial loading conditions for 14.3 m long blade and study focused the strain-time series without declaring the fatigue life of the blade [22]. Karol Zawadzki et al. presented the research on a 3D printed blade prototype of 0.195 m length and fractured after 525900 cycles with the main objective to identify the fatigue properties of 3D printed materials [23]. Peterson and Clausen completed the fatigue test on a 1.0 m long wooden blade to study the fatigue properties of natural material for small wind turbine blades [24]. Joshua et al. tested a 9 m long Carbon Fiber blade with Spar Caps and predicted CX-100 blade life as $\times 10^6$ cycles [25]. Su et al. have conducted a research to identify the fatigue failure regions of a Carbon Fiber blade of rotor radius of 0.7 m at various rpm conditions and identified more possibility failure in the 0.70–0.75 R [26]. A research to predict the expected fatigue life of full scale GFRP small wind turbine blades (without spar) using computational and experimental techniques can be an important contribution.

Astle et al. discussed the fatigue testing results of wood as a material for SWT blade [27]. Sai and Chai studied the fatigue of fiber-metal composites for small wind turbine blades [28]. These two studies mainly presented the fatigue properties and possibilities of natural material and metal laminated blades. Knowing the well-known acceptability for various applications of cost-effective, durable, high strength to weight ratio GFRP materials blade can be a good option for further static and fatigue study.

From the attainable works in literature, it is perceived that very limited research is carried out on static and fatigue strength evaluation of small wind turbine blades. The detailed static strength study of full scale glass fiber reinforced plastic blades (without spar) and the further determination of blade life can be important research. From the studied research articles by the authors it is also seen that the static tests are carried out on the basis of cut-out speed ranging from 10 m/s to 17 m/s. When the blade is put in actual application, it should be capable of withstanding any unpredictable situations like random variation in directions, high wind speeds, cyclones, etc. Hence, similar to large wind turbines these results should be based on survival wind speed may be around 60 m/s. Also, the research on use of dedicated fatigue test software FEMFAT (Finite Element Method Fatigue) for fatigue testing of small wind turbine blade can be the attainable significant research. In addition to this, it is also learnt from the research that the combined computational and experimental research predicting the fatigue life of real small wind turbine blades can be added to scientific records.

Hence, this research paper is prepared on the basis of an extended experimental static test to sustain survival wind speed of 60 m/s. For this study a real full scale blade of 1.5 m length capable of producing 1 kW rated power at 8.4 m/s rated wind speed is considered. This paper also added the results including the damage and life prediction through computational fatigue test conducted using FEMFAT software. The computational fatigue test results are also verified using explicitly developed physical experimental set-up for this blade testing. The experimental fatigue test was carried out for 1.6×10^7 cycles at 8 Hz frequency. This is considerably higher than expected life 10^6 cycles.

2. Methodology

This section provides the methodology used for this research paper and describes experimental static test procedure, computational test procedure fatigue using FEMFAT and experimental fatigue test procedure respectively.

A small wind turbine blade of 1.5 m length [20] taken for study comprises two newly designed airfoils. First thick airfoil (15 % thick) is used for 30 % length near the root and thin airfoil (9 % thick) is used for remaining length. The 3 mm thick blades are manufactured through hand lay-up process using epoxy based GFRP of 250 MPa tensile strength. Wooden piece is inserted in the blade root to reduce the weight. The static test is carried using physical experimentation. During the static test, the extended physical experimentation is carried out on the wind turbine blade. In the previous research [20], stresses are measured in a narrow range near the root, as mentioned in the introduction. In the current research total six strain gauges are mounted as shown in Fig. 2 at distances of $l_1 = l_4 =$ 0.375, $l_2 = l_5 =$ 0.75 and $l_3 = l_6 =$ 1.125 m from the blade root on upper and lower surfaces respectively to measures strains in a wider range. Loads of 0.5, 1, 1.5 and 2 kN are applied at 1.45 m distance and strains are recorded at said three distances from the blade root on upper and lower surfaces.

The fatigue tests are conducted using both, computational and physical experimental methods.

The computational analysis is carried out using FEMFAT (Finite Element Method Fatigue). Use of appropriate size of meshing is highly important to get better results through any finite element method. For deciding the acceptable meshing size authors referred some previous research articles and accordingly found that the mesh size used for this present research is significantly better. Muyan et al. [13] used approximately 35,000 nodes for the 5 m long blade which is more than 3 times long compared to the present 1.5 m long blade. Choi et al. used 33,345 elements for the 3.55 m long blade [16]. Kale and Hugar used around 45,800 nodes and 26,000 elements for the 1.5 m long blade and results were in good agreement with experimental [20]. In the present research for 1.5 m long blade total number of tetrahedral elements are more than 48,000 and which shows considerable fine mesh size and ability to deliver acceptable results. During computational fatigue analysis the blade is fixed at root and load is applied at 1.45 m distance from root. Figure 3 presents FEMFAT images, in which (a) shows the fine meshing used and (b) shows the boundary conditions and loading point at the upper surface of the blade. The completely reversible amplitude of 100 mm is applied to the blade during the computational test carried out on FEMFAT as shown in Fig. 3 (b).

A special test setup is developed to conduct static as well as fatigue tests on the blade and its schematic is shown in Fig. 4. The test setup includes the blade mounting arrangement, a variable speed electric motor with variable frequency drive, a crank which is connected in between eccentric plate and blade. The physical test set-up under working conditions is shown in Fig. 5. An eight channel data logger is used to record the strain values obtained from the strain gauges. The natural frequency of the blade is obtained as 10 Hz using a Fast Fourier Transform (FFT) analyzer. For the fatigue strength, the blade is tested at 8 Hz frequency and completely reversible amplitude of 100 mm. During the fatigue test the blade is held in the clamp at 1.45 m distance and strains are continuously recorded at same distances l_1 to l_6 as used in case of static test from the blade root on upper and lower surfaces.

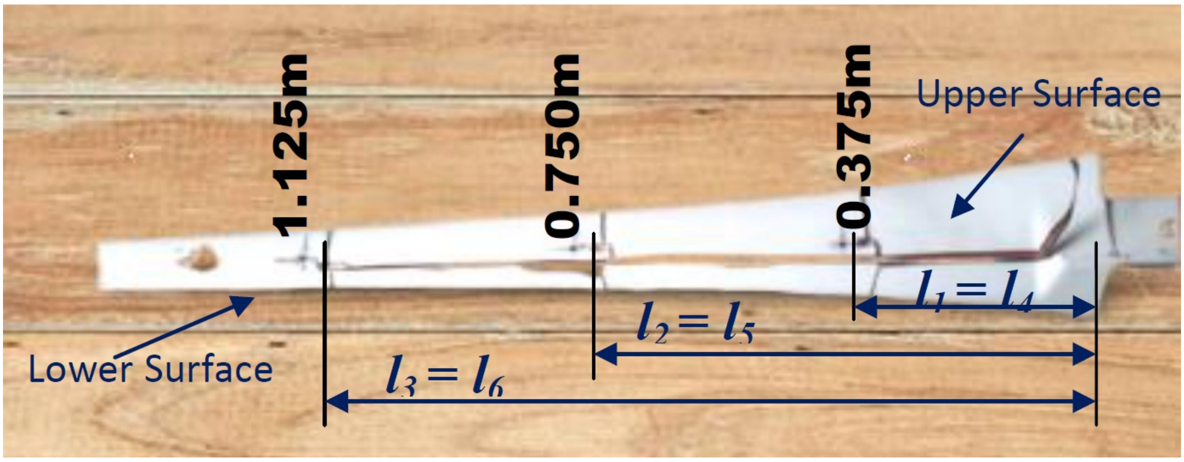


Fig. 2: Strain gauge locations on the blade from blade root

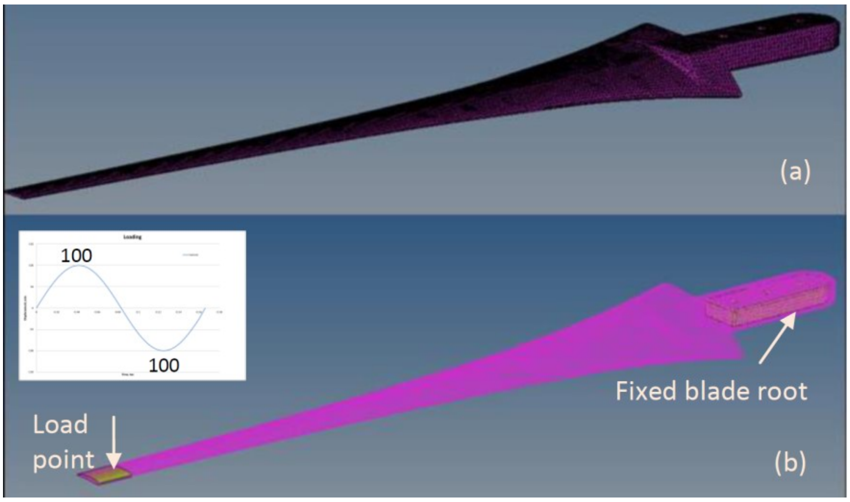


Fig. 3: FEMFAT images (a) Blade meshing, (b) Boundary conditions - fixed root and load point

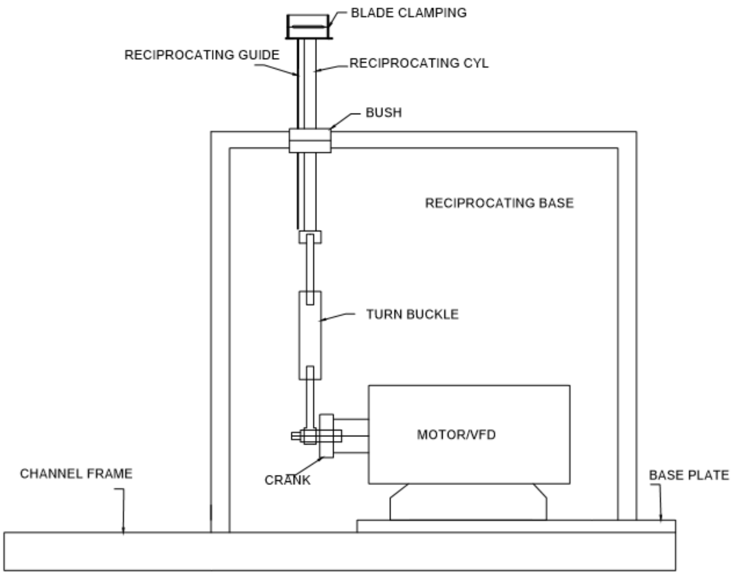


Fig. 4: Schematic of experimental set-up for fatigue testing

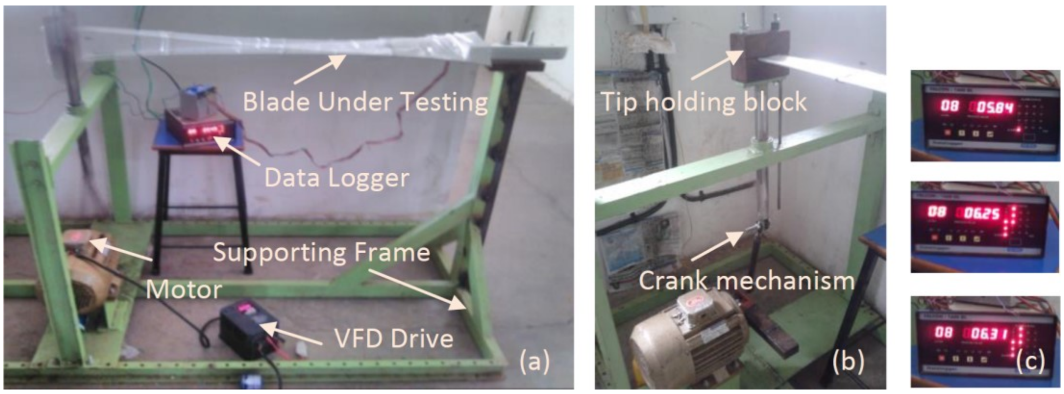


Fig. 5: The working experimental set-up for fatigue testing (a) Exploring blade motion and overall arrangement, (b) Exploring mechanism, (c) Dynamic data logger displays

3. Results and Discussion

This section presents the results obtained from experimental static tests and also presents the fatigue test results of computational and physical experimentation.

3.1 Experimental Static Test

The strain values from the static test experimentation are measured for the forces of magnitudes 0.5, 1, 1.5 and 2 kN. These forces are equivalent to 60, 85, 105 and 120 m/s respectively, based on the calculated projected blade area. For the large wind turbines, survival wind speed is about 55 - 60 m/s taken. Hence, 60 m/s equivalent is also quite a higher load for static strength. Still, to study the stresses induced at such high loads are applied. The strain values are recorded at l_1 to l_6 from the blade root on upper and lower surfaces of the blade. Further the stress values are calculated using the simple relation between stress-strain and presented in Table 1.

Table 1: Static stresses (MPa) induced in the blade at different locations at various loads

		Strain gauge distances from root (m)		
Load (kN)	**Surface**	**0.375**	**0.75**	**1.125**
2	U	138.85	178.50	210.10
1.5	U	109.18	137.63	156.13
1	U	74.88	102.50	103.85
0.5	U	40.15	53.63	51.53
0.5	L	-46.18	-43.95	-50.70
1	L	-93.13	-87.80	-103.13
1.5	L	-140.25	-132.78	-153.03
2	L	-183.68	-173.70	-175.38

These results are also plotted in the graph as shown in Fig. 6. From the graph it is observed that the stress values at the upper surface are slightly higher than that of the lower surface for considering the load. The stresses induced at 0.5 kN (equivalent to 60 m/s) are ranging from 40.15 to 53.63 MPa and significantly less than the 250 MPa. The stresses induced at 2 kN (equivalent to 120 m/s) are ranging from 138.85 to 210.10 MPa and less than 250 MPa. Hence, the blade has very good ability to sustain the heavy loads significantly higher than the operating range of around 10 m/s at moderate windy sites.

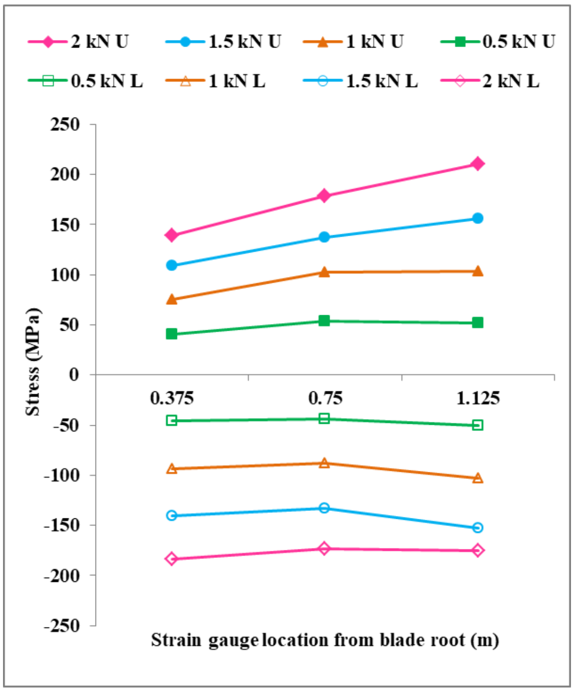


Fig. 6: Static stresses induced in the blade at different locations at various loads

3.2 Computational Fatigue Test

Figure 7 is a representative snapshot obtained during cyclic loading using FEMFAT. It shows maximum and minimum stress values at particular instant and the element number. Figure 8 shows the fatigue damage contours on the (a) upper surface and (b) lower surface of the blade respectively. From the results it is observed that no cracks are observed in the blade till 1.11×10^9 cycles. The cracks at blade edges are appearing from 1.11×10^9 to 10^{10} cycles as shown in Fig. 9. These cycle numbers are well accepted when compared with the results presented by Mayan and Coker [16]. A few damage points on the outer surfaces are appearing after such a high number of cycles. Hence, it is very much clear that the blade is safe and able to carry more than 10^6 cycles at which most of the components or materials are tested during fatigue [26]. Figure 9 shows the fatigue life contours on the (a) upper surface and (b) lower surface of the blade respectively. The results obtained using FEMFAT also predicted the blade life more than 20 years.

3.2 Experimental Fatigue Test

Similar to computational analysis, completely reversible amplitude of 100 mm is applied during the experimentation. The blade is tested for 1.6×10^7 cycles (test stopped after this) and no cracks are observed by the naked eye on the blade surfaces during testing. Hence, it is recognized that the blade has such considerable safe

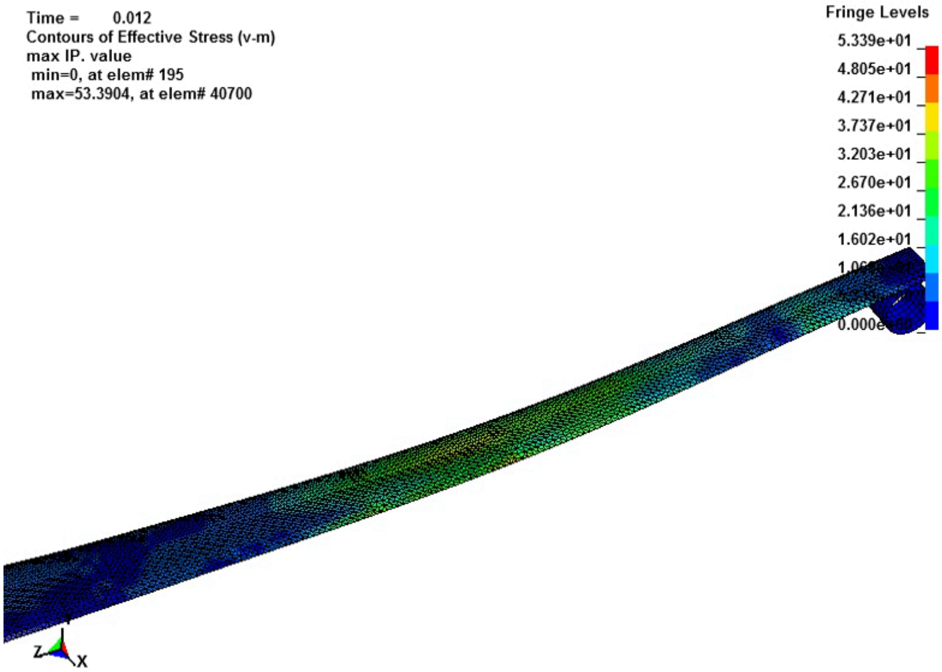
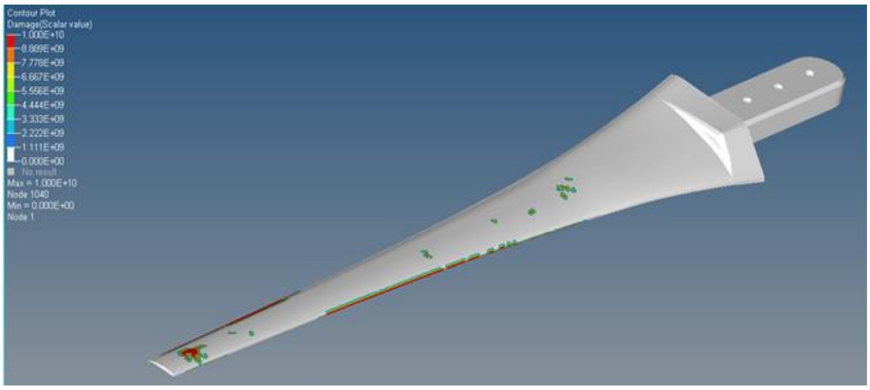
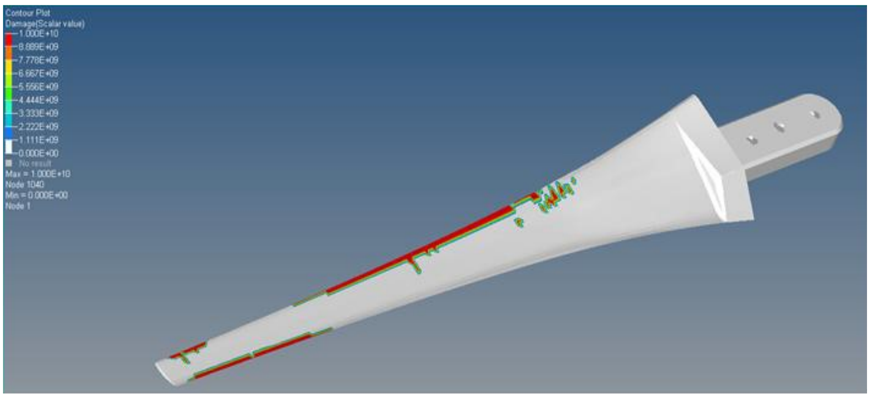


Fig. 7: A snapshot of FEMFAT showing the stresses during the cyclic loading

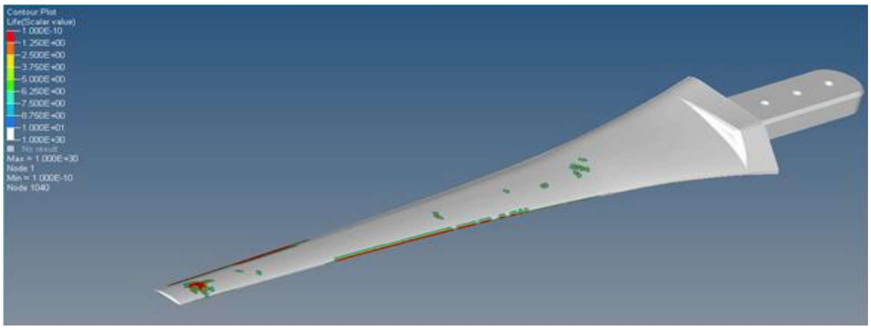


(a) upper surface

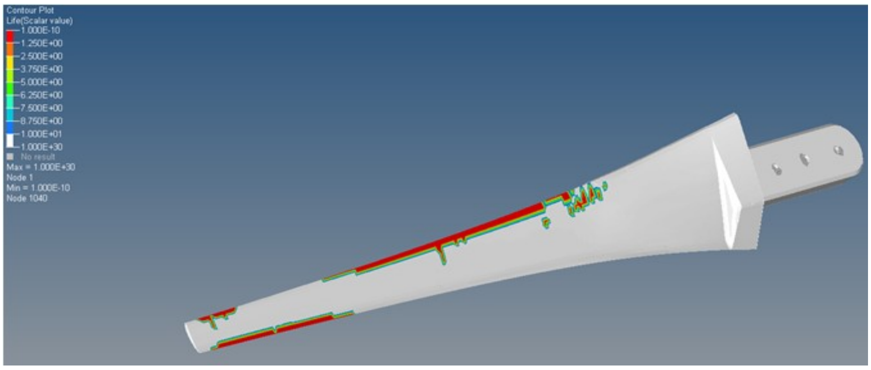


(b) lower surface

Fig. 8: Fatigue damage contours on blade surfaces



(a) upper surface



(b) lower surface

Fig. 9: Fatigue life contours on blade surfaces

life at accelerated test. The stresses obtained through the strain recordings of six strain gauges are plotted individually as shown in Fig. 10 (a) to (f). From these plots it is clearly observed that the magnitudes of stresses are decreasing with an increase in number of cycles. The same trends are also observed in the research work conducted to test materials for wind turbine blades [7, 29, 30].

The objective of the static test was to check the results in an extensive length range. Su [30] identified more possibility failure in the 0.70 – 0.75 R. In the present study also it is clearly seen that at distance 1.125 m (around 0.75 R) the static stresses values are maximum and indicated good agreement with the previous results. In addition to ANSYS results [20], the stress values are well matching with current stress values using FEAMAT at 0.375 m distance. The stresses induced in the blade are considerably less at the extreme survival speed also hence it can be well predicted to lower stress in operating wind speed ranges even up to 17 m/s in good windy sites.

The FEMFAT predicts the blade life more than 20 years and no cracks observed till 1.11×10^9 cycles. Also, no cracks observed during the experimental fatigue test conducted for 1.6×10^7 cycles which is quietly exceeding the expected fatigue life of 20 years. From these results it is seen that the blade is safe in fatigue conditions and having good reliability in order to serve a desired life without failure [29, 30]. The frequency conditions and amplitude used during the tests are considerably higher than that of the possible in actual working conditions. In spite of these overload conditions good fatigue damage and life are observed during the tests. This also indicates that there is further scope to optimize the blade thicknesses at various regions in order to reduce the blade weight.

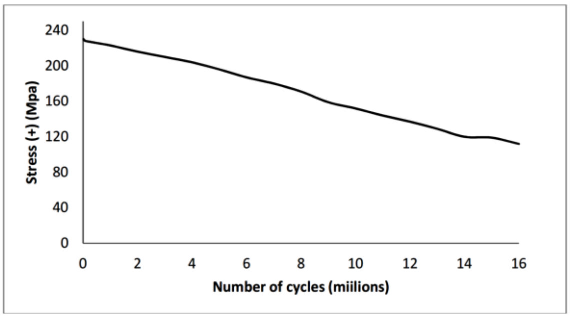
This study is mainly focused on fatigue analysis of the blade on the basis macroscopic study and checks the appearance of cracks on the outer surfaces. The further study may be conducted to study the internal damage, delamination and microscopic changes during such tests.

4. Conclusion

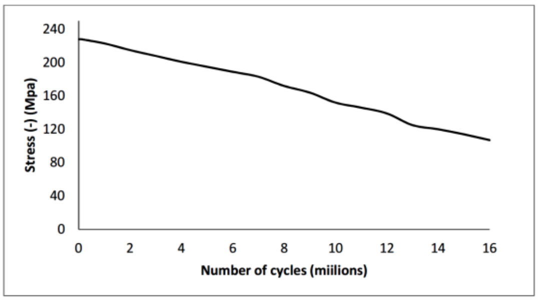
The experimental static test, computational and experimental fatigue test on a small wind turbine blade of 1.5 m length are conducted to evaluate the stresses and predict fatigue life of the blade.

- From the static test it is concluded that the maximum stress (53.63 MPa) induced at survival wind speed of 60 m/s is considerably lower than the limiting strength of blade material 250 MPa and confirming the factor of safety more than 4.6. The stress values are considerably increasing at 1.125 m with applied load. Even at four fold applied load the maximum induced stress (210.10 MPa) is not crossing the limiting strength of blade material gives indication of possible material and weight reduction.3

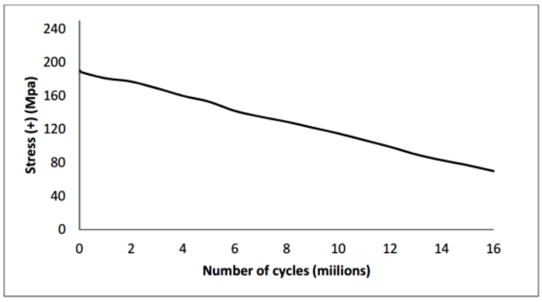
- The computational FEMFAT test results direct the safe blade life till 1.11×10^9 cycles which is considerably higher than expected service life of 20 years (10^6 cycles). This indicates that the blades have the ability to sustain the 100 mm reversible amplitude for such accelerated testing frequency of 8 Hz.
- The results of the experimental fatigue test with similar conditions to that of the computational test also clearly predict life without failure even after completion of 1.6×10^7 cycles (test stopped after this) and confirm well acceptable service life for more than 20 years. Hence, it also validates the failure free predicted service cycles observed in computational tests.
- From these results, it is confirmed that the blade is capable of providing its expected service for designed long life without failure even in extreme static and fatigue wind load conditions without failure.



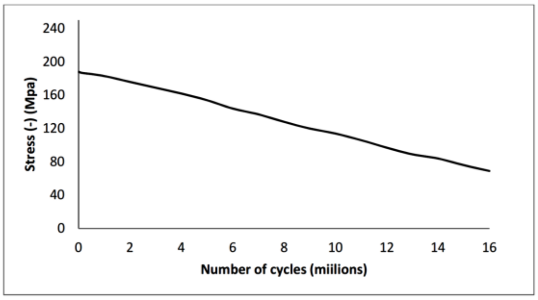
(a) Stresses at upper surface (1.125 m)



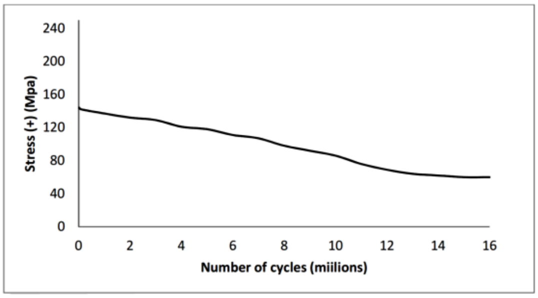
(b) Stresses at lower surface (1.125 m)



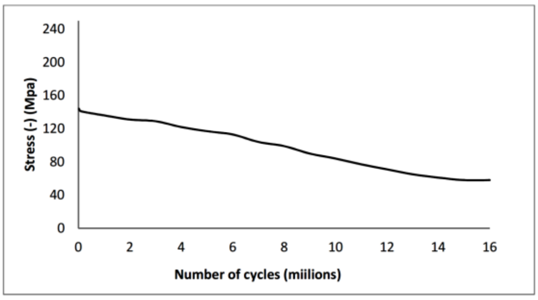
(c) Stresses at upper surface (0.75 m)



(d) Stresses at lower surface (0.75 m)



(e) Stresses at upper surface (0.375 m)



(f) Stresses at lower surface (0.375 m)

Fig. 10: Stresses induced during fatigue testing at different locations

Nomenclature

FEMFAT	:	Finite Element Method Fatigue
FFT	:	Fast Fourier Transform
GFRP	:	Glass Fiber Reinforced Plastic

L	:	Lower blade surface
l	:	Strain gauge distances from root
R	:	Rotor radius
SWT	:	Small Wind Turbines
U	:	Upper blade surface

5. References

[1] P. Arumugam, V.Ramalingam, and K. Bhaganagar (2021). A pathway towards sustainable development of small capacity horizontal axis wind turbines - Identification of influencing design parameters & their role on performance analysis, *Sustainable Energy Technologies and Assessments.* Vol No. 44, pp. 101019. DOI: 10.1016/j.seta.2021.101019.

[2] S. A. Kale and S. N. Sapali (2014). Development and Field Testing of an Inclined Flanged Compact Diffuser for a Micro Wind Turbine. ASME International Mechanical Engineering Congress and Exposition Proceedings. Vol. No. 6B, DOI:10.1115/IMECE201437883.

[3] K. Wirtayasa and C. Y. Hsiao (2022). Performances comparison of axial-flux permanent-magnet generators for small-scale vertical-axis wind turbine, Alexandria Engineering Journal. Vol. No. 61(2), pp. 1201-1215. DOI:10.1016/j.aej.2021.06.074.

[4] L. P. Maskepatil, A. U. Gandigude, and S. A. Kale (2014). Selection of material for wind turbine blade by analytic hierarchy process (AHP) method, Appl. Mech. Mater. vol. No. 612, pp. 145–150. DOI:10.4028/www.scientific.net/AMM.612.145.

[5] Evans S, Dana S, Clausen P, Wood D. (2021). A simple method for modelling fatigue spectra of small wind turbine blades, Wind Energy. Vol. 24, pp. 549–557. DOI: 10.1002/we.2588.

[6] Anup K C, J. Whale, S. P. Evans, P D. Clausen (2020). An investigation of the impact of wind speed and turbulence on small wind turbine operation and fatigue loads, Renewable Energy, Vol. 146, pp. 87-98, DOI: 10.1016/j.renene.

[7] D. A. Miller, D. D. Samborsky and B. L. Ennis (2019). Mechanical Testing Summary: Optimized Carbon Fiber Composites in Wind Turbine Blade Design, Sandia National Laboratories, Sandia Report, SAND2019-10780.

[8] R. K. Garmode, V. R. Gaval, S. A. Kale, S. D. Nikhade (2022). Comprehensive Evaluation of Materials for Small Wind Turbine Blades Using Various MCDM Techniques, International Journal of Renewable Energy Research, Vol. No. 12(2), pp. 981-992. DOI: 10.20508/ijrer.v12i2.12992.g8481.

[9] K. Haixia, A. Zongwen, and G. Xu (2020). Lifetime Prediction of Wind Turbine Blade Based on Full-Scale Fatigue Testing, J. Shanghai Jiao Tong Univ. (Sci.), pp. 545-552. DOI. 10.1007/s12204-020-2174-3.

[10] P. Broøndsted, and R. P. L. Nijssen (2013), Advances in wind turbine blade design and materials. Advances in Wind Turbine Blade Design and Materials. Elsevier Inc., pp. 1–461. DOI. 10.1533/9780857097286.

[11] P. H. Nielsen, P. Berring, C. Pavese & K. Branner (2013). Rotor blade full-scale fatigue testing technology and research, DTU Wind Energy, E No. 0041.

[12] G. B. Taware, S. H. Mankar, V. B. Ghagare, G. P. Bharambe, S. A. Kale (2016). Vibration analysis of a small wind turbine blade, International Journal of Engineering and Technology. vol. No. 8(5), pp. 2121-2126.

[13] M. M. Luczak, R. Riva, S. C. Yeniceli, S. H. Madsen, Di Lorenzo (2021). Identification of the test setup influence on the modal properties of a short wind turbine blade during fatigue test, Measurement, Vol. No. 174, pp. 108960.

[14] O. Al-Khudairi, H. Hadavinia, C. Little, G. Gillmore, P. Greaves and K. Dyer (2017). 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. No.10 pp. 1152. DOI:10.3390/ma10101152.

[15] L. Michal, P. Czapski, and D. Obidowski (2020). Fluid-Structure Interaction Numerical Analysis of a Small, Urban Wind Turbine Blade, Energies. Vol. No. 13(7). DOI:10.3390/en13071832.

[16] C. Muyan and D. Coker (2020). Strength analysis of a 5-m composite wind turbine blade under static and fatigue loading conditions, Conf. Ser.: Mater. Sci. Eng., Vol. No. 942 (012045), DOI: 10.1088/1757-899X/942/1/012045.

[17] M. H. Rady, R. K. Garmode, M. Gooroochurn, S. A. Kale (2022) Effect of Blade Root Dimensions on Physical and Mechanical Characteristics of a Small Wind Turbine Blade, International Journal of Renewable Energy Research, Vol. No. 12(3), pp. 1339-1346.
DOI: 10.20508/ijrer.v12i3.13283.g8518

[18] K. Zawadzki, C. Kuzalski, W. Śmiechowicz, M. Tarkowski, D. Kadrowski, M. Stępień, M. Kulak, and M. Lipian (2020). Assessment of Blade Strength for Small Wind Turbine Applications. In E3S Web of Conferences, Vol. No. 160. EDP Sciences. DOI:10.1051/e3sconf/202016001007.

[19] D. K. Choi, B. D. Pyeon, S. Y. Lee, H. G. Lee, J. S. Bae (2020). Structural design, analysis, and testing of a 10 kW fabric-covered wind turbine blade, Energies. Vol. No. 13 (3276). DOI:10.3390/en13123276.

[20] S. Kale and J. Hugar (2015). Static strength design of small wind turbine blade using finite element analysis and testing. In ASME International Mechanical Engineering Congress and Exposition, Proceedings, Vol. 4B-2015, American Society of Mechanical Engineers.
DOI. 10.1115/IMECE201553485.

[21] Choi H, Yu H, Lee E, Loza B, Pacheco-Chérrez J, Cárdenas D, Minchala L, Probst O (2019). Comparative fatigue life assessment of wind turbine blades operating with different regulation schemes, Applied Sciences (Switzerland), Vol. No. 9 (21).

[22] O. Castro and K. Branner (2020). Preliminary multi-axial strain analysis in wind turbine blades under fatigue test loads, IOP Conf. Ser.: Mater. Sci. Eng., Vol. No. 942 pp. 012044.

[23] K. Zawadzki, A. Baszczyńska, A. Fliszewska, S. Molenda, J. Bobrowski, and M. Sikorski (2022). Fatigue Testing of the Small Wind Turbine Blade, International Journal of Mechanical Engineering and Robotics Research. Vol. No. 11(4).

[24] P. Peterson and P.D. Clausen (2004). Timber for High Efficiency Small Wind Turbine Blades, Wind Engineering, Vol. No. 28(1), pp. 87–96.
DOI.: 10.1260/0309524041210865

[25] J. Paquette, J. van Dam, S. Hughes, J. Johnson (2008). Fatigue Testing of 9 m Carbon Fiber Wind Turbine Research Blades, 46th AIAA Aerospace Sciences Meeting and Exhibit, 07 Jan 2008 - 10 Jan 2008, Reno, Nevada American Institute of Aeronautics and Astronautics, pp. 1-10, DOI: 10.2514/6.2008-1350

[26] R. Su, Z. Gao, Y. Chen, Y. Bai, J. Wang (2023). Experimental on the fatigue failure areas of wind turbine blades' rotating fundamental frequency. AIP Advances, Vol. No. 13 (6): 065123.
DOI: 10.1063/5.0142967

[27] C. Astle, I. Burge, M.Chen, T. Herrler, L. Kwan, N. Zibin snd D. Wood (2013). Timber for small wind turbine blades, Energy for Sustainable Development. Vol. No. 17(6), pp. 671–676.
DOI. 10.1016/j.esd.2013.03.001.

[28] W. Sai, G, Chai (2018). Fatigue in Fiber-Metal Laminates for Small Wind Turbine Blades Application, MATEC Web of Conferences, Vol. No. 165, pp. 07005. DOI. 10.1051/matecconf/201816507005

[29] O. Al-Qabandi, A. De Silva, S. Al-Enezi and M. Bassyouni (2014). Synthesis, fabrication and mechanical characterization of reinforced epoxy and polypropylene composites for wind turbine blades, Journal of Reinforced Plastics and Composites. Vol. No. 33(24), 2287–2299.
DOI: 10.1177/0731684414561538.

[30] K. Ziane, S. Zebirate and A. Zaitri (2016). Fatigue strength prediction in composite materials of wind turbine blades under dry–wet conditions: An artificial neural network approach, Wind Engineering, Vol. No. 40 (3) pp. 189-198.
DOI: 10.1177/0309524X16641849.