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Structural Design Optimization of Laminated Composites for Vertical Axis Wind Turbine Blades: A Single Objective Approach

Ahmed A. Geneid[1], Mostafa R. A. Atia[2], Adel Elsabbagh[1], Mohammed Hedaya[1],

[1] Design and production engineering department, Faculty of Engineering, Ain shams university, Cairo, Egypt.
[2] Arab Academy for Science, Technology and Maritime Transport, Cairo, Egypt.

Correspondence to: Ahmed A. Geneid (ageneid@eng.asu.edu.eg; ageneid@gmail.com)

Abstract. Vertical-axis wind turbines are considered a proper solution for today's energy needs. To make it affordable for domestic usage, this requires a reduction in the turbine cost, blade weight, and an increase in blade life. The challenge in VAWT blade design is fatigue and blade life prediction, besides surviving centrifugal force and repeated load pattern effects. The paper focuses on the blade structure modelling and optimization to assess the design for integrity, fatigue, life, sustainability, and cost. The presented model can examine varied materials, including new biodegradable materials, while reducing computation time and resources. The structure analysis is based on classical lamination theory (CLT) and polynomial failure theory (Tsai-Hill and Tsai-Wu). Fatigue analysis and blade life are based on damage evaluation using Miner's rule for loading steps, evaluated stresses and strains, and loading cases. The approximation model simplifies the dynamic and fatigue analysis procedures to make the model integrable with the optimization method. The beam element method is used to approximate the fundamental frequencies of blade structure. The genetic algorithm is the optimization method used for single objective function, non-linear constrained, mixed integer problem. Decision variables vary according to the scope of optimization which includes the five main composite structure parameters: lamina thickness, orientation, volume fraction, and material selection for resin and fiber. However, in the case of pre-defined laminae materials, only the thickness, orientation, and selection index are used. The commercial finite element software ANSYS is used to validate results.

Keywords: Sustainable design - multi-objective optimization - Vertical axis wind turbines - Fatigue – Composite laminate life

Acronyms

CLT	Classical Laminate Theory
GA	Genetic Algorithm
GL	Germanischer Lloyd
HAWT	Horizontal Axis Wind Turbine
HS	High Strength
IEC	International Electrotechnical Commission
NACA	National Advisory Committee for Aeronautics
NSGA	Non-Sorting dominated Genetic Algorithm
SOBF	Single Objective Function
VAWT	Vertical Axis Wind Turbine
TOF	decision variables set of Thickness, Orientation, and lamina material selection
TOFMV	decision variables set of Thickness, Orientation, Fiber and Matrix selection, and Volume fraction

Nomenclature

E_1	GPa	Longitudinal Modulus of Elasticity
E_2	GPa	Traverse Modulus of Elasticity
G_{12}	GPa	In-plane Modulus of Rigidity
N^{k}	cycles	Life in cycles
$\mathrm{S}_1^{\mathrm{C}}$	MPa	Compressive strength Longitudinal
$\mathrm{S}_1^{\mathrm{T}}$	MPa	Tensile strength Longitudinal
$\mathrm{S}_2^{\mathrm{C}}$	MPa	Compressive strength Traverse
$\mathrm{S}_2^{\mathrm{T}}$	MPa	Tensile strength Traverse
v_{12}	-	Major possion’s ratio
v_{21}	-	Minor possion’s ratio
B_1	mm	chord length
L_C	cycles	Blade estimated life
L_y	years	Blade estimated life
N^k	-	Lamina life in cycles
S_{max}	MPa	Maximum Stress
S_{mean}	MPa	Mean Strength
S_{min}	MPa	Minimum Stress
FI	-	Fiber material selection index
MI	-	Matrix material selection index
NF	rad/sec	first fundamental frequency
OI	°	Fiber orientation index
R	-	Ratio between maximum and minimum stress / strain
t	mm	Lamina thickness
TI	-	Number of sub-laminae
VF	-	Fibre volume fraction
W	rad/sec	Rotational speed
x	-	optimization decision variable solution vector
α	-	Fatigue model material parameter
β	-	Fatigue model material parameter
γ	-	Frequency of VAWT operation
ρ	kg/m3	Density

σ	MPa	Stress
τ	MPa	Shear strength
f	-	Failure criterion
ε	-	Strain

1 Introduction

Energy nowadays is the focus of economic dominance. Wind energy has become the proper solution for domestic usage due to its wide range of operation compared to solar energy, which requires batteries and generates only during sunny periods. Small-scale wind turbines, such as vertical axis wind turbines (VAWT), are a solution for residential usage and farming needs. The design of VAWT has advantages over the horizontal axis wind turbine (HAWT) design, where the turbine accepts wind from any direction. The VAWT has a low level of vibration and generates a low level of noise, which makes the VAWT design suitable for installation in cities over buildings and in streets. The installation procedure is simple, and construction is quick, which reduces the cost and time for commissioning. Regarding production, the VAWT designs start production at low wind velocity, which ranges between 2.5 and 3.5 m/s according to commercial wind turbines.

VAWT blades exhibit extreme centrifugal load besides fatigue over the blades, which affects the structure's integrity and reduces blade life. VAWT models are produced from light metals to overcome these issues in the blade design and to reduce the cost of using expensive fiber, which will reduce the production rate. Consequently, the VAWT's blade designs still need development to deploy more efficient material. Another crucial point in the field of VAWT blade material is the concept of sustainability after the blade's life. This point requires extending the blade life to reduce waste material, besides replacing used material with new biodegradable material. However, this issue will require more attention for structure design and optimization, including various parameters. The paper herein presents an approach for modelling and optimizing the VAWT blade structure. Such a model could be used with biodegradable material for laminate composite structures. The modelling is based on the static structure analysis, including the failure assessment, and the dynamic analysis, including fundamental natural frequencies, fatigue, and blade life. The objective includes reducing cost and mass and maximizing blade life and fundamental frequency. The composite structure model considers as decision variables the volume fraction, laminae thickness, reinforcement orientation, and material used.

VAWT design should consider both load of operation and load of severity conditions, with ultimate strength and structural integrity being crucial factors. The blade's structural design should consider dynamic stiffening and be made from short fiber composite material (Deng et al., 2020; Wanru et al., 2022; Bedon et al., 2013). Design load cases depend on operational and external conditions, with requirements like IEC61400-1 and Germanischer Lloyd (GL) unsuitable for VAWTs (Commission, 2019; Lloyd, 2003). Ultimate strength analysis is considered for both normal and extreme conditions, while fatigue analysis depends on normal conditions. Other working conditions include startup, normal shutdown, and emergency stop (Lin et al., 2019b; Lin et al., 2019a).

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A numerical analysis of the VAWT H-rotor blade structure against extreme operation conditions is necessary to determine the material that can support maximum load (Hand and Cashman, 2020; Hand et al., 2021). Experimental investigations have been conducted to study design, manufacturing, and conforming structure integrity for H-type Darrieus wind turbines, while field testing, vibration analysis, and measurements have been conducted to predict aerodynamic load, model performance, fatigue, and ultimate strength (Vergaerde et al., 2019; Jin et al., 2020; Zhang et al., 2020; Lap-Arparat and Leephakpreeda, 2019). These findings contribute to the development of VAWT design and modeling, ensuring safety and reliability in various conditions (Geneid et al., 2022; Raciti Castelli et al., 2013).

Fatigue analysis and fatigue life prediction are crucial for designing composite material structures, as there are no systematic methods or general models available. This complicates the optimization process and increases computational costs. The fatigue life of rotor blades under vibratory loads is essential for durability analysis(Liu et al., 2019; Liu et al., 2023). Phenomenological fatigue models define damage in terms of macroscopically measured properties but do not predict the initiation or growth of fatigue damage. The fatigue behavior of laminated materials is governed by parameters such as fiber and matrix type, fiber volume fraction, fiber orientation, layer thickness, number of layers, and stacking sequence(Xiong et al., 2021; Fernández-Canteli et al., 2021; Mandegarian and Taheri-Behrooz, 2020).

Rotor blades made of laminated materials exhibit competing fatigue modes, and their fatigue life depends on fabrication methods and environmental factors. Fatigue and VAWT life assessment are crucial for structural integrity and safety, especially in large-scale wind turbine design, where compressive loads cause more damage than tensile loads (Lin et al., 2019b; Lin et al., 2019a). Implementation of theoretical fatigue assessment method for HAWT 2 MW blades was conducted by (Liu et al., 2023).

VAWT blade structure optimization focuses on improving performance, economy, and structural integrity. Complex optimization is recommended for interrelated design parameters (Geneid et al., 2022). Lamina stacking sequence optimization involves finite element analysis and genetic optimization algorithms, with constraints such as buckling, modal analysis, blade deformation, and stress distribution. Hybrid composite material structure optimization involves particle swarm algorithms, genetic algorithms, and harmony search algorithms (Megahed et al., 2020; Wei et al., 2019; Schaedler De Almeida, 2019; Vergaerde et al., 2019; Geneid et al., 2015). Validation and conforming procedures are introduced to ensure durability and prevent hazards due to sudden structure failure (Kusnick and Adams, 2012).

The VAWT blade faces complex loading conditions, particularly dynamic and centrifugal loads, which require a structural design based on interrelated parameters. Fatigue and life prediction are crucial for the composite laminate structure, as well as vibration analysis. An integrated design approach, coupled with optimization, can help manage different loading conditions, interrelated design parameters, and performance characterization to enhance sustainability in blade construction.

The paper presents a SOBF optimization model to improve the structural design of VAWT blades made from composite material. The research aims to introduce an integrated design approach, a structural model, and a single objective optimization model, covering diverse loading conditions, structural integrity aspects, cost, mass, and fatigue and blade life. The models embedded in the approach can analyze laminate composites.

2 System description

The VAWT blade's structure is made from composite laminate structure. Carbon fiber and fiberglass are commonly used as reinforcement in the fiber reinforced polymer, and the commonly used resin is epoxy. The blade is manufactured using vacuum infusion. The blade exhibits two loads, the inertia load, and the aerodynamic load. Inertia load is considered the static critical load for designing the VAWT blade structure, this is due to the centrifugal load. However, the critical load for fatigue is considered aerodynamic load. Working conditions affect the blade life and structure integrity, the sudden stop and start is considered crucial in the case of no control is used. Consequently, the hypothesis herein that the blade will be used in wind turbine equipped with advanced controller to prevent sudden changes in load.

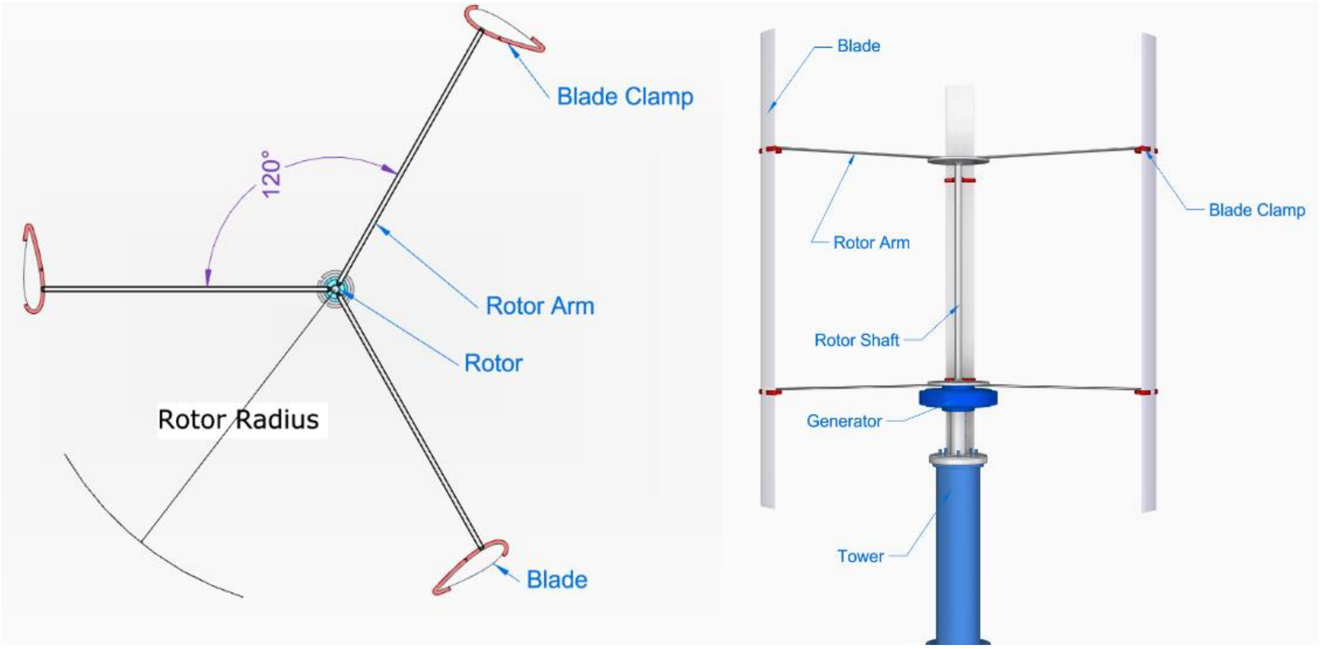

Figure 1: Vertical Axis Wind Turbine's (H-darriues) components and terminology

2.1 Modelling and validation

The total mass of the blade depends on the summation of every lamina mass. The blade cost is the summation of every lamina volume multiplied by the material cost index. The paper proposes a model for evaluating the fatigue condition for every lamina, at every load step and for every factor. After that blade life depends on combination of the fatigue model results, selecting the minimum lamina's life as the blade life. The classical laminate theory known as CLT is used to estimate the structural stiffness matrix. Then the midplane strain is calculated using the stiffness matrix and the load per unit length applied to the blade. Then, the global and local stress/strain is determined within the lamina. The determined local stress / strain is used to evaluate the failure criteria and the fatigue model. The model is based on Wei et al. (Wei et al., 2019).

The introduced model assumes the blade fail after first ply failure to ensure the safety of the optimum design, where composite lamina first ply failure does not mean the total failure of structure because the remaining structure could continue with reduced properties. Load cases included in the structural integrity are the power production at normal and maximum wind conditions. The model depends on a hypothesis of CLT besides the simulation of every load step at the maximum wind conditions. Evaluation of structure integrity depends on the modified quadratic failure criteria in equation (2) (Chen et al., 2019; Vasiliev and Morozov, 2018; Deveci and Artem, 2018). In the quadratic equation both Tsai-Hill and Tsai-Wu are used, the Tsai-Wu is used for evaluating the condition of strain like Tsai-Hill annotation, but strain values are used instead of stress. The 1, 2, 3 notations denote strength components in normal, traverse, and shear according to stress/strain situation whether a tension or compression. The k is the notation of lamina index, j is the load index and the i denotes the principal direction of stresses/strain. The T and C are notation for tension and compression, respectively.

$$f = \left(\frac{[\sigma_1]_j^k}{\mathrm{S}_1^{\mathrm{T}}}\right)^2 + \left(\frac{[\sigma_2]_j^k}{\mathrm{S}_2^{\mathrm{C}}}\right)^2 + \left(\frac{[\sigma_3]_j^k}{\tau}\right)^2 - \frac{[\sigma_2]_j^k}{\mathrm{S}_1^{\mathrm{C}}}\frac{[\sigma_3]_j^k}{\mathrm{S}_1^{\mathrm{C}}} \qquad (1)$$

Three stages of failure due to fatigue in the case of composite laminate material. The first stage depends on fiber breaking and interfacial debonding. Second stage is the failure from matrix cracking, interfacial shear failure. The third stage is the fatigue limit of matrix. The model here in depends on considering the fatigue failure independently for every lamina, then the final life depends on least life lamina in either case the life due to strength or ultimate strain.

Fatigue in laminated composite material is a controversial issue, but this study simplifies the optimization model by considering average parameters for every material type. The blade's life evaluation model using Miner's rule is used to evaluate damage and structural integrity. The cycle life of laminas due to fatigue load is shown in (2), with the lamina stress/strain ratio (R) shown in equation (3) (Deveci and Artem, 2018). Lamina life depends on mean lamina strength/ultimate strain, with three states depending on tension, compression, or the mean between tension and compressive ultimate strength/strain.

$$N^k = \left(1 + \frac{S_{mean} - S_{max}^k}{[S]_{max}^k \times \alpha \times (1-R)}\right)^{1/\beta} \qquad (2)$$

$$R = \frac{S_{min}^k}{S_{max}^k} \qquad (3)$$

The final blade life, depending on first ply failure, is estimated as shown in (4), where the life in cycles is determined from the lamina with the minimum cycle number due to fluctuation of stress/strain. Furthermore, the life in years depends on the normal operation rotation speed, which causing the fluctuation of stress / strain, and the frequency of wind turbine operation, as shown in (5). The W is the rotational speed in RPS, and γ is the frequency of operation, ranging between 20 to 40 % according to (Hand et al., 2021).

$$L_c = min([N^k{}_{\sigma} \quad N^k{}_{\varepsilon}]_i) \qquad (4)$$

$$L_y = \frac{L_c\,\gamma}{W} \times 100 \qquad (5)$$

In this research, four objective functions are considered: (1) minimization of mass, (2) minimization of cost, (3) maximization of the fundamental frequency, and (4) maximization of the blade life in years. A Single Objective Functions (SOBF) approach is evaluated with four models by altering the considered objective function as shown in equation (6) to (9).

$$1^{st}\ SOBF([x]) \ = min\ (M) \tag{6}$$

$$2^{nd}\ SOBF([x]) \ = min\ (C) \tag{7}$$

$$3^{rd}\ SOBF([x]) \ = max\ (L_y) \tag{8}$$

$$4^{th}\ SOBF([x]) \ = max\ (NF) \tag{9}$$

The design to be optimized is the composite laminate structure for a uniform cross-sectional blade. The thickness of the composite lamina will depend on fiber thickness. Thus, the number of laminae will be considered constant, and the number of sub-laminae will be variable. Therefore, the decision variables that represent the design parameters of composite laminates are lamina thickness, reinforcement orientation angle, fiber material selection index, matrix material selection index, and volume fraction.

The optimization problem is bounded by three categories of constraints. The first category is the search domain limits, which represent the bounds of every decision variable, besides the fiber volume fraction (VF), which is bounded between 20 and 80 % (Geneid et al., 2022; Kaw, 2005; Megahed et al., 2020). Equation (10) shows the bound constraints. The second category is the nonlinear failure criteria vector constraint functions, including the failure criteria and the blade life, as shown in equation (11). Blade life is constrained to be more than 15 years. The third category focuses on geometric dependence, including thickness limits. The structural hypothesis is plane stress; hence, the total thickness to chord length ($^{t}/_{B_1}$) should be less than 1:15. The lamina thickness should not exceed the geometry constraint of airfoil thickness, equation (12) shows the continuous constraints.

$$S.T. \begin{cases} tI_{min} \le tI \ \le tI_{max} \\ OI_{min} \le \ OI \ \ \le OI_{max} \\ FI_{min} \le \ FI \ \ \le FI_{max} \\ MI_{min} \le \ MI \ \ \le MI_{max} \\ 0.2 \le \ VF \le 0.8 \end{cases} \tag{10}$$

$$S.T. \begin{cases} L_y > 15 \\ f < 1 \end{cases} \tag{11}$$

$$S.T. \begin{cases} ^{t}/_{B_1} \le {}^{1}/_{15} \\ 2.5 \sum_i^n t_i \le \ B_1 \end{cases} \tag{12}$$

The Genetic Algorithm (GA) method evolves an optimal solution over successive random generations called populations; the method mimics the concept of evolutionary selection. The method is suitable for stochastic, nondifferentiable, and discontinuous problems that cannot be solved using standard conventional optimization techniques. The GA technique differs from conventional classical optimization methods in the concept of the population point step and the randomness in the next

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generation. The problem of optimizing the composite structure consists of interchangeable parameters. This complexity makes the problem nondifferentiable, discontinuous, and stochastic; hence, the genetic algorithm technique is suitable for this type of problem. Every GA iteration consists of initiating a random population, encoding chromosome representation, fitness evaluation and ranking, GA operators, and checking stopping criteria, as shown in Figure 3.

The technique starts by generating an initial population of proposed optimal designs. This population is evaluated against the objective function to determine the fitness of the population, then ranked according to the evaluated fitness. The encoding is representing population individuals into chromosomes; the encoding form herein is the bit string. Genetic algorithm operators are used to generate a successive population (a new generation). starting with the selection of parents according to the fitness rank, then crossover to generate offspring from parents, and after that, the mutation of offspring to add randomity. The crossover operator is the swapping of chromosomes between selected parents. The mutation is the flipping of random chromosome element(s) to add the randomity feature for the new generation. Elite selection is the concept of survival of the best fitness from the current generation to the next. After that check, the achievement of stopping criteria, including number of generations and average change in tolerance function.

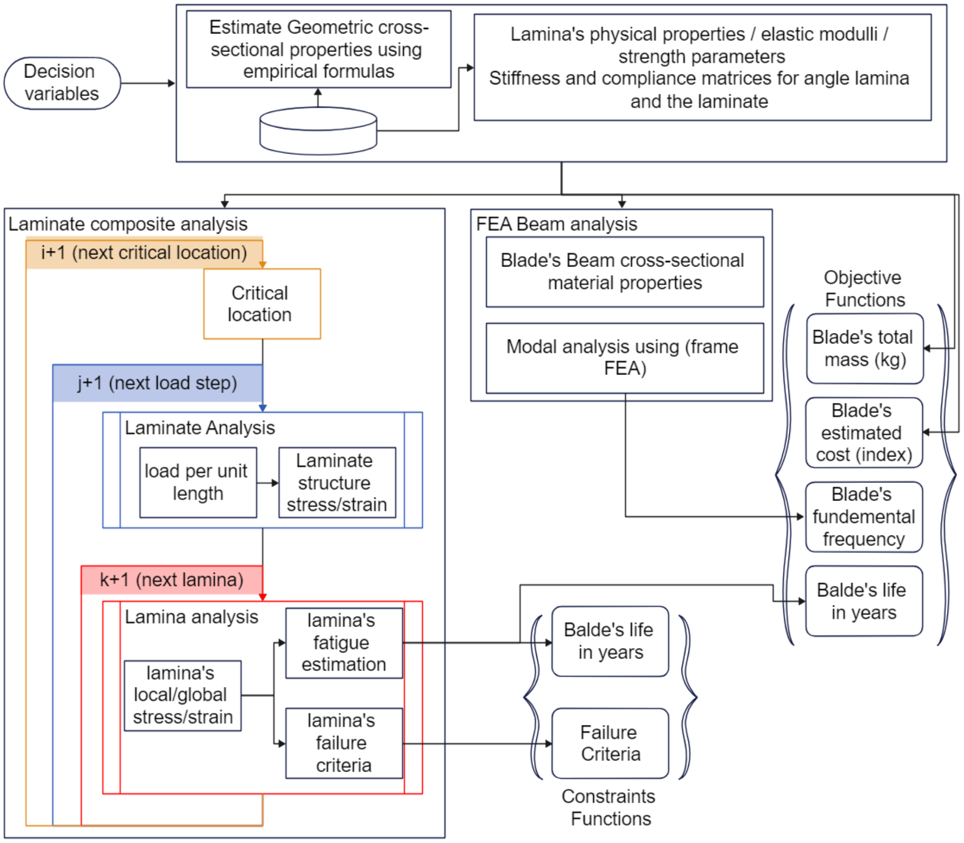


Figure 2: Framework for the blade analysis model

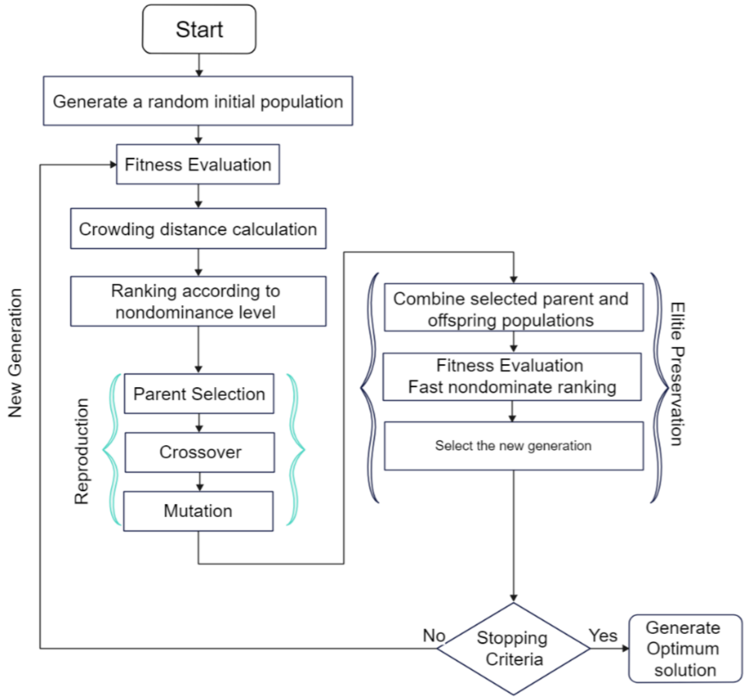


Figure 3: Optimization algorithm using NSDGA II

3 Results

The model is formulated in MATLAB, and the GA optimization tool inside MATLAB is used. In MATLAB, the computer processor is an Intel (R) Core (TM) i7-8700T CPU @ 2.40 GHz, and the RAM is 16 GB. The mode is validated using the commercial finite element software package ANSYS 16 ACP-Tool. Four optimization objectives are considered in the investigation with two decision variables sets (TOF and TOFMV), and the same constraints. The investigation compares the outcomes of minimizing mass, minimizing material cost, maximizing the first fundamental frequency, and maximizing blade life. The adopted case study is the design of the H-Darrieus vertical axis wind turbine’s blade structure. The blade is made from a composite laminate structure. The blade is uniformly cross-sectional along the span and has an airfoil profile of NACA 0012. The chord length is 90 mm, and the blade length is 1400 mm. The blade supports are located at the quarter of the blade length using clamps. The rotor radius is 1000 mm. Reinforcement materials considered in the tradeoff are two types of glass fiber and two types of carbon fiber. The matrix materials considered in the tradeoff are epoxy and polyester resin. The blade is manufactured using vacuum infusion as two halves with hand layup of lamina. Table 1 and Table 2 show the material properties used in the study for reinforcement and resin materials respectively. Figure 4 shows the adopted VAWT and the parameters. The applied load shows critical load at specific azimuthal angle as shown in Figure 5.

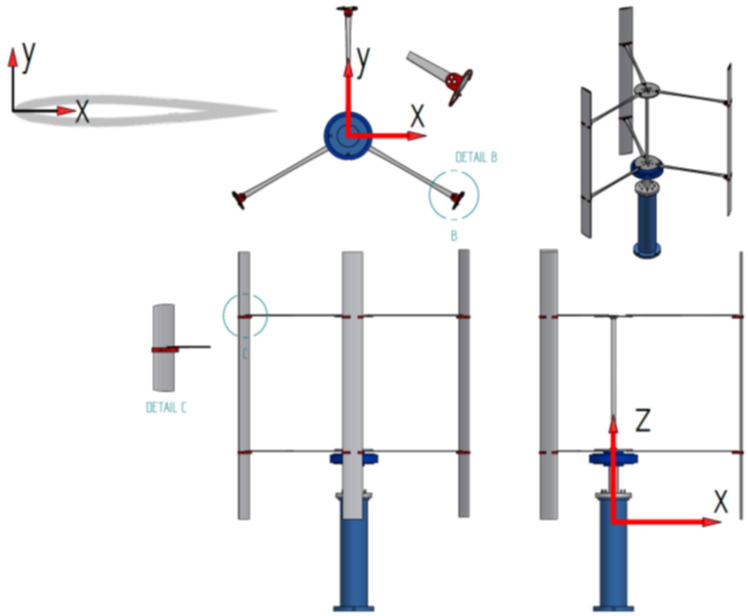
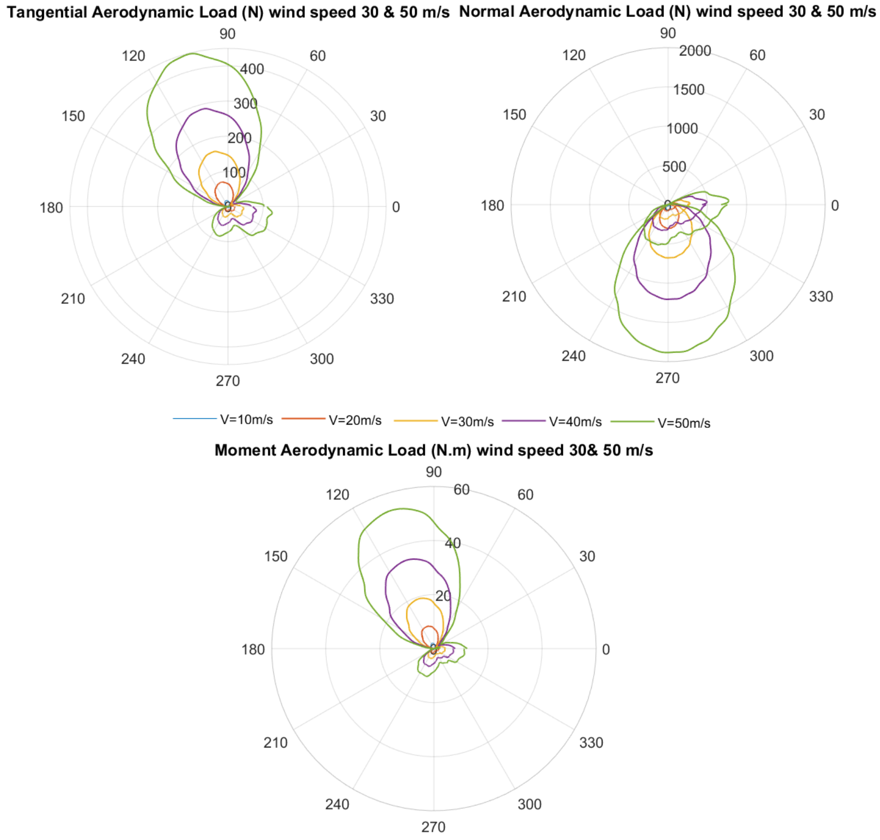


Figure 4: Vertical Axis Wind Turbine (H-darriues) showing global coordinate and blade cross-section profile


Tangential Aerodynamic Load (N) wind speed 30 & 50 m/s

Normal Aerodynamic Load (N) wind speed 30 & 50 m/s

Moment Aerodynamic Load (N.m) wind speed 30& 50 m/s

Figure 5: Comparing aerodynamic load at different wind speed, showing the load at extreme speed.

Table 1: Reinforcement's material mechanical properties courtesy ((Kaw, 2005; Liao et al., 2018; Chong et al., 2017; Choi and Park, 2019))

Symbol	Unit	e-glass	s-glass	GRAPHITE	Carbon	T700
ρ	kg/m^3	2.5E3	2.2E3	1.8E3	1.6E3	1.82E3
C	LE/ kg	1000	1200	1900	1800	1900
E_1	GPa	85	86	230	145	214
G_{12}	GPa	35	35	22	48	22
v_{12}	---	0.2	0.22	0.3	0.25	0.25
S_1^T	MPa	1550	8.2E3	2067	1240	3470
S_1^C	MPa	1550	5.0E3	1999	1100	2100
S_2^T	MPa	1550	8.2E3	77	41	3470
S_2^C	MPa	1550	5.0E3	42	1100	2100
τ	MPa	35	5.0E3	36	80	98

Table 2: Resin's material mechanical properties courtesy ((Kaw, 2005; Liao et al., 2018; Chong et al., 2017; Choi and Park, 2019))

Symbol	Unit	Epoxy	Polyamide
ρ	kg/m^3	1.3E3	1.2E3
C	LE/ kg	1500	1200
E_1	GPa	3.4	3.5
G_{12}	GPa	1.308	0.24
v_{12}	---	0.3	0.35
S_1^T	MPa	72	54
S_1^C	MPa	102	108
S_2^T	MPa	72	54
S_2^C	MPa	102	108
τ	MPa	34	34

The VAWT operation conditions considered in the study are rated power at wind speeds between 6 m/s and 10 m/s for normal operation, and the frequency of operation at normal conditions is 40 %. Otherwise, the VAWT is considered parked and not operating.

The optimization parameters depend on the parameters studied to select a suitable population size, GA operators' conditions and methods, and the elite rate. The parameter study conducted herein depends on repeating the same run with the same parameters 10 times, taking the average of the best optimum solution, changing one of the parameters, and repeating again. The population size is considered the main factor affecting the optimization model's behavior and results. The four objective functions are evaluated for different population sizes including 20, 50, 200, and 500. The effect of population size is critical for life and natural frequency objectives, because small population sizes cause the algorithm to trap easily and stop without finding any results. This is due to the scarcity of optimal results. However, in the case of minizine mass, the algorithm easily found the optimum result after 5-10 repeated trial runs. The best population size used in the study after that is 500, which achieve a robust result for the four objectives.

The results of optimization run for every objective shows that the algorithm used which is Genetic algorithm is efficient for solving the problem with the selected optimization parameters. The four objective functions, for both TOF and TOFMV decision variables, are compared to the average distance between individuals as shown in Figure 6, where the x-axis is the % of the maximum generation number. The comparison shows that the four approaches has similar behavior using the selected optimization parameters. The best and mean fitness are the optimization monitoring parameters. Figure 7 and Figure 8 show fitness values during iterations for minimizing mass and cost, respectively. The optimization study included several population number to select the most optimum population number that will be efficient for all the included objective functions, the result of study is 500 population number.

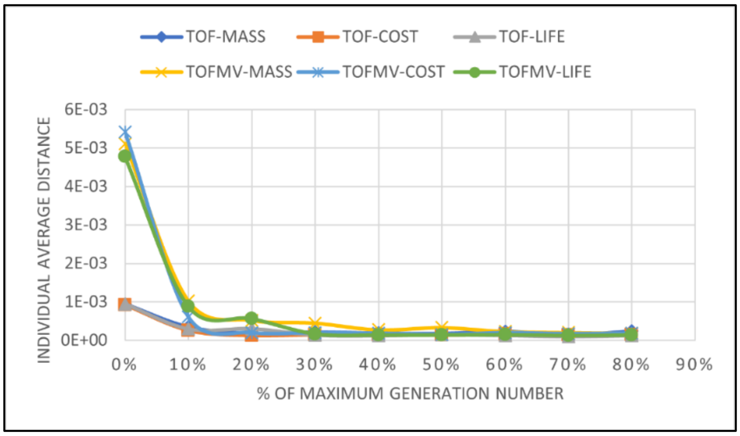


Figure 6: average distance between the best selected individuals (population 500)

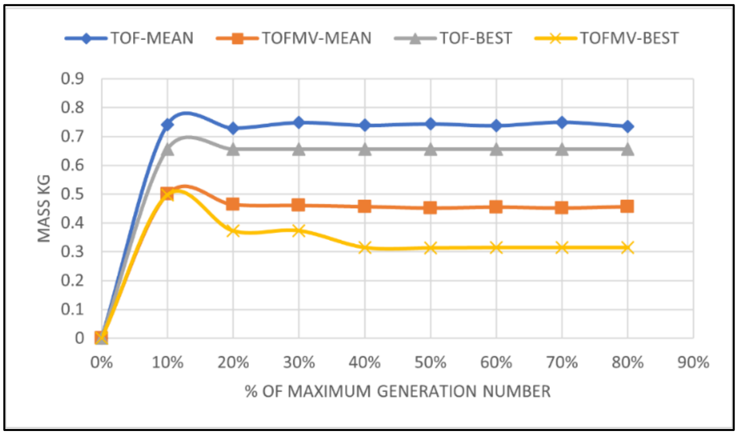


Figure 7: Minimizing mass TOF and TOFMV models, comparing Fitness and Best solution.

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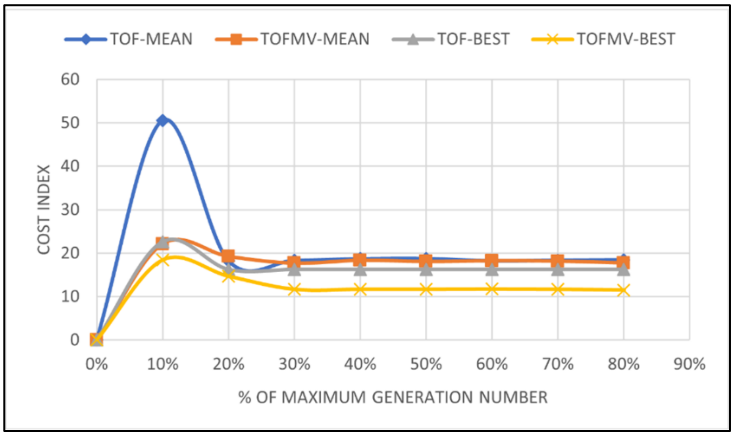

Figure 8: Minimizing cost TOF and TOFMV models, comparing fitness and best solutions

The results from every objective function are compared for both decision variables TOF and TOFMV as in Table 3 and Table 4 respectively. The TOF model represents the decision variables lamina thickness, orientation, and material selection. The TOFMV represents the five decision variables including thickness, orientation, fiber selection, matrix selection, and volume fraction. The optimum design found according every objective is evaluated against other objectives. The comparison shows that the mass as SOBF is not enough to find optimum blade design to satisfy the static failure and dynamic performance required, in addition to, the economic objective. The NF objective shows highest cost and fail in the economic objective, besides the lowest life in the comparison. The life objective shows moderate cost, highest mass, and moderate low frequency. Although the life objective shows the highest mass and moderate low frequency, but the life objective show overall performance better that other objectives. The comparison of different models for percentage change from the most optimum are shown in Figure 9 and Figure 10.

Table 3: comparing the results of TOF model objective functions. (* is the objective function of the model)

OBF	Mass (Kg)	Life (years)	Cost (EGP)	NF (rad/sec)
Min Mass (Kg)	0.7*	40	10,500	222
Max Life (years)	1.1	30	17,00*	120
Max NF (rad/sec)	1.6	43*	20,300	185
Min Cost (EGP)	1.1	41	13,800	437*

Table 4: comparing the results of TOFMV model objective functions. (* is the objective function of the model)

OBF	Mass (Kg)	Life (years)	Cost (EGP)	NF (rad/sec)
Min Mass (Kg)	0.45*	40	23,900	123
Max Life (years)	0.65	15	16,00*	104

Max NF (rad/sec)	**0.94**	**44***	**24,000**	**123**
Min Cost (EGP)	**0.78**	**16**	**21,700**	**536***

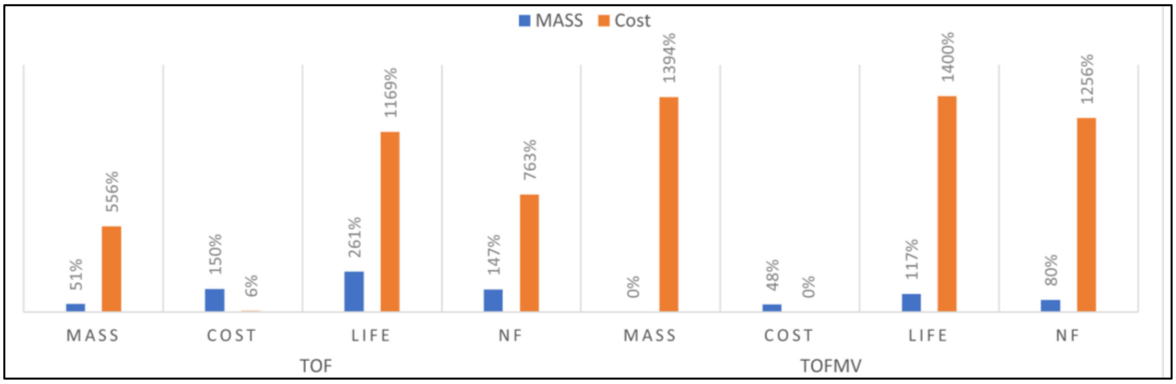

Figure 9: comparing change % of the most optimum value for the mass and the cost objectives

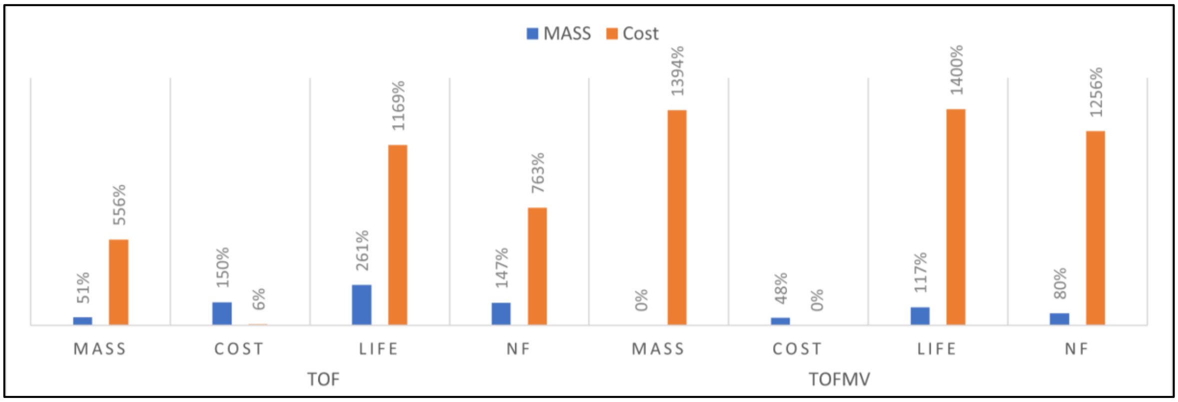

Figure 10: Comparing change % of the most optimum value for life and fundamental frequency objectives

Table 5 comparing optimum design parameters for the four objectives and the two decision variables sets (C: carbon, EG: E-glass, SG: S-glass, EP: Epoxy, HS: high strength carbon, HM: high modulus carbon, PY: polyamide, VY: vinyl ester)

OBF	DV	TOFMV	TOF
MASS	**T (mm)/O(°)**	**[0.2]$_2$,0.6,0.4 / 30,[150]$_2$,0**	**0.5,0.6,1.5,0.5 / 180,150,180,90**
	F / M	**HS/PY, [HS/EP]$_2$, HS/PY**	**[C/Ep]$_4$**
	VF (%)	**20,22,20,29**	**-**
COST	**T (mm)/O(°)**	**0.5,0.2,0.5,0.7 / [0]$_2$,120,180**	**[0.6]$_4$ / 30,150,135,180**
	F / M	**SG/VY, [EG/VY]$_2$, EG/VY**	**[SG / Ep]$_4$**
	VF (%)	**[20]$_3$,27**	**-**

LIFE	**T (mm)/O(°)**	**.6,.4,1.0,1.0 / 180,0,135,0**	**1.5,1.8, [1.0]$_2$/90,180,90,45**
	F / M	**[HS/EP]$_2$, HM/EP, HS/EP**	**C/EP, EG/EP, [C/EP]$_2$**
	VF (%)	**63,65,32,63**	**-**
NF	**T (mm)/O(°)**	**0.6,0.8, [0.4]$_2$ / 180,[90]2,180**	**[0.5]$_2$,1.5,0.6 / [90]$_4$**
	F / M	**HS/EP, [HM/EP]$_3$**	**[C/EP]$_3$, EG/EP**
	VF (%)	**65,70,74,73**	**-**

The final optimum design obtained from every objective and decision variable set are shown in Table 5. The selected optimum values show that the structure design is dominated for specific materials in case of cost (Fiberglass) and in case of other parameters the design is directed to carbon fiber. The high modulus fiber is the selection for NF objectives. The high strength carbon fiber is the selection for life objective. Moreover, the selection of lamina orientation and thickness are affected by the objective function used. All the presented optimum designs satisfy the proposed constraints, which bound solutions for minimum life and maintain structure integrity. Concluding from this variation of selection requires integrating all objectives functions into multi-objective function model, which will be able to tradeoff between these functions equally without deviating to a single objective.

The lamina stress and strain distribution are evaluated for the optimum result of Life objective using TOFMV DV set. The main observation for the distribution is the critical of Normal stress/strain (noted as direction 1 in the plot) which exceed the values of traverse and shear (noted as direction 2 and direction 3). The selected plots are selected for critical location and at wind speed of 6 m/s which is considered highest frequency speed. Distribution of strain and stress are shown in Figure 11 and Figure 12 respectively. Furthermore, the distribution of failure criteria for every stress/strain type, which shows that due to high compressive strain the third lamina become critical in the traverse direction, this will be valid by dominating the reinforcement angle direction to orthogonal directions. The stress/strain ratio's failure criteria are shown in Figure 13 and Figure 14 for strain ratio and stress ratio respectively.

The inertia load is considered the critical load in case of static failure and the aerodynamic load is considered the load factor for fatigue and life. This is clearly observed from deflection plot for a blade at wind speed 6m/s and at critical load. This plot is for 1-D finite element using the equivalent material cross-sectional properties. Figure 15 shows the comparison between deflection of inertia, aerodynamic and total loads.

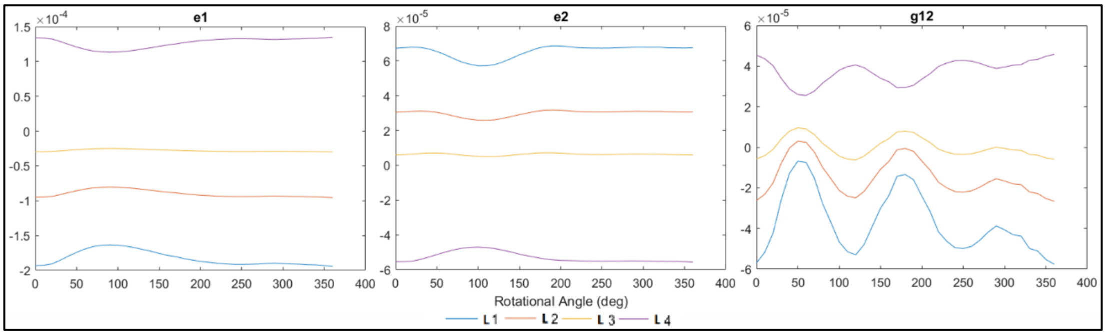

Figure 11: Lamina maximum strain at wind speed of 6 m/s and critical location, LIFE is the objective function and TOFMV is the decision variables

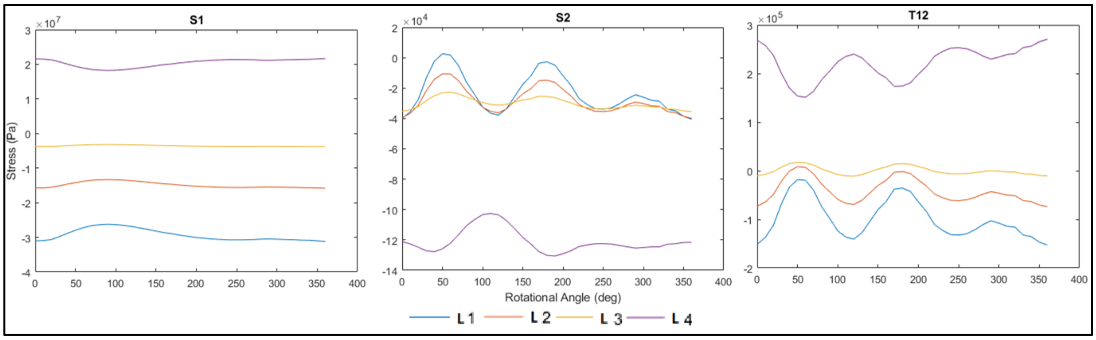

Figure 12: Lamina maximum stress at wind speed of 6 m/s and critical location, LIFE is the objective function and TOFMV is the decision variables

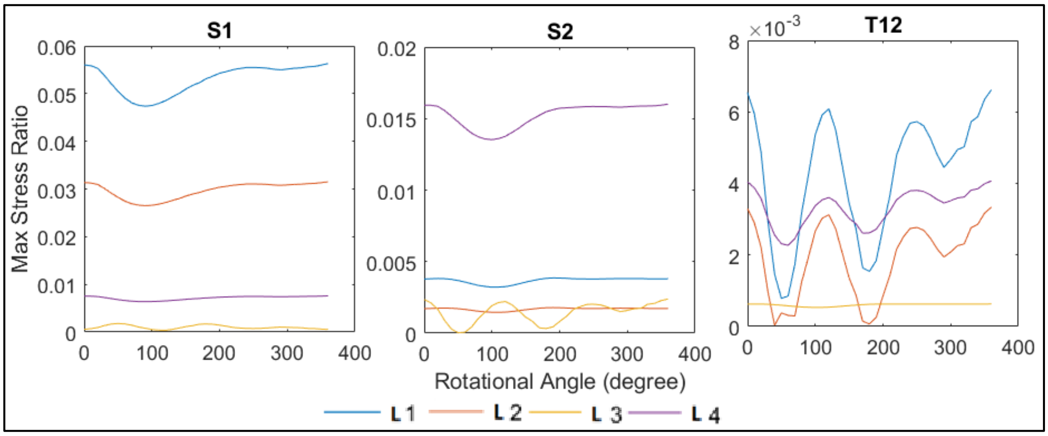

Figure 13: Lamina maximum stress ratio at wind speed of 6 m/s and critical location, LIFE is the objective function and TOFMV is the decision variables

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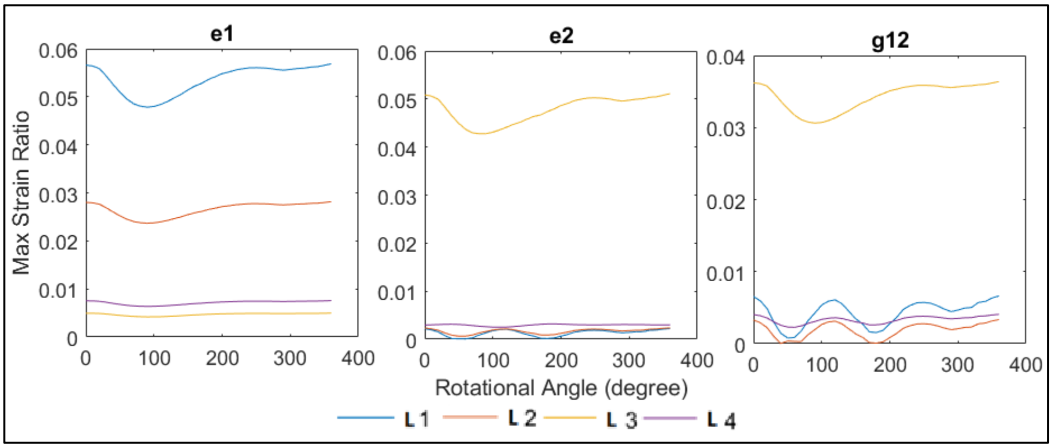

320 **Figure 14: Lamina maximum strain ratio at wind speed of 6 m/s and critical location, LIFE is the objective function and TOFMV is the decision variables**

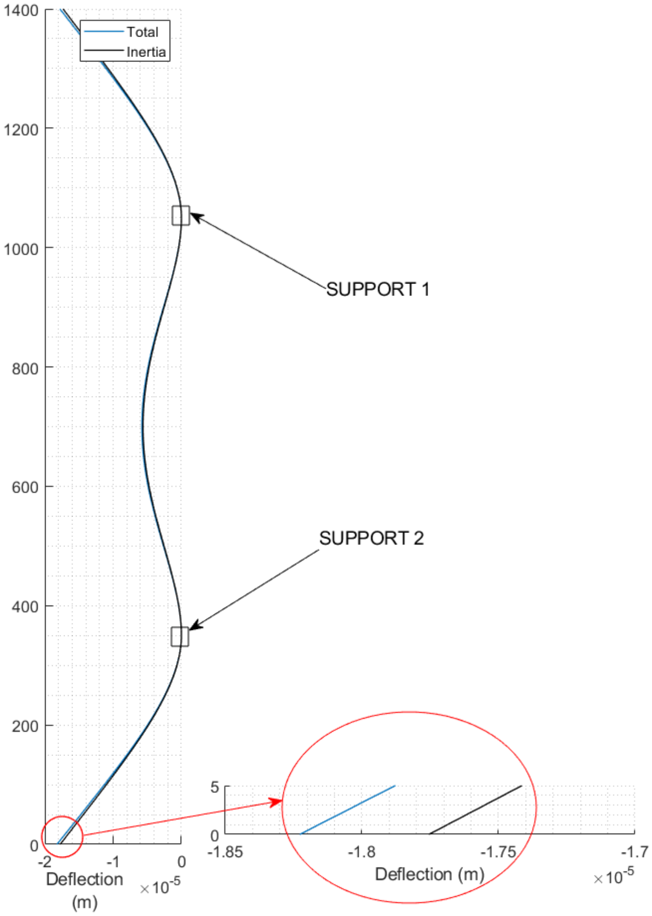

Figure 15:Comparing deflection due to inertia load, and total deflection at selected critical location and load for wind speed 6 m/s.

The results of the four objective functions are evaluated using the ANSYS-ACP model to validate the results. The validation depends on the failure criterion, the maximum and minimum stress/strain, and the location of max/min stress/strain. The comparison shows that all designs have low failure criteria values of less than one, for the four criteria selected. Moreover, the max/min stress/strain are remarkably close to the MATLAB model results with a variation of +/- 1 %, which is considered acceptable. The variation is due to tail correction which is used in the MATLAB model. The locations of max/min stress/strain coincide with the proposed MATLAB model. The maximum load is recorded at azimuthal angle between 90 and 120-degree, Figure 16 shows the results stress plot from ANSYS-ACP model for the final design achieved from SB model which is maximizing the blade life.

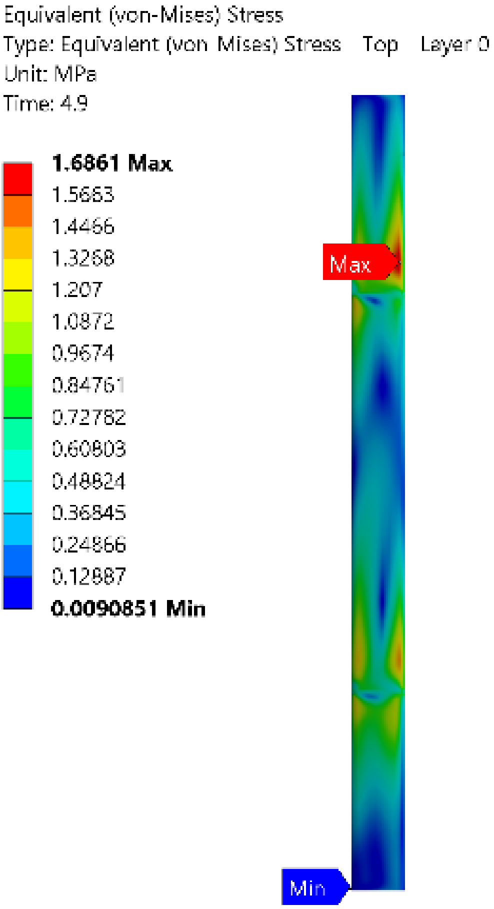

Figure 16: Equivalent Von-misses at the maximum loading conditions for the SB final design.

Conclusion

The paper novelty is in presenting an integrated model to be used in designing of vertical axis wind turbine blade to include the four critical design parameters, which are the mass, cost, life and fundamental frequency. The model evaluates the mass, the life and the first natural frequency of the blade, besides approximating the cost due to selected material sequence. The blade life depends on simplified fatigue model. The model is embedded into an optimization approach. The presented optimization method is Genetic algorithm for single objective function, minimizing mass and cost, as well as, maximizing life and fundamental natural frequency. Two decision variables set include the TOF and TOFMV. The TOF represents design parameters for optimizing lamina sequence, including thickness, orientation, and material selection for every lamina. The TOFMV represents the designing of laminae and sequence of lamina, including thickness, orientation, fiber selection, resin selection and volume fraction for every lamina.

The optimization results show that the including of single objective will contribute to enhancement of single parameter with percentage of reduction/increase that exceed tribble the unoptimized value. The including of more decision variables increases the capability of the optimization. The design of vertical axis wind turbine blades depends on strength and ultimate strain, besides the maximum deflection of the blade. The results show that the blade will survive the operation loads according to failure criterion for every lamina including both strength and ultimate strain limits. Blade structure results show that the on-axis angles are preferred for orientation sequence, this is due to the high centrifugal load which coincide with the publications (Hand et al., 2021; Geneid et al., 2022; Vergaerde et al., 2019).

The result from the presented approach concedes with validation model of ANSYS-ACP to a great extent, in addition to previous publications. The centrifugal load is considered as critical load for static structure behavior depending on rotation speed of the turbine. The fatigue and blade life depends on factors that could be simplified into basic model and integrated into the optimization approach. This allows significant improvement in the optimum design, including of life as constraints or even as objective.

The four objective functions show that there are interchangeable characteristics between them, which largely affect the final design. The study shows that the blade life shall affect the final structure design to a major extent, besides the natural frequencies. This will require the introduction of an augmented approach to include all objectives, function and decision variables in a single model to achieve better results. Nowadays artificial intelligence impacted our research scope, consequently, the implementation of AI in the fatigue evaluation and life prediction could be more efficient if deployed in the presented approach. As in future, the researchers are investigating to use deep learning mechanism for fatigue and life prediction. Another crucial usage for the presented approach is the implementation of sustainable cheap material such as natural bio-degradable fibers and resin.

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