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# Fatigue life time assessment of wind turbine blades based on vibration analysis

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***Abstract-***The fiber glass wind turbine blades need to detailed description of the vibration, the fatigue caused by vibration as mass missing and fatigue behaviour. It may be accomplished through the introduction of experimental study on the model of the rotating wind turbine. Data that has been obtained from the change of the rotor speed and different amplitude moments together with the ultimate moment. The theoretical M-N correlation and taking a slope of (10) due to the fact that it has been commonly reported for high efficiency unidirectional laminates. Theoretical M-N correlation and Palmgren-Miner\s rule have been deployed for the prediction of the safe life for wind turbine model blades.

Equation:- $Ma = Mu \times N^{(-1/m)}$ for the analysis of wind turbine blades that are subjected to the spectrum load by several of the rotor speed values. The original rule of the linear damage accumulation based on Miner and Palmgram has been utilized besides the suggested theoretical M-N correlation. Which is why, total damage at failure has been one, then it may be observed that for the two spectrum loading types (decreasing and increasing), the actual value of the damage at the failure has been a little over one. For the estimation of the number of the cycles to the failure, experimental data has been obtained from rotor speed change, the amplitude moments and air speed together with ultimate moment through utilizing the bending test .

***Key Words:*** *wind mill blades, composite materials, Fatigue failure, vibration, damage, Safe life.*

## Introduction

The corrosion stress behavior and Fatigue crack growth are must important factors for designing and performance of structural materials. The residual stresses generated during processing, instructs the fatigue performance. The fatigue crack propagation occurs, depending on the material's structure, if there were no residual stresses. The accumulative damage between corrosion and fatigue were happened due to the change in speed of rotor of wind turbine as the vibration occur when there was a missing in mass of the turbine blades. The study of the influence of the vibration on blade fatigue is required to predict due to continuous working of the wind turbine without interruption. The damage accumulation in micro-structure, including matrix cracking and fiber breakage, de-bonding, transverse-ply cracking and de-lamination, take place occasionally interactively and independently sometimes, and dominations of one or other could be highly influenced by the material variables as well as testing conditions. K.Suresh Babu *etal* [1] discussed the selection of the materials for the wind turbine blades utilizing the Technique for order preference by similarity [TOPSIS] (to the optimal solution) with different fuzzy linguistics. The process of material selection is one of the integrated steps, all design processes, it was observed from the analyses that in the case where the blades of wind turbine were made of fiber glass materials utilizing the carbon fibers, then they possess a low density, high stiffness, and long fatigue life. X. R. Wu & Y. J. Guo [2] investigated the (FRMLs) fatigue crack growth in laminates of fiber reinforced metal under variable and constant amplitude loadings, analytically and experimentally. Madsen *etal.* [3] explained that the design of wind turbines should include investigating the strength due to fatigue and ultimate loads. Those loads could result at the extreme situations like the excessive wind speed with settled rotor, or during yawing motion with unlocked yawing mechanism in normal operating conditions.

Papanikos .P. et al [4]. Developed a model for gradual fatigue damages so as to peet the accumulation of the damage and the life of the carbon fiber-reinforced plastic composite laminates (CFRP) with the random geometry and stacking sequence exposed to cyclic loading with constant amplitudes. The model covers the stress analysis components, fatigue failure analyses and degradation of fatigue material characteristic. V. M. Harik et al [5] studied low-cycle fatigue behaviors of the polymer matrix composites when subjected to the axial tensile load in the longitudinal fiber orientations [0]. The fatigue life was found to be < (10000) loading cycles under high loads that's as a result of the high property of degradation rates which have been significantly higher compared to the ones that have been noticed during high-cycle fatigue.

Sandia National Laboratories [7] tested the save life of the blades of the wind turbine that were exposed to different loading environments of the atmospheric wind and the results were described with random data analysis procedures. V. Bellenger et al [6-] proceeded fatigue tests using alternative bending device taking an R=-1 ratio at 23C ,45%RH with 2 different frequency values, 2Hz and 10Hz, the applied strain varied from 0.0116 to 0.0223. Tina Kashef and Steven R. Winterstein [8] calculated the fatigue life-time for members who have been subjected to the cyclic load with the use of the Miner's rule and S - N curves. The number of the cycles to failure has been associated with stress amplitude S by-:

$N(S) = 1/cS^b$. Researchers in the next few decades will spend determining the way of building better blade. They must be reach to superior processes of manufacturing, advanced materials, and more efficient blade design all in an effort for developing the blades which are more light-weight, more reliable from the structural point of view, and less costly.

## Nomenclature

| Symbol | Definitions | Units |
|---|---|---|
| $a$ | Axial speed interference factor | - |
| $a$□ | Tangential speed interference factor | - |
| $C$ | Chord length of blade | m |
| $B$ | Number of blades | - |
| $C_D$ | Drag coefficient - | - |
| $C_L$ | Lift Coefficient | - |
| $C_{FA}$ | Thrust coefficient | - |
| $R$ | Radius of rotor | m |
| $r$ | Radial distance from rotor axis to root of the blade | m |
| $U$ | Rotational speed measured by the tachometer for the model | rpm |
| $V$ | Mean wind speed | m/s |
| $u$ | Reduction in axial component of wind speed at the plane of wind turbine rotor disc | m/s |
| $V_1$ | Undisturbed wind speed | m/s |
| $V_2$ | Wind speed down stream of rotor | m/s |
| $d_{sh}$ | Shaft diameter | m |
| $d$ | Rotor Diameter | m |
| D | Drag force | N |
| $F$ □ | Circulation reduction factor | - |
| $FA$ | Thrust force | N |

## GREEK LETTERS

| Symbol | Definitions | Units |
|---|---|---|
| $a$ | Angle of attack (i.e angle of incidence) | deg |
| $a$ *opt* | Optimum attack angle | deg |
| β | Blade setting, twist angle | deg |
| $\sigma$ | Local solidity (B.C / 2□ r ) | □ |
| $\upsilon$ | Kinematic viscosity |  |
| □ | Angle of Yawing rotor | deg |
| □ | Rotor angular velocity | rad/s |
| $Q$ | Rotor torque | N.m |
| $\psi$ | Relative flow angle | deg |
| Λ | Tip speed ratio | - |
| $\Lambda_d$ | Rotor's design tip speed ratio of rotor | - |
| $\Lambda_r$ | Rotor's Local speed ratio of rotor | - |
| □$_{ba}$ | Coefficient of friction in deep grove ball bearing | - |
| $\mu_t$ | Total coefficient of friction | - |

| | | |
|---|---|---|
| $\rho$ | Air density | kg/m$^3$ |
| $W$ | Relative flow velocity through the rotor | m/s |
| $r$ | Radial distance from rotor axis to root of the blade | m |
| R$a$ | Arching radius | m |
| $rb$ | Radial distance from rotor axis to blade element | m |
| $R$ | Radius of rotor | m |
| $V$ | Mean wind speed | m/s |
| $u$ | Reduction in axial component of wind speed at the plane of wind turbine rotor disc | m/s |
| $V1$ | Undisturbed wind speed | m/s |

## Theory

To determine the forces on the blades for a given value of (a) and (a'), consider an element of a blade, situated at radius (r), of width (dr) and of chord (C), where (C) is in general a function of (r), see Fig (1). This element has a speed in the rotation plane $(\Omega.r)$. The flow itself is rotating in the same plane

at $a'\Omega$ and thus the air velocity relative to the element in this plane is $(\Omega.r(1+a'))$. The axial speed

of the air at this plane is (V1 (1-a)). Values of (a) and (a') may vary with the radius. Then the total velocity of the flow relative to the blade is (W) see fig (2). The forces which act on the blade are a result of lift and drag of the section profile of the blade element. The lift and drag forces can be analysis into components perpendicular and parallel to the direction of the undisturbed wind velocity, these components combined together to form the net force *(FA)* in the undisturbed wind speed direction, and the net force. *(FT)* (Tangential force) in the direction of translation. The force *(F T)* is available to do active work. To determine the interference factor values *(a)* and *(a')*, the axial force on the blades is set equal to the axial momentum change of the flow, and the torque on the blades is put equal to the angular momentum change. Consider now the axial momentum of flow through the annuls to determine the expression for the axial speed induction factor. The thrust can be obtained by the following equation [10].

$$dF_A = 4\pi.\rho.r.a.V^2(1-a)dr \qquad \ldots (1)$$

$$dQ = 2\pi.a'(1-a)V.\Omega.r^2 ds \qquad \ldots. (2)$$

The M-N curve (applied moment versus the allowable cycles to failure) will be defined by the relationship [11].

$$Ma = Mu \times N\ (-1/m) \qquad \ldots.(3)$$

Where -:

Ma represents the amplitude moment in on load cycle

Mu represents ultimate moment in the blade ,

N represents allowable cycles to failure,

m represents slope of M-N curve

The associated damage with the curve may be estimated through the application of Palmgren – Miner’s rule as follows:

$$\text{Damage} = \sum_{i=1}^{j} \frac{n_i}{N_i} \qquad \ldots.. (4)$$

Where,-:

i is the load case number ,

ni is the number of load cycles for case I, and

j is the total number of load cases ,

Ni is the number of load cycles to failure for case 1.

## Experimental Work

The experimental work used for measuring the applied moments ant it is necessary to measure the velocities of the generated air acting on the wind turbine blades. This work is to reach a safe estimate for blades life of wind turbine, which the model will be subjected to various speeds (80-430) Rpm according to simplified load spectrum approach to calculate the equivalent damage fatigue testing, which will be only dependent upon vibration and the design- load spectrum. Which is why, rather than the S-N curve there will be M-N curve (i.e. applied moment vs. number of cycles to failure) for blades. The relationship below (equation No3) will be defined the curves drawing between moment and Nf. The damage happened with every one of the curves may be estimated through the application of the Palmgren – Miner's rule (equation N0.4). The FORTRAN station 90 program was used to determine the moments that affected the blades. For the purpose of accelerating the levels of the damage that occur in blades, through the increase in the load amplitude .The wind turbine speeds and acceleration according to various air velocities were measured using the vibration analyzer type (PCE-VM5000) as shown in figure (3), *and* to ensure acceleration measurement in the X and Y axes, two accelerometers have been mounted perpendicular to each other. The rotor blade model was used as the same model by Ref[12], which consist of ( hop, Brass ring, 18 fiber glass blades, steel shaft 30mm diameter and two flange bearings, as shown in figure (4).

## Results and discussion

The motor speeds between 80 and 430 Rpm were selected to insure that the machine will start to rotate at the cut –in the rated wind speed and to insure the maximum power tip speed ratio design. The estimated of computation moments obtained from the optimization theory, have been plotted against the air velocity as shown in table (1) and figure (5), a small scattering in the variation may also be due to the mechanical performance of the rotor rig assembly. An increase in velocity within the range of velocities of the experimental program will cause an increase in the amplitude moment exerted on the blades. The M-N curve method was found to be the most way to characterizing the fatigue behavior of the blades for wind turbine. This method usually consists of the determination of the number of the cycles to failure of moment ranges associated with a particular load history, and it has been chosen to analyze the blade fatigue. The resulting M-N curve yields an estimation of the mean time –to- failure as a function of amplitude moment ranges. The adhesive material was of the same composite material used to manufacture the blade and it's failure led to excessive vibration of the wind turbine blades. Figure (6) shows cumulative damage predictions according to the experimental M-N equation after the amplitude moment subjected and vibration rang increasing Figure (7) shows the M-N relationship for the range of rotor speeds (80-430) Rpm used at slope equal (12) and different moments from (0.4-4.5)

N.m , the figure shows a very good analysis of wind turbine blades failure. The fatigue life varies inversely with the amplitude moment. To verify the general effect of the vibration with respect to amplitude moment as shown in table (2) and figures (8) and (9), where if the moment increasing with the (unbalance of the machine), the number of cycle to failure will be decreasing and the damage will be increasing and according to this statement the figures (10) and (11) shows the 3D graphs , these 3D figures are very useful tools to prediction the fatigue life and damage percentage of rotating wind mill turbine blades. The fatigue failures occur in different locations of turbine blades, like the failure of skin laminate failure in the tension or the local buckling adhesive failure in the shear or peel or bolt joint figure (12).

## Conclusions

The present work showed that the increasing of applied moment when the rotor speed increasing and the rate of vibration also increase ,then the value of damage happened on the wind turbine blades reaching more than one ,so the safe life will be reduce. The failure of few bonded joints led to excessive vibration of the wind turbine blades and because of the stress concentration at these region.

## Acknowledgement

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**Table (1) Damage according to the theoretical equation with slope12.**

| rpm | Moment N.m | ni cycle | ∑ni cycle | Nf cycle | Damage |
|---|---|---|---|---|---|
| 80 | 0.415 | 960000 | 960000 | 1.437E19 | 6.860E-14 |
| 140 | 0.575 | 1680000 | 2640000 | 2.871E17 | 9.195E-12 |
| 180 | 0.825 | 2160000 | 4800000 | 3.773E15 | 1.272E-11 |
| 210 | 1.26 | 2520000 | 7320000 | 2.342E13 | 3.124E-7 |
| 240 | 1.425 | 2880000 | 10200000 | 5.350E12 | 1.905E-6 |
| 260 | 1.84 | 3120000 | 13320000 | 2.490E11 | 5.347E-5 |
| 290 | 2.3 | 3480000 | 16800000 | 1.711E10 | 9.815E-4 |
| 315 | 2.755 | 3780000 | 20580000 | 1.961E9 | 0.0104 |
| 340 | 3.00 | 4080000 | 24660000 | 7.058E8 | 0.034 |
| 370 | 3.310 | 4440000 | 29100000 | 2.168E8 | 0.134 |
| 390 | 3.675 | 4680000 | 33780000 | 6.181E7 | 0.546 |
| 430 | 4.15 | 5160000 | 38940000 | 1.437E7 | 2.709 |

**Table (2) applied moment, air velocity and No. of cycle to failure with slope12**

| NO. | rpm | velocity | Moment N,m | Nf cycle 12 | Damage |
|---|---|---|---|---|---|
| 1- | 15 | 2.19 | 0.1375 | 8.213E24 | 2.191E-20 |
| 2- | 39 | 3.1 | 0.355 | 9.363E19 | 5.221E-15 |
| 3- | 80 | 3.57 | 0.415 | 1.437E19 | 8.797E-14 |
| 4- | 126 | 3.8 | 0.460 | 4.179E18 | 5.625E-13 |
| 5- | 140 | 4.1 | 0.575 | 2.872E17 | 7.479E-12 |
| 6- | 148 | 4.6 | 0.69 | 3.221E16 | 7.669E-11 |
| 7- | 180 | 5.1 | 0.825 | 3.773E15 | 8.666E-10 |
| 8- | 196 | 5.4 | 0.92 | 1.020E15 | 4.218E-9 |
| 9- | 208 | 6.02 | 1.15 | 7.011E13 | 5.345E-8 |
| 10- | 240 | 6.51 | 1.425 | 5.350E12 | 7.562E-7 |
| 11- | 260 | 7.16 | 1.84 | 2.491E11 | 1.328E-5 |
| 12- | 274 | 8.0 | 2.06 | 6.428E10 | 6.443E-5 |
| 13 | 291 | 8.5 | 2.3 | 1.712E10 | 2.684E-4 |
| 14- | 315 | 8.94 | 2.755 | 1.962E9 | 2.195E-3 |
| 15- | 391 | 11.32 | 3.675 | 3.52E07 | 0.1045 |
| 16 | 412 | 11.94 | 4.100 | 3.25E07 | 0.4109 |
| 17- | 429 | 12.01 | 4.15 | 2.99E07 | 0.7601 |
| 18- | 442 | 12.65 | 4.595 | 2.87E07 | 2.013 |

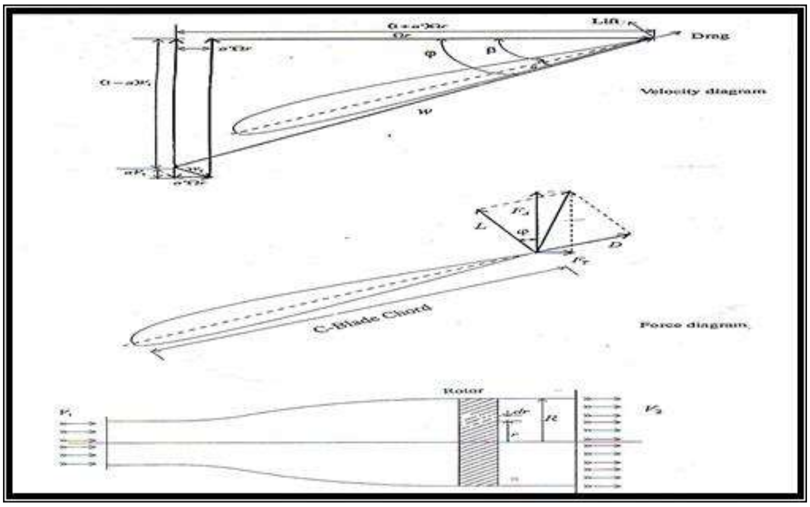

Fig. (1) Force and flow geometry for blade Ref [9]

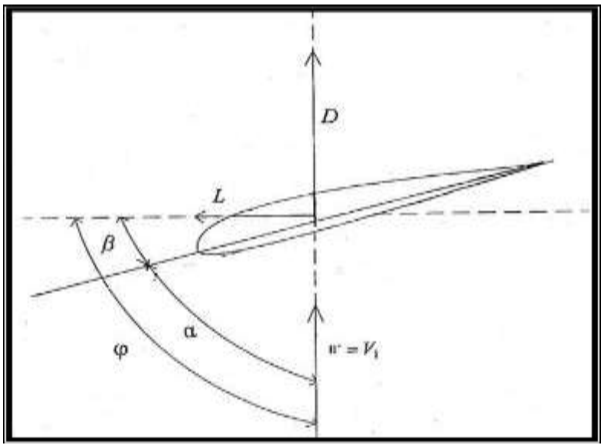

Fig (2) Lift and drag at starting Ref [9]

**Figure (3) vibration meter type PCE-VM5000**

Figure (4). Windmill turbine system

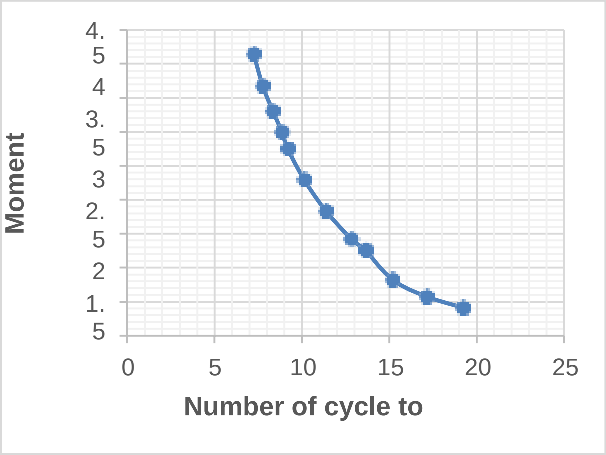

Figure (5) The moment and No. of cycle to failure

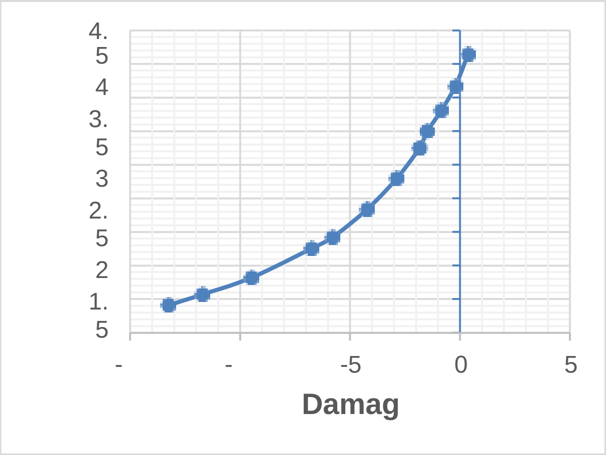

Figure (6) The moment and damage

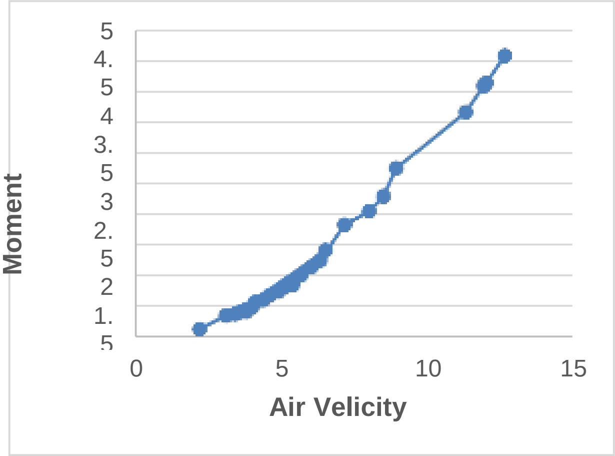

Figure (7) The moment and Air velocity

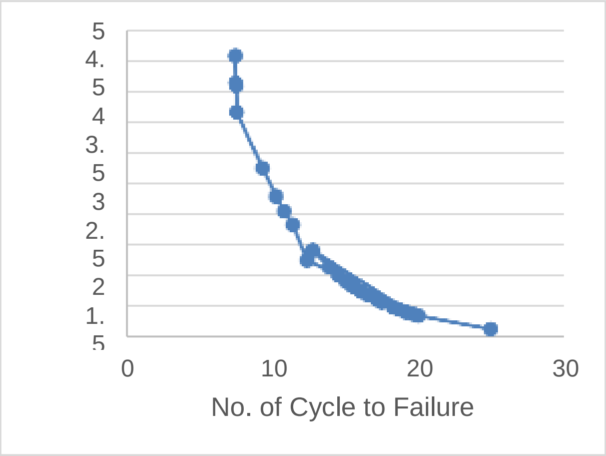

Figure (8) The moment and No. of Cycle to

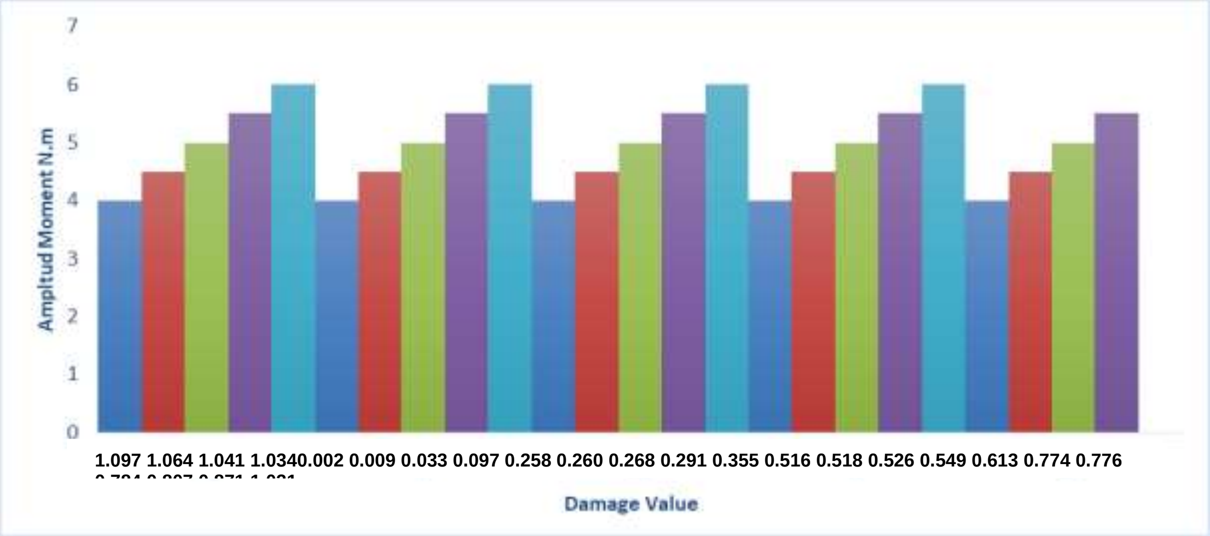

Figure (9) The program of increasing moment

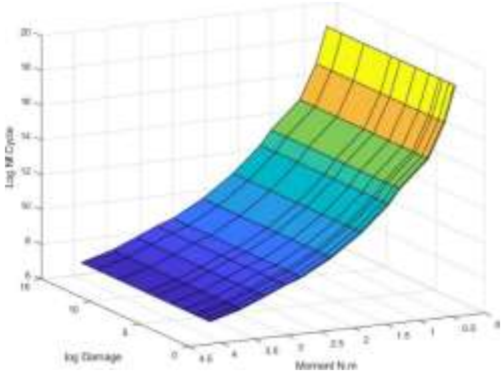

Figure (10) Damage and applied moment with Nf

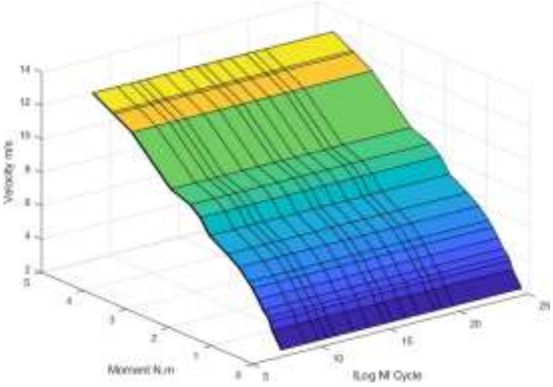

Figure (11) Velocity and applied moment with Nf

Figure (12) Blade failure in wind turbine at adhesive joint.