Optimisation of the Structural Design of a Wind Turbine

Beatriz Navales

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In **Chapter 3** the methodology introduced in the previous chapter is applied on the rotor blades of the GMIT wind turbine installation, and consequently its fatigue allowable is obtained. First the specification and operational characteristics of the wind turbine are given. The process carried out to define a stress spectrum is presented. A model of the wind turbine is developed. A loading, consisting in aerodynamic, gravitational and centrifugal forces, is applied on the model to obtain a stress history spectrum. The information contained in the spectra is then organised into a relevant fatigue spectrum. Finally, the fatigue methodology introduced in chapter 3 is applied to the fatigue spectrum, and the fatigue allowable is obtained.

In **Chapter 4** the blade for the GMIT wind turbine is redesigned to optimise its fatigue life. A FEM structural analysis is carried out to compute stress distributions along the blade and identify hot spots. Various design alternatives are then developed and compared.

Chapter 5 presents the conclusions drawn by the fatigue analysis and design optimisation. A discussion of the factors that yield the results is given. Assumptions considered for the wind turbine model, and loading conditions are examined. Finally, recommendations to improve the fatigue life of the wind turbine are given.

Symbols and Units

GENERAL:

Symbol	*Nomenclature*	*Unit*
B	number of blades	[-]
c	chord	[m]
$\mathbf{C_d}$	drag coefficient	[-]
$\mathbf{C_l}$	lift coefficient	[-]
D	drag force	[N]
I	turbulence intensity	[-]
L	lift force	[N]
$\mathbf{V_{mean}}$	mean wind velocity	[m/s]
α	attack angle	[^{0}]
β	setting angle	[^{0}]
ρ	air density	[kg/m^3]
η	wind turbine efficiency	[-]
ϕ	angle of inclination, flow angle	[^{0}]
σ	natural turbulence	[-]
Ω	rotor speed	[RPM]
ϖ	natural frequency of the component	[rad/sec]
λ	tip speed ratio	[-]

FATIGUE

Symbol	*Nomenclature*	*Unit*
α	empirical exponent for S-N line	[-]
i	index of layers in the spectrum	[-]
I	number of layers in one spectrum	[-]
$\mathbf{K_a}$	surface finish factor,	[-]
$\mathbf{K_b}$	size factor,	[-]
$\mathbf{K_c}$	reliability factor,	[-]
$\mathbf{K_d}$	temperature factor,	[-]
$\mathbf{K_e}$	modifying factor for stress concentration	[-]
$\mathbf{K_f}$	miscellaneous effect factor	[-]
m	n^0 of repetitions of the spectrum required to cause fatigue failure	[-]
$\mathbf{N_f}$	fatigue lifetime under spectrum loading	[cycles]
$\mathbf{n_i}$	number of cycles applied at stress level S_i	[cycles]
$\mathbf{N_i}$	fatigue lifetime at a constant stress level S_i	[cycles]
R	stress ratio (minimum/maximum)	[-]
$\mathbf{S_{alt}}$	alternating stress	[MPa]
$\mathbf{S_{avg}}$	mean or average stress of the cycle	[MPa]
$\mathbf{S_{cyc}}$	alternating stress	[MPa]
$\mathbf{S_e}$	endurance limit	[MPa]
$\mathbf{s_i}$	stress ratio for the ith layer	[-]
$\mathbf{S_i}$	stress parameter in the cycle upon which fatigue damage is primary dependent	[MPa]
$\mathbf{S_I}$	empirical stress coefficient for S-N line	[MPa]
$\mathbf{S_{max}}$	maximum stress of the cycle	[MPa]
$\mathbf{S_{maxmax}}$	largest stress in the stress spectrum	[MPa]
$\mathbf{S_{mean}}$	mean or average stress of the cycle	[MPa]
$\mathbf{S_{min}}$	minimum stress of the cycle	[MPa]
$\mathbf{S_{range}}$	maximum to minimum stress range	[MPa]

Contents

Chapter 1. Previous Work in Fatigue on Wind Turbines

Chapter 2. Selection of Fatigue Methodology

Chapter 3. Application of Fatigue Methodology

Chapter 4. Optimisation of Blade Design Against Fatigue

References

Bibliography

Appendix I - FORTRAN PROGRAMS

Chapter 1. Previous Work in Fatigue on Wind Turbines

1.1. Introduction

The aim of this chapter is to examine the previous work carried out by various researchers in the study of the fatigue life for wind turbines.

After a brief review on the fatigue problems found in wind turbines, the different methodologies developed to assess the fatigue life of wind turbines will be addressed. Findings of the research programs relevant to the present work will be highlighted.

Finally, a description of the methodology selected to study the fatigue life of the GMIT wind turbine installation is presented.

1.2. Fatigue Research Programs Review

1.2.1. Fatigue Problems with Wind Turbines

Fatigue has been identified as a major cause of failure for wind turbine components[1]. It was a fatigue failure that brought down a blade from the Smith-Putnam wind turbine in 1945 [1]. The machine remained parked for several years, during that time, the parked blades were subjected to vibrations induced by strong winds. These repeated vibrations, finally fatigued one blade. A small crack developed, which eventually led to a blade failure[1] . In addition, Rocky Flats Testing [2] reported that fatigue was identified as the major cause of small wind systems structural failure. Approximately half of the failures documented up to that date occurred in the rotor assembly or rotor blades. Accordingly, the Rocky Flats Wind Energy Research Center initiated a research project on the fatigue life of wind turbines. Similar results were reported by the Sandia Laboratory [3]. Virtually all of the turbines built in California in the early eighties experienced fatigue problems in energetic sites (sites with an average wind speed of 7 m/s or more). Research programs at the Sandia Laboratories include the measurement of material fatigue properties, definition of turbine loadings, and the development of fatigue life time prediction tools. Consequently, turbines installed more recently have demonstrated tremendous improvements.

1.2.2. Fatigue Design Procedures

There are two approaches to analyse against fatigue failures in wind turbines. The traditional S-N approach, that bases its analysis on the nominal stress in the region of the component being analysed, and the fracture mechanics approach which provides a model of the crack-propagation state. Both of them have been used successfully in the fatigue design of wind turbines [24]. The S-N approach is used in high cycle fatigue applications, as is the case of wind turbines, and it will be used in this project. This method is the one used by the vast majority of researchers, and is the currently accepted to assess fatigue life in the European Standards [30].

1.2.3. Fatigue Methodologies Review

1.2.3.1. First Approach

As part of the Rocky Flats Research Program, a report by Waldon [2] discussed the theory of fatigue, and reviewed techniques for predicting fatigue life loads and fatigue life. In order to assess the fatigue life, first the loading to which a wind turbine is subjected has to be analysed. This loading include centrifugal, aerodynamic thrust and torque, gravity, gyroscopic and aerodynamic loads induced by crossflow or yaw motion. These loads could be calculated by the use of aerodynamic codes (PROP, MOSTAB) [2].

Once the loading on the wind turbine is estimated, a method to predict the fatigue life is required. Four methods were documented by Waldon[2], three of them to assess fatigue during the design phase, the fourth during testing.

These include:

1. the strength of materials method,
2. the fatigue curve method,
3. and the fatigue event method.
4. testing method.

The strength of materials method is the most simplified of all and it was used in first designs as in the 8kW Grumman Wind Turbine [1] . In this method, the endurance strength is considered to be a factor of two on yield strength. The biggest drawback was that some materials do not follow this factor of two rule.

The fatigue curve method involves using a S-N fatigue curve. The cycles of loading are calculated using a Weibull distribution and the operational characteristics of the wind turbine (rpm). This technique assumes one stress level: the maximum, what can lead to possible over-design[2].

The last method analysed is the Fatigue Event Method based on aircraft techniques. In this method the wind turbine operation is divided in different operating conditions. These would include: start-up, normal operation, rotor speed control, yaw, shutdown (normal, and emergency), and high wind-speed survival. The loads to which the wind turbine is subjected in each of these conditions are then calculated. The next step is to estimate the number of hours of operation in each condition using the Weibull distribution. Then, the number of cycles is calculated using the dominant frequency of the components operation (1 cycle per revolution for the blades). Next a fatigue damage rule must be chosen to estimate fatigue. Several rules had been used up to date, these included Palmgren-Miner[4], Manson Double Linear Rule [5], Corten-Dolan Theory [6]. Considering that as the number of cycles increases, so does the accuracy of the life prediction the Palmgren-Miner rule has been identified as the best choice for fatigue prediction in wind turbine components[10]. At present is used by most researchers, and it is used in this project.

The testing method reported by Waldon [2] for predicting fatigue life, include a cycle counting method. There are various cycle counting methods, peak-count, mean-range and rainflow [7]. For wind turbines where fatigue cycles involve varying mean loads the rainflow method performs better [8]. It is the counting method currently used by most researchers, and consequently it is the one used in this project.

The testing methodology suggested by Waldon follows 4 basic steps:

1- Estimate magnitude and frequency of occurrence of the loads
2- Estimate the component fatigue strength
3- Select a cumulative damage rule
4- Measure loads and count cycles to develop the overall distribution of loads and compare to those estimated in 1.

However, at that time there were some unknowns such as how to estimate the frequency of occurrence of yaw-induced loads, pitch-down, and shut-down, as well as the amount of data required for each of them.

1.2.3.2. Yaw Effects

A further study was carried out by Waldon on the effect of yaw rate on the fatigue life[9]. Induced gyroscopic loads during wind system free yawing were found to be critical in the test machine under consideration. A database was obtained characterising the fatigue loads experimented by a wind system under various wind conditions. Analysis of these showed that the highest loadings were usually associated with periods of yaw motion. The bending moments were doubled when a 5 deg/sec yawing rate was experienced. Although the causes of yaw motion were not so clearly identified, it was found that the change in wind direction was not the main cause of it, but the non uniform wind velocity profile along the rotor disk These changes resulted in a horizontal wind shear that would be the principle cause of yawing.

In order to assess the percentage of time the machine yaws at particular rates, counting yaw load cycles was performed, showing that the percentage of time for each yaw rate was hardly affected by the mean wind speed. Conclusions drawn by Waldon also include design considerations affecting free-yaw systems, these require low quasi-steady cyclic design stress, as well as control or damping of yaw rate.

Based on Waldon findings Eddersson and Stoddard reported a method to predict the fatigue life of Wind Turbines [10]. They also identify gravity and centrifugal forces as the primary fatigue loads in large HAWT. However, the dynamics affects due to the wind were still not well understood.

1.2.3.3. Importance of Dynamics

The importance of the inclusion of dynamics and turbulence to predict fatigue is discussed in detail by Harrad and Hassan[11]. The problem of turbulence was first addressed by Rosenbrock[12] in 1955. However, most work in this area was made from the late seventies by Frandsen[13], Raab[14], and Hassan[15]. The latter referred to the general problem of the "eddy slicing", process that the turbulence undergoes when seen from a rotating frame of reference. Research on this area has grown since, Raab [16] attempted to use the turbulence model to excite the dynamics of the wind turbine structure. Anderson, Garrad and Hassan [17] showed the first results from structural response calculations, Mandsen and Frandsen [18] gave then a treatment of the structural response and its implications on fatigue life. Mandsen later published a detailed analysis on the effects of dynamics in fatigue damage of wind turbines [19]. Following lines similar to those adopted by Madsen, Garrad and Hassan[11] have also developed analysis proceedings to predict the dynamic response of the turbines and the resulting fatigue damage.

The dynamic response of a wind turbine contains a deterministic cyclic element, and superimposed on top of that is a stochastic, random element which arises as a result of the turbulence in the wind. The relative importance of both sources of load was investigated theoretically by Harrad and Hassan[11] in which the fatigue damage resulting from both sources was evaluated for a hypothetical weld on the Danish Nibe B turbine. Figure 1-1 illustrates this effect, it is shown that removing the turbulence effects, and leaving only the cyclic input can underestimate the dynamic loads by a factor of two, which has a very strong effect on the damage rate. The same results where found by Murtha[20], when studying the cumulative damage of turbulence by computing the difference between full-time and non turbulence damage in the Hamilton Standard WTS-4, four megawatt machine.

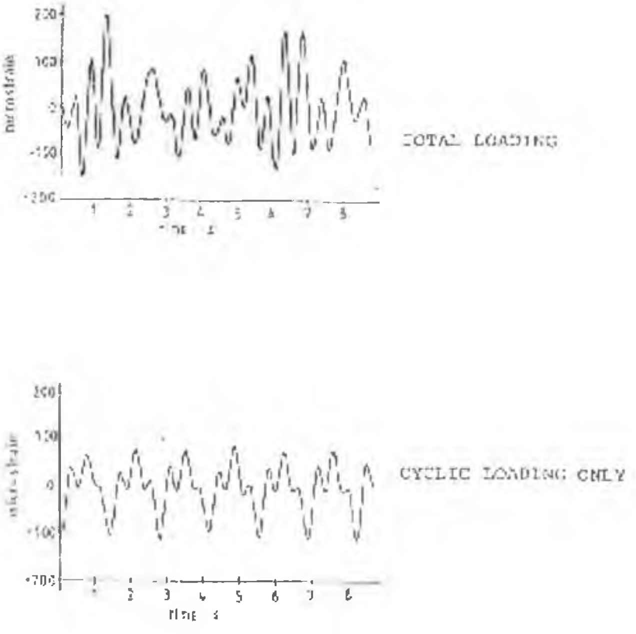


Figure 1-1. Flatwise Strain Measurements taken on the Howden HWP300 Wind Turbine[11].

1.2.3.4. Computer Codes for Calculating Dynamic Loads

Various computer codes had been developed to calculate the dynamic loads in HAWT. One of the first codes was the MOSTAB-WT, based on an existing helicopter blade analysis code called MOSTAB. The MOSTAB-WT code contained one degree of freedom. New codes with multiple degrees of blade freedom were developed in order to design advance wind turbines. They included other components apart from the blades such as the drive train, controls and the tower.

Seven of them, MOSTAB-WT,-HFW, AND -WTE, MOSTAS, REXOR-WT,GETSS, F-762 are compared by Spera [23] . In this study, the loads calculated by each code were compared with steady state Mod-0 wind turbine data. Four of the seven codes include rotor-tower interaction (MOSTAS, REXOR-WT,GETSS, and F-762) and three were limited to rotor analysis (MOSTAB-WT,-HFW, AND -WTE). Criteria to verify the codes included agreement of calculated loads to nominal measured load, and prediction of harmonics. Six of the seven codes (MOSTAB-WT, AND -HFW, MOSTAS, F-762, REXOR-WT, and GETSS) calculated loads which on the average were within 6% nominal loads measured on the Mod-0 wind turbine. The REXOR-WT code appeared to be the most consistent in producing calculated loads close to nominal loads. Loads calculated using the MOSTAB-WTE were 15% above nominal levels, still inside validation range. All codes except the MOSTAB-WT and -HFW, calculated satisfactorily the general pattern of flatwise and edgewise loads. These two codes contain the assumption of rigid rotor support which eliminates some edgewise load harmonics. Accordingly, the four codes which include rotor-tower interaction were validated for calculating dynamic loads for rigid or semi-rigid wind turbines, is expected that they perform the same when verification using soft system data. The three other codes analysis (MOSTAB-WT,-HFW, AND -WTE) are limited to analysis of rotor loads. However, for rigid or semi-rigid systems, these codes are often sufficient. In addition, use of rotor codes rather than system codes can result in substantial savings in computer time and input data preparation.

1.2.3.5. Definition of Load Cycles

Murtha's work [20] revealed that the cumulative damage depends to a great degree on the number of starts and stops , mean wind speed, and degree of turbulence. These causes are in good agreement with the three fatigue cycles identified by Finger [21] and currently adopted by fatigue theory. Figure 1-2 shows these cycles, Type I load cycles occur once per revolution (1P loads), and are caused by the narrow band turbulence about a mean, Type II are caused by a varying mean wind speed, and Type III are the start up/shut down cycles.

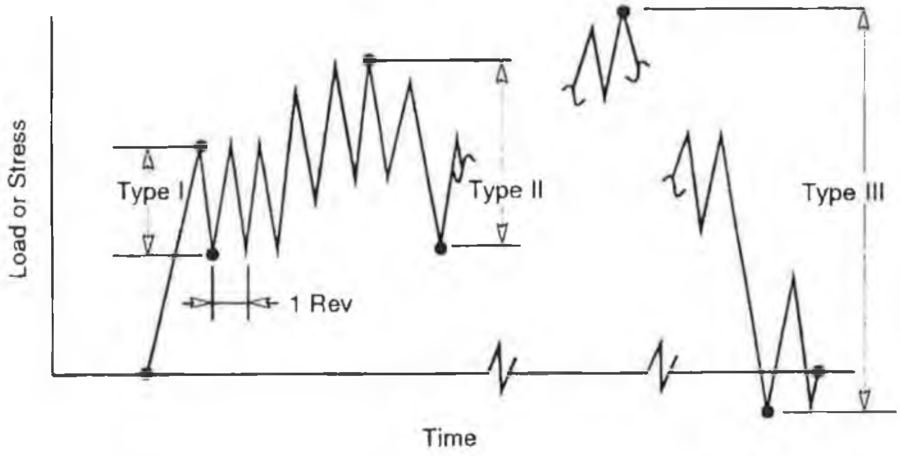


Figure 1-2. Idealised types of fatigue cycles [24]

The methodology developed by Finger[21] was used for the structural design of the 2.5 MW Mod-2 and the 3.2 MW Mod-5B Boeing wind turbines. A similar procedure is followed in this project, although some modifications were made to accommodate it to the data available. The original method developed by Finger involves the following steps:

1. load prediction (load spectrum)
2. cycle counting
3. fatigue allowables definition

For the load prediction five individual loading conditions were considered: mean flap moment, alternating flap moment, mean chord moment, alternating chord moment, and centrifugal forces. The loads were calculated by using the MOSTAB 1- HFW computer code. This program is a general purposes analysis code for calculating the dynamic loads and investigating the stability of HAWT. For the development of the cyclic loads, the MOSTAB program was used with prescribed wind gradients and gust simulation to represent the narrow-band turbulence variation about a mean wind and longer period variation of the mean wind. The machine was tested and the measured loads were compared to the predicted values. The data was processed using the rainflow counting procedure using DATAMYTES (also used for the data processing of the Hamilton Standard WTS-4). Analysis of these data showed that Type I cycles were the overwhelming portion of fatigue damage, and so, were the only cycles considered for the fatigue damage. The fracture mechanics method was used to define the fatigue allowable stress, and therefore the fatigue life. The use of a fracture mechanics approach was in part because of the extensive experience at the Boeing Company and its subsidiaries with its application and verification. Findings include that the varying chordwise cyclic loads has a negligible impact on the fatigue stress spectrum. Finding that will be collaborated later by Winterstein and Lange [22].

As mentioned before a similar path was followed in this project, although some modifications have been made. The loads are computed making use of the code 'WindForces'. The program was implemented during this project to account for the aerodynamic forces acting on the blades. Instead of considering a statistical wind profile, a real time history wind speed was considered for the input. The most critical wind speed period was considered. The rainflow algorithm was implemented during this project to account for the stress cycles. The S-N approach was selected to estimate the fatigue allowable, as it is recommended in the European Standards [30].

1.2.3.6. Fatigue Lifetime Estimation Codes

Sandia Laboratories developed the program LIFE2 to calculate the fatigue lifetimes of wind turbines[3,24]. The package leads the user through the input definitions required to predict the service lifetime of a turbine component: (1) the annual wind speed distribution at the site, (2) fatigue data, (3) the stress cycles of the total stress states on the component as a function of the operating state of the turbine and the average wind speed, and (4) the operating parameters and stress concentration factor of the components. The code uses the either Miner's rule or a linear crack-propagation rule to numerically calculate the time to failure making use of S-N based cumulative damage. The distribution of mean and amplitude stresses are entered for the various operational states of the turbine, and those values can be obtained from simulated or measured time series data (using rainflow counting techniques) or from analytical/numerical models. The predicted service lifetime for the turbine is obtained by summing the damage caused by the stress cycles at each operational state over the distribution wind speed.

An additional code, FARROW[3] (Fatigue and Reliability Of Wind Turbines), was developed to assess the degree of confidence with which the component meet its targeted design life. This code is based on the theory of structural reliability. The work performed shows that even for comparatively well understood and tested turbines, with a long median lifetime, the probability of failure is relatively high.

Empirical equations were developed by Spera [25] to create design trends charts for estimating cyclic load levels versus their probability of exceedences. The fatigue loads can be predicted with these charts during the design phase. The equations are based on measurement in eight HAWT with rated powers from 50 to 4000 kW, with a sample size of nearly 1 million rotor revolution. The measuring parameter were wind velocity, cyclic torque in power train, cyclic flatwise and chordwise blade bending load, and small sample of cyclic tower bending loads. Only Type I cycles were included in this study.

New trends in fatigue life analysis, consist on the performance of a fatigue analysis on the wind turbine components, specially the rotor blades.

1.2.3.7. Blade Testing

A series of tests have been performed on blade material composites[27]. Thes applied only on the blades, and not on the whole turbine as in the previous w consist on the application of a load spectrum on the blades in a laboratory. accepted spectrum is WISPER (WInd SPEctrum Reference) which simulate condition in the flap direction, at a point close to the blade root. It is measurements from 9 different wind turbines, the sequence represents appro months service of a generic wind turbine at a rotor speed of 45 rpm. The WI sequence is intended for comparative purposes only, to evaluate materials details, dimension, design alternatives, and fatigue lifetimes. A further spectrum currently used is the WISPERX, where the low range cycles are they are considered not to have influence on the fatigue life. The dama calculated by means of a rainflow counting procedure. The predicted lifetim determined applying the Palmgren-Miner's rule. However, studies carried out and Bach[28] using this methodology shows that the use of this rule unconservative predictions for some materials.

1.2.3.8. Standards

The problem of fatigue is discussed in the wind turbine standards. The IEC focused on small wind turbines, and addresses the fatigue problem by n conservative safety factor. The EUR 16898 EN [30] , whose objective was to uniform methodology to derive wind turbine design load spectra when anal scale wind turbines, covers the subject in depth. In addition to the damage/ calculation, a probabilistic fatigue analysis, to assess the fatigue reliability o turbine components is given. The latter will not be further treated in this report and the reader is referred to the bibliography for further information.

In this standard, the fatigue damage which the main wind turbine components experience is derived from the load spectra. Two steps must be carried out:

1. determination of stresses or strains from load data,
2. and application of a damage calculation model.

For the determination of the load spectra, the individual load cases are identified and are distributed according to the frequency distribution of the wind speed (Weibull).10-minutes time series (at least 6 per wind speed interval) have to be counted using the rainflow counting technique. It is common practice to derive the load spectra for 1 year of wind turbine operation. The spectra are presented as cumulative load spectra. In addition, some possibilities are given to account for the load cycles between the load cases (low frequency cycles occurring less than once per 10 minutes).Wind direction changes should also be considered as part of the low frequency analysis, even in combination with the low frequency wind speed changes. These wind direction changes are considered to be very important for the fatigue strength of the tower.

For the stress/strain calculation, all six load components (3 moments and 3 forces) have to be considered. As the axial stresses due to bending moments (flatwise and edgewise) and centrifugal forces are dominant, the fatigue analysis is usually only performed with the axial components. Methods for calculating the stresses include from simple engineering formulas to Finite Element Codes if necessary. Figure 1-3 shows the scheme for fatigue life evaluation as prescribed by the standard. For the damage code Palmgren-Miner rule is commonly applied.

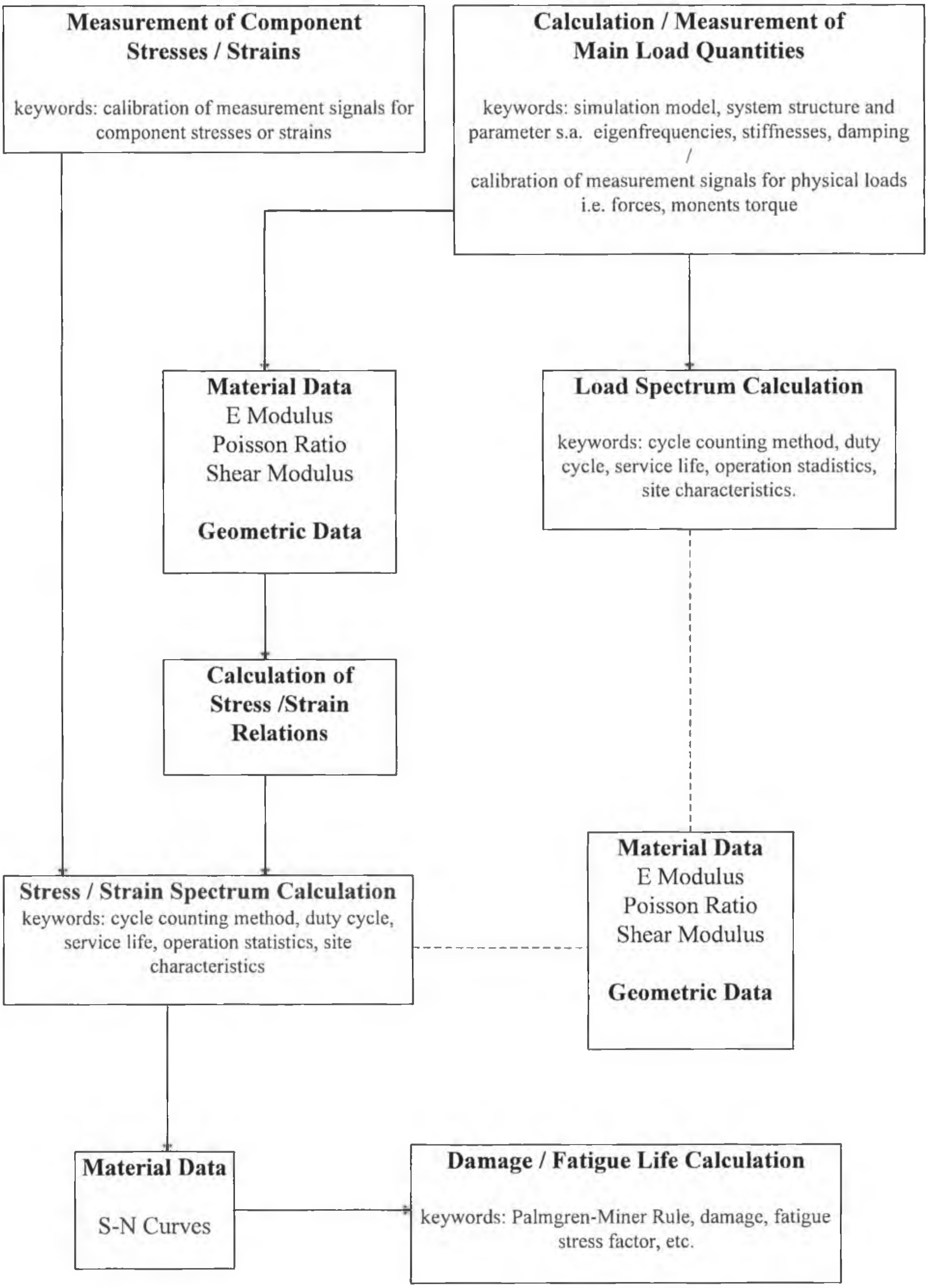


Figure1-3. Scheme for Fatigue Life Evaluation[30]

1.3 Methodology employed in this Project.

The aim of the present project is to assess the fatigue life of the GMIT wind turbine installation. The methodology reported by Spera [26] will be followed. This methodology is in good agreement with the proceedings described in the EU Standards [30].

The methodology involves the following steps:

1. Load prediction (Load Spectrum),
2. Stress Spectrum determination,
3. Cycle Counting,
4. Fatigue Allowable Determination.

The analysis will be applied on the turbine blades as they are the most fatigue sensitive component of the turbine [24]. This is due to the magnitude and number of stress cycles they experience.

The load spectrum is calculated by analytical methods, and it will be verified by experimental monitoring, which is a part of the overall research project. The loads considered included aerodynamic, gravity, and centrifugal forces. Turbulence was included as variation of mean wind speed. Small scale turbulence and yawing effects were neglected for being a small wind turbine system.

The stress spectrum was developed making use of the finite element package ANSYS. The rainflow algorithm has been implemented to account for the cycles experienced by the wind turbine blades.

Finally, the S-N linear damage method is followed to calculate the allowable fatigue stress of the machine.

1.4 Conclusions

The work performed by different researchers in the fatigue analysis of wind turbines has been reviewed.

Two different approaches for fatigue life prediction have been addressed: (1) the S-N method, (2) and the Fracture Mechanics. The former been currently accepted to assess fatigue life in the European Standards.

Similar steps are followed by most researchers to assess the fatigue life of wind turbines. These are: (1) load spectra determination, (2) stress spectrum, (3) and application of a fatigue damage rule. However, there is still incomplete agreement in how to estimate each of them, and previous researchers have tended to develop their own fatigue and test methods, which are internally validated.

The load spectra is usually determined by experimentation, although some codes, and experimental equations have been developed to implement this task during the design phase. Whether either method is chosen, the load spectra must account for the effect of deterministic loads (gravity, aerodynamic, and centrifugal), and those due to yawing and turbulence. It is common practice to use Palmgren - Miner rule for fatigue damage calculation.

Chapter 2. Selected Fatigue Analysis Methodology

2.1. Introduction

In this chapter, the importance of fatigue assessment on wind turbines is addressed. Then, a methodology to predict the fatigue life of wind turbines is presented. Special emphasis is placed in the description of how to address the cumulative damage assessment.

2.2. Fatigue Life

Like all rotating machines, windmills are generators of fatigue. Every revolution of its components produces a load cycle, known as a fatigue cycle. Each of these cycles causes a finite amount of damage, resulting in a reduction in the components fatigue life. When enough cycles are experienced, a fatigue crack may develop. Continued loadings will cause propagation of the crack until failure results. The number of repetitions of significant loads that can be sustained before cracks begin (the initiation phase) and grow to an allowable length (the propagation phase) is usually refered as *cycles to failure* [26].

Wind turbine structures present many difficult fatigue design problems because they are,

- relatively slender and flexible,
- subject to vibration and resonance,
- acted upon by loads which are often non-deterministic,
- operate continuously in all types of weather with a minimum of maintenance,
- and constantly competing with other energy sources on the basis of life-cycle costs.

Fatigue requirements often drive the design of the majority of the primary structure of a wind turbine [26]. Figure 2-1 illustrates a typical pattern of design drivers for a horizontal-axis wind turbine (HAWT).

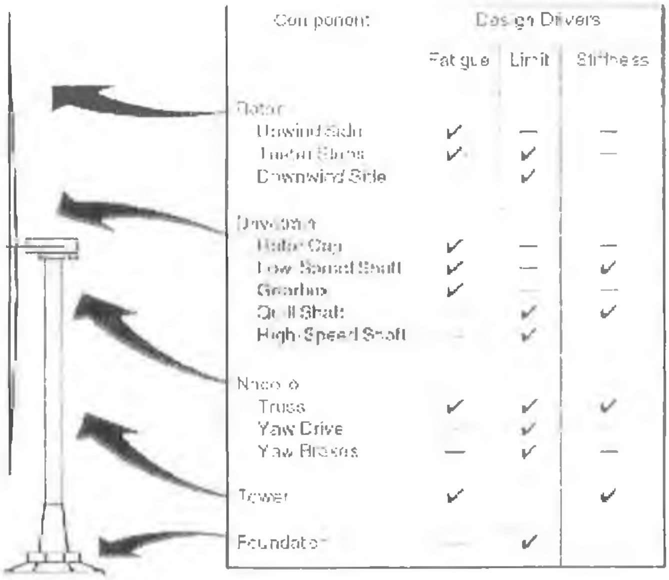


Figure 2-1. Typical patterns of design drivers for the primary structural and mechanical components in a HAWT[26]

The reason that fatigue is the design driver for most wind turbine components is that wind turbines must achieve very long operating lives, of the order of 25 years or more, in order to be cost-effective [26].

Fatigue life is very sensitive to the amplitude of stress variation. Turbine blades are the most fatigue-sensitive component of the turbine because of the magnitude and number of stress cycles they experience. They are subjected to full gravity reversals once each rotor revolution. During the course of a service lifetime, they may experience over at least a billion of fatigue cycles[24]. These large number of loading cycles are seldom sustained by other structures. Design lifetimes of wind turbines contain more load cycles than those of other structures, so cyclic stresses in a wind turbine must be lower than those allowable in other structures as illustrated in Figure 2-2.

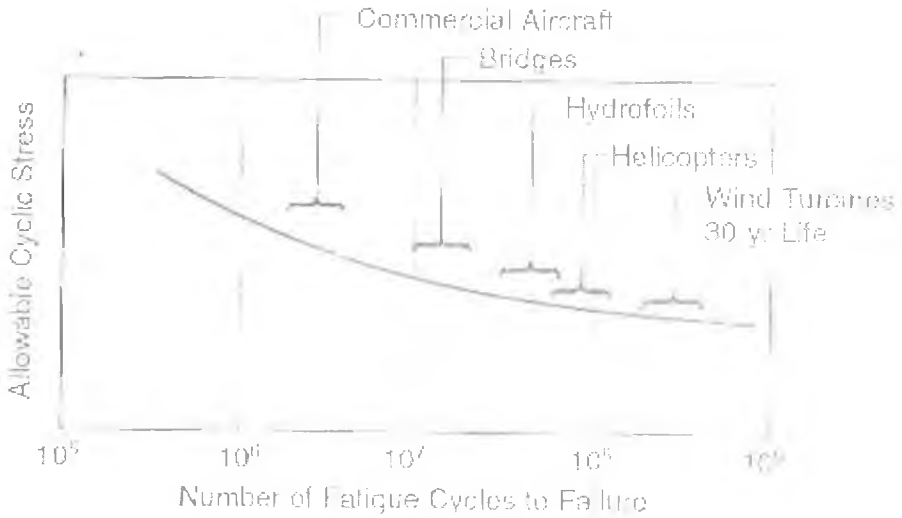


Figure 2-2 Schematic S-N curve illustrating the severity of wind turbine fatigue requirements compared to those of other structural systems.

Because fatigue life is an important factor in the design of wind turbine, it is necessary to posses a simple method to estimate component fatigue lives during the design phase.

Wind turbine fatigue life estimation requires data on the component fatigue characteristics and loading. The loading to which wind turbines are subjected include combinations of wind, gravity, and gyroscopic loading that are highly irregular in nature. This loading may be determined using either strain gauge measurements from an operating wind turbine, or numerical structural analysis. Fatigue characteristics are obtained from component testing or from material test and careful component stress analysis. Difficulty to predict fatigue life is incremented because fatigue properties can be difficult to find for those materials not already used in aerospace or ground vehicle applications (as is typical for most wind turbine blades).

Once the material fatigue properties and loading are determined, diverse techniques have been used to estimate fatigue life. As reported in the previous chapter, this techniques range from safety factors on material yield strength to load and cycle estimates used in conjunction with linear damage rules (Palmgren-Miners') and material fatigue data. The latter will be used in this report to estimate the life of a wind turbine.

The methodology reported by Spera[26] to predict the fatigue life of wind turbine components will be presented. This methodology follows the steps identified in the EU Standards [30].

Economics represent an additional problem on fatigue design. Wind turbines are designed to produce electrical power, and therefore compete economically with conventional sources of electrical power generation. The use of aerospace class materials to reduce weight and to enhance the reliability and structural properties of turbine blades is almost impossible because of the cost. The wind industry typically builds blades using fiberglass composites from boat building technology or aluminium alloys typically reserved for architectural trim [24].

2.3. Fatigue Design Procedure

The fatigue analysis involves the definition of two elements:

1. the load and consequent stress spectra in the critical components of the wind turbine
2. and their allowable fatigue stress.

When the fatigue load spectra have been defined for the critical sections in a wind turbine the problem of designing wind turbine components to resist these loads for the design lifetime becomes one for which accepted and validated procedures are available. Standard stress analysis procedures are used to convert load spectra to stress spectra, and allowable fatigue stresses are based on standard laboratory tests of the materials of construction.

One of the most important elements in the fatigue design process is the definition of allowable fatigue stresses. This is a technical speciality of its own, in which engineers modify the results of laboratory fatigue tests on material and joint specimens to account the expected spectrum of stress, size effects, cost-effective manufacturing and inspection procedures, environmental effects, and maintenance planned for the structural system during its lifetime. Thus, the specification of fatigue allowable stresses for various materials in a structure is an integral part of the manufacture and operation of that structure.

The S-N Linear Damage Method has been used successfully to account for the stress spectrum effect[6], and it will be explained. This is one of the first steps needed to modify laboratory test data into fatigue allowable stresses.

2.4. Fatigue Load and Stress Spectra

In a structure with highly-variable loading, such as a wind turbine, fatigue damage is determined by the amplitudes and frequencies of stress cycles or stress spectra at critical locations.

These cycles are normally idealised into a time sequence of alternating minimum and maximum values connected by straight lines. In this way, the shape of the path between a given minimum and the next maximum is usually disregarded, and only the size and number of the minimum and maximum stresses is modelled. [5],[6]

A time-history of load or stress is assumed to be composed of three types of cycles [26], as illustrated previously in Figure 1-2,

- Type I: Minimum to maximum during one rotor revolution
- Type II: Minimum to maximum during one large-scale change in wind speed
- Type III: Minimum to maximum during one run, from startup to shutdown

Type I cycles occur once per rotor revolution and are caused by gravity, wind shear (i.e. vertical gradient of the wind speed near the ground), tower blockage, and small-scale turbulence. These fatigue cycles can occur more often than once per rotor revolution under two general conditions:

(1) When the primary loading on the component is related to the blade passage (e.g., the yaw drive on a two-bladed HAWT), in which case the number of fatigue cycles per revolution equals the number of blades,

(2) and, when a resonance exists, in which case there are ϖ/Ω fatigue cycles per revolution. Here ϖ is the natural frequency of the component and Ω is the rotor speed, and their ratio is typically three or larger.

Type II cycles are caused by large-scale turbulence, such as a gust that envelops the entire rotor, and longer-term changes in the steady wind speed at the wind turbine site.

Finally, Type III cycles also referred as " start-run-stop" cycles, account for one cycle from start to stop of the machine.

The sum of the three type of cycles gives the number of cycles that a wind turbine experiences during a star-run-stop period.A shortcoming of this simple counting scheme is that identifying Type II cycles requires some judgement. The rainflow model [7], based in the ASTM standards, is implemented for counting fatigue cycles.

2.5. S-N Linear Damage Method

Fatigue damage is both a physical process (e.g. the initiation and propagation of defects in the material) and a mathematical representation of that process. Only the latter will be discussed. In general, fatigue damage and fatigue lifetime are inversely proportional. One of the simplest models of the accumulation of fatigue damage during repeated cycles of stress is the linear damage hypothesis, proposed by Palmgren and Miner.

According to this hypothesis, if the stress cycle remains constant through a fatigue lifetime equal to N, then the fraction of that lifetime consumed on every cycle is constant and equal to 1/N. This fraction is also defined as the damage per cycle, and it follows that the total damage at failure is equal to unity. Furthermore, if the stress cycles change during the lifetime, the damage fractions per cycle are linearly additive, and fatigue failure still occurs when the accumulated damage reaches unity.

If a stress spectrum is subdivided in groups of cycles or layers within which the stress cycles are relatively uniform, then

$$m\sum_{1}^{I}\frac{n_i}{N_i}=1 \qquad \text{at fatigue failure} \qquad (2\text{-}1)$$

where,

$$m=\frac{N_f}{\sum_{1}^{I} n_i} \qquad (2\text{-}2)$$

and,

i = index of layers in the spectrum

I = number of layers in one spectrum

m = number of repetition of the spectrum required to cause fatigue failure

n_i = number of cycles applied at stress level S_i

N_i = fatigue lifetime at a constant stress level S_i

S_i = stress parameter in the cycle upon which fatigue damage is primarily dependent

N_f = fatigue lifetime under spectrum loading

Inherent in Equation (2-2) is the assumption that the order of applying the layers of stress to the material is not important. The previous is acceptable when high- and low- stress layers are randomly mixed and a large number of spectra are applied[26], as is the case of wind turbines.

The dependence of N on repeated cycles at a constant level S, is typically expressed by a power-law equation as:

$$S = S_l N^{\alpha} \qquad (2\text{-}3)$$

$$S \geq S_e \qquad (2\text{-}4)$$

where

S_l = empirical stress coefficient (kN/m^2)

α = empirical exponent

S_e = *endurance limit*, below which no fatigue damage occurs (kN/m^2)

Equation (2-3) is plotted in Figure 2-3 on log-log co-ordinates as a straight line with an intercept of S_l at N equal to one cycle and a slope of α, down to a stress of S_e (typically, α is less that about -1/8). Solving equation (2-3) for N with S equal to S_e, the fatigue life at the knee of the S-N curve is obtained. To the right of this point the curve becomes a horizontal line.

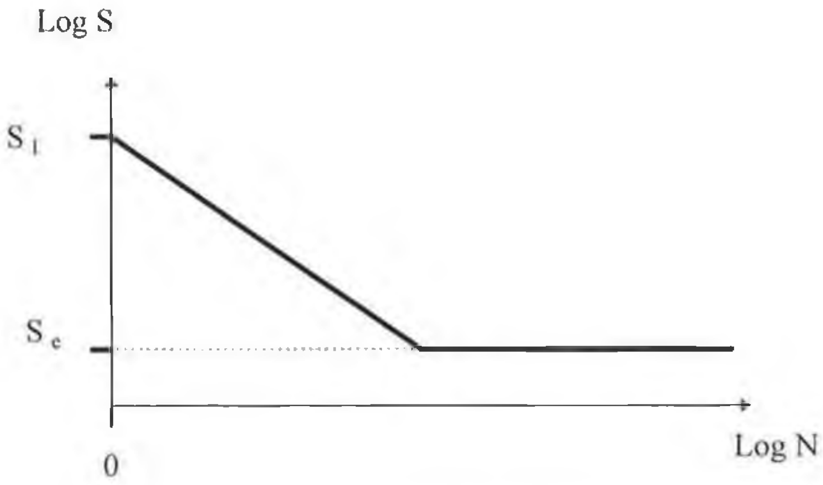


Figure 2-3. S-N curve

The next step in defining an allowable stress for the spectrum is to express the layer stresses as fractions of the largest stress in the spectrum, S_{maxmax}. This produces a set of normalised stresses analogous to the normalised loads. The largest stress, S_{maxmax}, can be used as a scale factor to proportionately increase or decrease all stress levels in the spectrum until the required fatigue lifetime is achieved.

Let

$$S_i = s_i S_{\max ma} \qquad (2\text{-}5)$$

where

s_i	stress ratio for the ith layer
S_{maxmax}	largest stress in the spectrum

Combining equations (2-3,4,5,6) produces the following equation for calculating allowable stresses by the S-N linear damage method,

$$S_{\max\max} = S_l \left[N_f \frac{\sum_{1}^{l} n_i s_i^{-1/\alpha}}{\sum_{1}^{l} n_i} \right]^{\alpha} \qquad (2\text{-}6)$$

This value of S_{maxmax} becomes the allowable fatigue stress for the loading condition. This stress represents the average fatigue strength of laboratory specimens, an it must first be modified by the so-called *knock-down factors*, to account for several conditions that can reduce fatigue strength in full-scale structures.

2.6 Correction Factors to the Theoretical Fatigue Strength

The fatigue strength obtained from the previous method must be modified to account for physical differences between the test specimen and the actual part being designed. Environmental, size and manufacturing processes must be taken into account. These and other factors are incorporated into a set of strength-reduction factors (knock-down factors) that are then multiplied by the theoretical estimate to obtain a corrected fatigue strength.

$$S = K_a K_b K_c K_d K_e K_f S_{\max\max} \qquad (2\text{-}7)$$

where,

K_a: surface finish factor,
K_b: size factor,
K_c: reliability factor,
K_d: temperature factor,
K_e: modifying factor for stress concentration,
K_f: miscellaneous effect factor.

Al these factors have been considered as one in this project.

2.7. Relevant Fatigue Data

The S-N linear damage method explained in section 2.6 will be used for calculating the effect of spectrum loading on fatigue strength for the GMIT wind turbine facility. The fatigue characteristics of the material considered are described below. These are based in a study performed by the University of Bath, UK [8].

2.7.1. Material Data

The properties of Khaya will be presented. The material data presented is based in the study performed by the University of Bath, UK [8].

2.7.2. Constant Amplitude Data

Tests carried out by the University of Bath resulted in the S-N curves presented in Figure 2-4. In the S-N curves maximum stress versus number of cycles to failure are presented at different R-ratios of -1 (reversed loading), -2, -10 (compression-tension) and 10 (compression-compression).

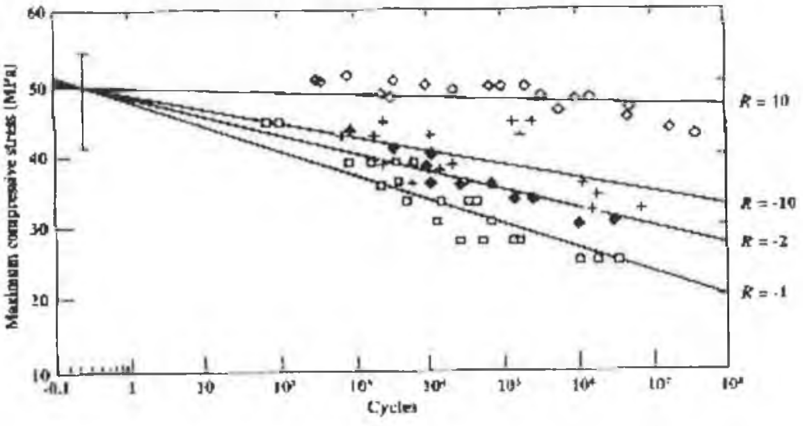


Figure 2-4. S-N characteristics for Khaya ivorensis/epoxi laminate loaded in axial tension/compression at R=-1,-2,-10, and 10 at a moisture content of 10 percent [27].

At R= -1 the fatigue life is the lowest at any given maximum stress level. The life increases as the tensile component of the reversed load becomes less (passing from R=-2 to -10) until the load is all compressive (R=10) where damage rates are low.

In tension-tension at R=0.1 (Figure 2-5) the straight line fit to the fatigue points passes through the mean static tensile strength (80 MPa). The dotted line represents the stresses below which there is a less than 5 percent probability of failure.

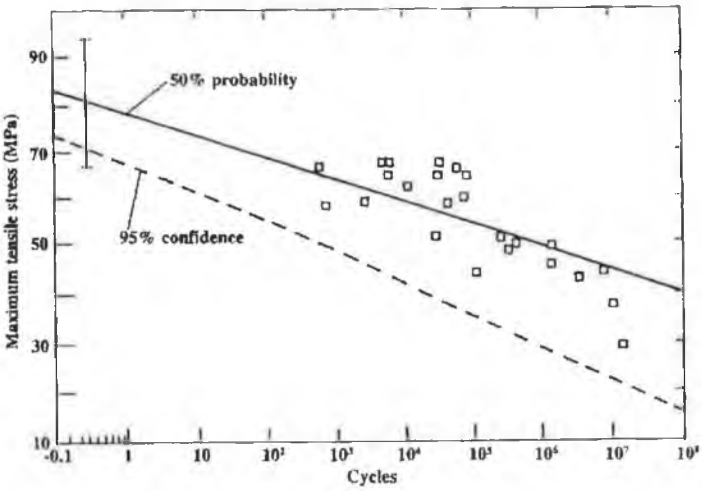


Figure 2-5. S-N characteristics for Khaya ivorensis/epoxy laminate loaded in axial tension/compresion at R=0.1 at a moisture content of 10 percent.

2.7.2.1. Constant Life Lines

S-N fatigue data from Figures 2-4 and 2-5 are used to construct a constant life diagram (Figure 2-6) for mean fatigue lives of 10^5, 10^6, and 10^7 cycles. Alternating stress σ_{alt} is plotted versus mean stress σ_{mean} and, for each life, the constant life line (s) constructed . The constant life diagram can be split into four regions, which passing clockwise around the diagram, represent compresion-compresion (R=1 to±∞) compression-tension (R=±∞ to -1), tension-compression (R= -1 to 0) and tension-tension (R=0 to +1).

As the R ratio passes from -10 to +10 the failure mode changes from mixed mode to compressive and this transition is accompanied by a region of inflexion in the constant life diagram. At positive R ratios in compression-compression (Figure 2-4) S-N curves become almost horizontal and fatigue life is stress-independent. Hence the constant life lines in this region of the constant life diagram become superimposed. Between R=±∞ and R=10 the constant life line is driven upwards temporarily before the decline in the alternating component of the stress draws the constant life line down to the R=+1 ultimate compressive strength limit.

From the point of view of simple fatigue design, the complex form of the constant life lines is unfortunate. However, a safe simplification of the lines can be made by constructing straight Goodman lines between the two R= +1 points and the R= -1 for each life of these straight lines.

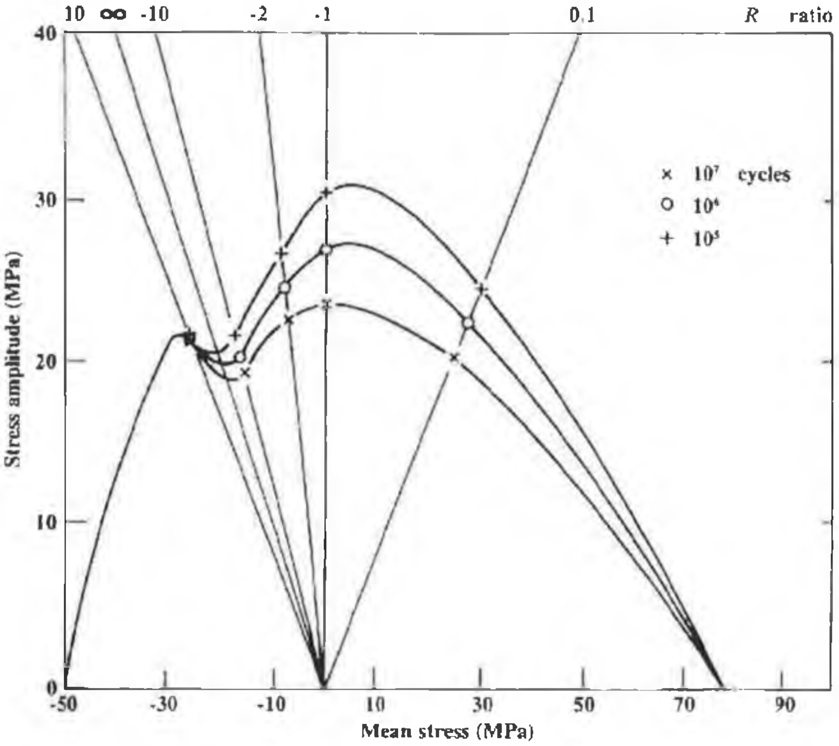


Figure 2-6. Constant life diagram for axially fatigued Khaya ivorensis/epoxy laminae for lives of 10^5,10^6, and 10^7 cycles.

2.7.3. Size Effects

The flexural strength of statically loaded wood (as well as most other materials) is influenced by size, so it might be expected that increasing the size of wood specimens would also have a detrimental effect on the axial fatigue life because of the increased likelihood of a large surface flaw occurring.

The fatigue results reported by Ansell, Bond Bonfield and Hacker [8] suggest that in axial tension-compression tests a size effect is not observed. Wood is resistant to propagation of lateral cracks because of its orthotropic structure. The absence of size effect in tension-compression suggests that there is no limit to the size of wood composites blades for commercial wind turbines.

2.8. Conclusions

In this chapter a methodology to predict the fatigue life of wind turbines has been presented. This methodology will be used in this project to assess the fatigue life of the GMIT wind turbine installation. Three elements must be defined for the wind turbine under consideration: 1) load spectrum, 2) stress spectrum, and 3) fatigue allowables.

The methodology presented is based on a S-N approach for the definition of the fatigue allowables. The aim of this method is the definition of a maximum allowable stress for a design life that accounts for the stress spectrum effect on the laboratory test data. With this purpose the linear fatigue damage accumulation hypothesis, proposed by Palmer-Miner, is combined with the stress spectrum of the turbine.

Finally, the fatigue properties for the blade material. These properties are based on laboratory test data based on Khaya composite samples. These material properties are reported to be similar to those of other wood composites.

Chapter 3. Application of Fatigue Analysis Methodology

3.1. Introduction

In this chapter the fatigue methodology explained previously will be applied on a wind turbine to predict its fatigue life. The fatigue life of a wind turbine can be defined in two different ways. The first one is to determine the number of years until a failure occurs. The second is to define a fatigue stress allowable for a desired design life, in order to ensure the design life all the stresses must be under the fatigue allowable. The latter is the method currently used in wind turbine design and it is the one applied here.

The fatigue stress allowable can be determined for all the components of a wind turbine. However as the rotor blades are the most critical components regarding fatigue, these will be the only components analyse here.

First, the characteristics of the wind turbine under consideration will be specified. Then, a stress spectrum will be developed for that wind turbine. Finally, the fatigue methodology will be applied on that spectrum to determine the fatigue allowable.

3.2. PROVEN WT6000 6kW Wind Turbine

The GMIT Wind Turbine Installation is based on the Proven WT6000 that is a 6 kW wind turbine. The specification and operational characteristics of this turbine are presented below.

3.2.1. Specification

Performance

Cut-In Wind Speed	2.5 m/s	(5.6 mph)
Cut-Out Wind Speed	>70 m/s	(>155 mph)
Rated Wind Speed	12 m/s	(22 mph)

Rotor

Type	Down-wind, Self-Regulating
Number of Blades	3, Flexible
Rotor Diameter	5.6 m.
Blade Material	Wood

Generator

Type	Brushless, Direct Drive, Permanent Magnet. (No Gear-Box)
Output	240V 3-phase AC (0-20 Hz)
Rated RPM	200 nominal
Rated Power	6000 Watts
Annual Output	7000-18 000 kWh depending on site

Noise

<45 dB	At 5 m/s
<60 dB	At 20 m/s
70-80 dB	Car 15 m away at approx. 40 mph.

Weight

WT6000	400 kg.

The power curve for the Proven wind turbine is shown in Figure 3-1. It indicates the net electrical energy output from the wind turbine as a function of the wind velocity at hub height.

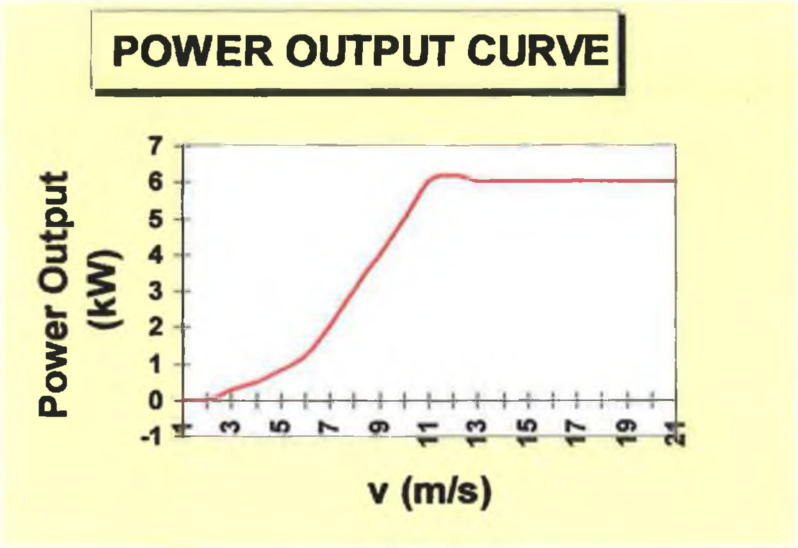


Figure 3-1. Power output curve for 6kW Wind Turbine

The variation of rotational speed with the wind speed is shown in the graph below.

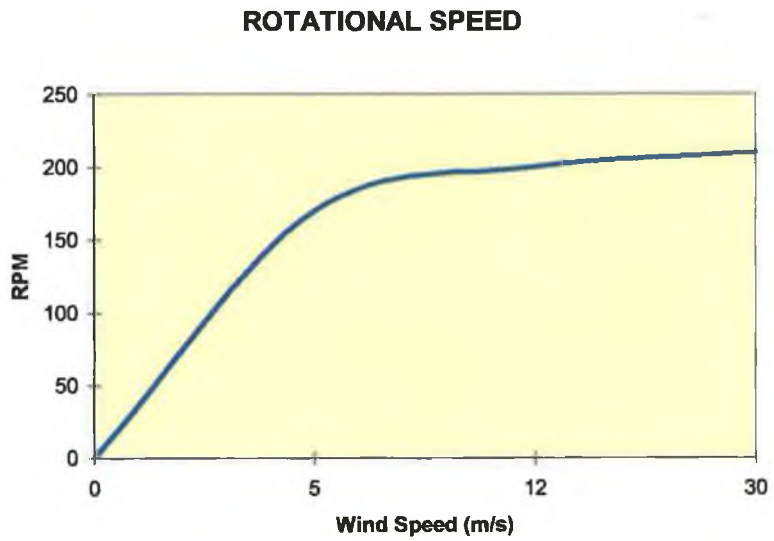


Figure 3-2. Relation between Rotational Speed and Wind Speed

3.2.2. Passive Pitch Change Mechanism

Above 12 m/s (25 mph) the blade pitch is automatically adjusted to maintain 200 rpm and full output up to 67 m/s (150 mph).

The rotor changes blade pitch angle in response to rotor speed, by means of a flexible hinge near the root of the blade. This hinge is called the *Zebedee Hinge*. The *Zebedee hinge* flexes in response to centrifugal force and is controlled by a large spring known as the *Zebedee spring*.

Table 3-1

Wind Speed	Blade Tip Setting	Remark
Low	$+5^0$	Start up
Medium	$+2^0$ to 0^0	Energy Production
Extreme	Negative	Brake to govern max. rotor output.

3.3. Stress Spectrum Definition

3.3.1. Introduction

The stress spectrum represents the stress history of a wind turbine component. Rotor blades have been identified as the critical components in wind turbines, and the root blade is where the maximum stresses develop. Therefore, the stress spectrum is defined at the blade root.

Ideally, the stress spectrum should be determined from actual measurements made on the wind turbine during operation. As this is not always possible, a process is needed to estimate them. Figure 3-3 shows the process employed in this project to determined the stress spectrum. This process is a modification of the methodology presented in the European Standards [30] specified in section 1.2.3.8. and shown in Figure 1-3.

To determine the stress spectrum, first the forces that act on the turbine must be known. The application of these forces involves the definition of a load spectra due to a wind velocity spectrum, to which centrifugal and inertial forces are added.

The load spectra is defined by the use of the computer code *'Wind Forces'* which was specially developed for this project. The centrifugal and inertial forces are added by means of an utility contained in the Finite Element Package ANSYS. This package computes all the forces acting on the wind turbine and generates the stress history at the root blade for the wind spectra introduced.

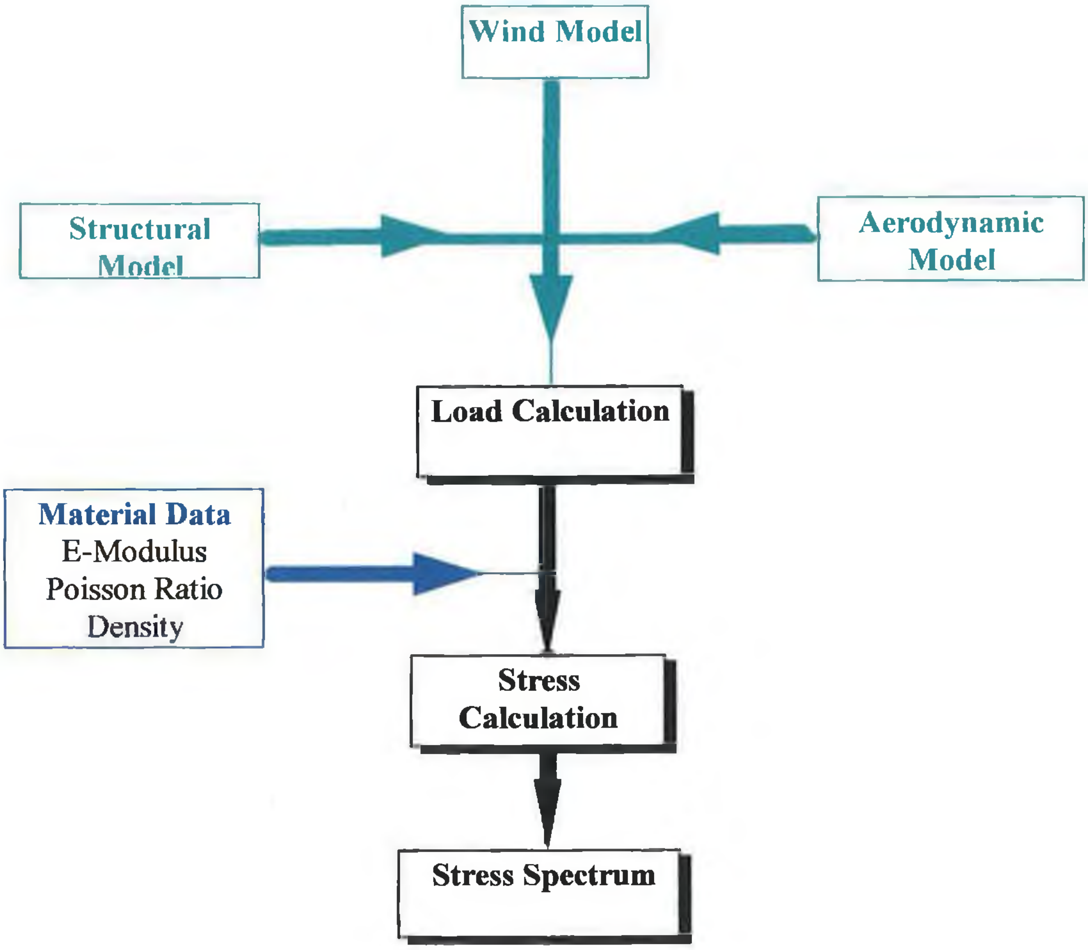


Figure 3-3. Scheme for the Stress Spectrum Definition

3.3.2 Analysis requirements

In order to develop a load spectra to apply to the wind turbine model different concepts must be considered, such as the wind speed, the geometry of the blades (aerodynamic design) and the rotational speed of the rotor.

3.3.2.1. Wind Model

The relevant wind data for the fatigue analysis is that one from the start-up to shut down of the wind turbine. It contains the maximum wind speed recorded in a year. The wind speed recorded during 1998 in Shannon Airport is been supplied by the Meteorological Service. A computer code *'MaxWindSpeed'* was specially developed in this project to identify the period under consideration. It combines the information from the wind speed records and the wind turbine specification to identify the wind speed spectra of interest. A plotting of the time history wind speed is shown in Figure 3-4.

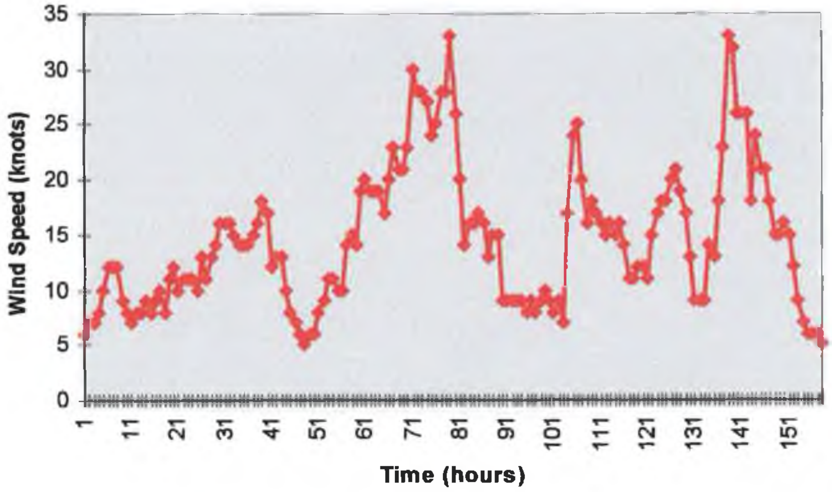


Figure 3-4 Time history wind speed.

Using such a wind spectra results in the following wind model:

V_{mean} = 14.57 knots (7.65 m/s)
Turbulence Intensity, I = 0.4344
Natural Turbulence (fluctuation of flow, RMS u(t)) , $\sigma = 6.33$

3.3.2.2. Wind Turbine Model

The model used to simulate the wind turbine involves an aerodynamic model and structural model. The aerodynamic model involves blade geometry and aerodynamic characteristics. The structural model includes geometry of the tower and rotor, and material properties. The wind turbine is modelled in the ANSYS finite element program to allow analysis of the response of the structure.

All the included data corresponds to the GMIT wind turbine. The required engineering constant were obtained from the findings of Ansell and Bond for wood composites[27].

3.3.2.2.1. Aerodynamic Model

The following data specifies the blade profile:

- constant profile (NACA 4412) through the blade
- constant chord (0.27m)
- constant setting angle through the blade (β=3.32)

These assumptions are based in the design implemented by the computer code *'Design'*. This program was developed during this project and performs an optimal design based on the momentum theory[32] . It combines the profile information and the wind turbine specification to perform the aerodynamic design of the blades. The value of the lift and drag coefficients for the different angles of attack are shown in Figure 3-5.

specification to perform the aerodynamic design of the blades. The value of the lift and drag coefficients for the different angles of attack are shown in Figure 3-4.

The program outputs the optimum chord and setting angle at different stations considered along the blade. The output of the program is shown below.

Station	Chord (m)	Setting Angle (degrees)
1	2.18	47.76
2	1.09	28.30
3	.73	18.45
4	.55	12.83
5	.44	9.26
6	.36	6.81
7	.31	5.03
8	.27	3.68
9	.24	2.62
10	.22	1.77

Table 3-2. Optimal chord and setting angle at different stations along the blade length.

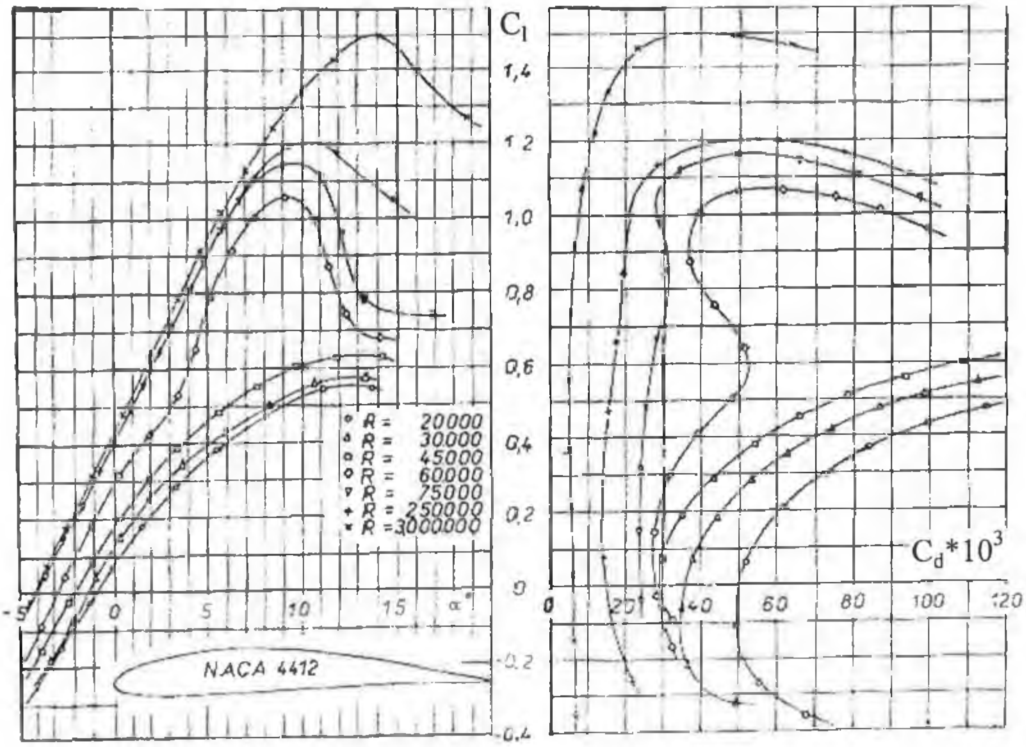


Figure 3-5 Characteristics of the NACA 4412 airfoil: C_l and Cd

3.3.2.2.2. Structural Model

A structural model of the wind turbine has been developed. ANSYS finite element program is used to analyse the response of the structure.

The wind turbine consist on two basic structures, the tower and the rotor. Three models are considered. These are

- One model for the complete wind turbine structure: tower and rotor.
- Two models for the rotor :
  1. rotorup: with one blade in the vertical up position corresponding to the most stressed blade
  2. rotordown: with one blade in the vertical down position corresponding to the least stressed blade.

In all of them the rotor is formed by three blades at 120^0 of each other. The tower is composed by 20 nodes and each blade by 10. Figures 3-6 to 3-8 show the models.

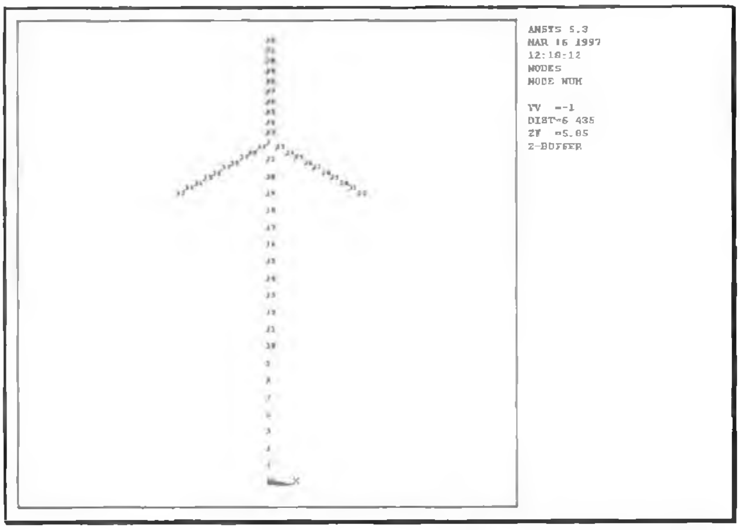


Figure 3-6. Model of the complete wind turbine structure

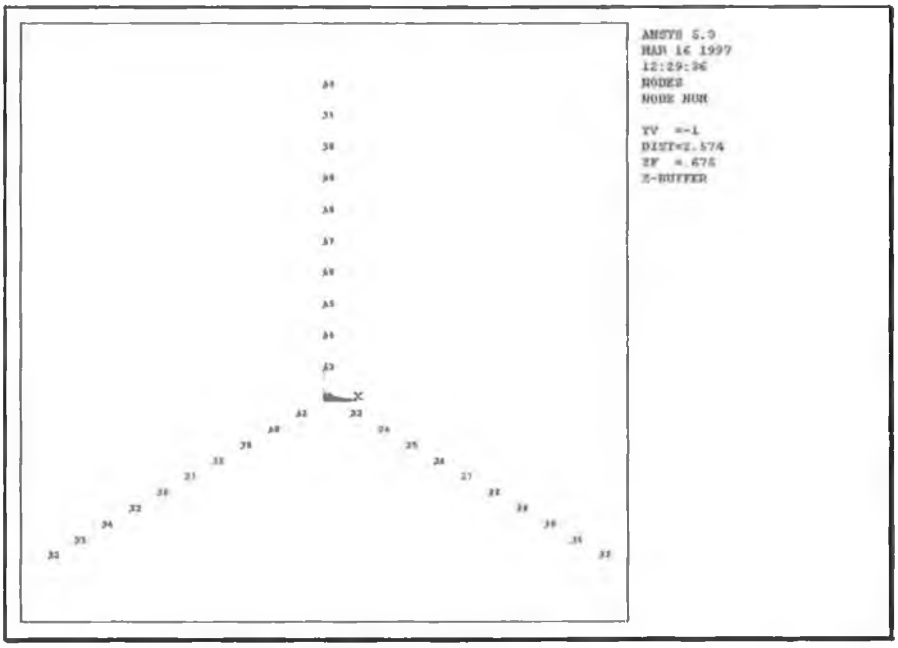


Figure 3-7. Rotor up

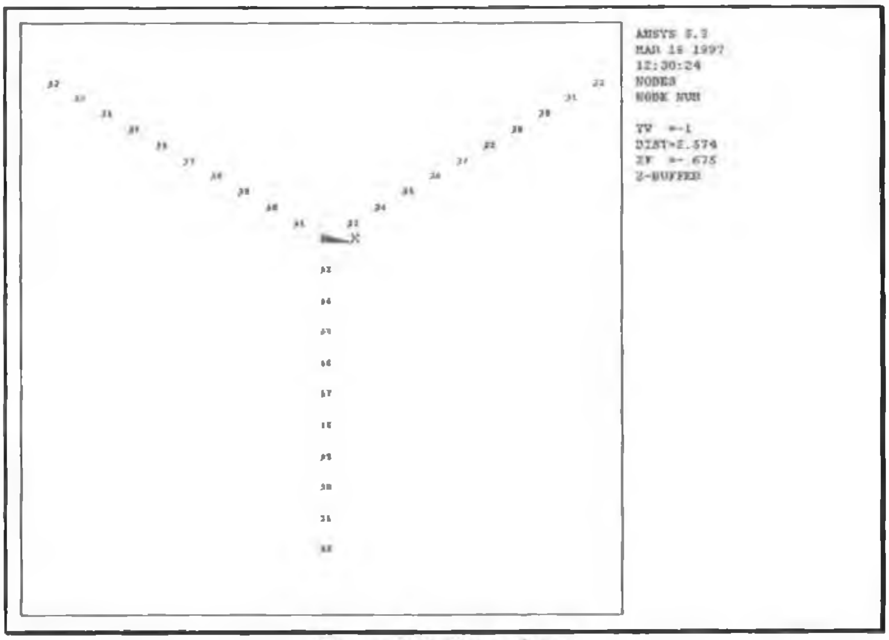


Figure 3-8. Rotor down

The co-ordinates of each node are recorded in a text file that is used later by the program *'WindForces'* to compute the forces that apply on the nodes.

3.3.2.3. Analysis Specification for the ANSYS Finite Element Code.

3.3.2.3.1. Modelling assumptions

(i) Large deflection
(ii) Elastic behaviour
(iii) Wind flow is simulated by applying drag and lift forces on the nodes.
(iv) Stress stiffening is considered when applying rotational velocity to the rotor.

3.3.2.3.2. Analysis code and revision

The finite element program used is ANSYS revision 5.3 , running on a PII 233 Hz. PC.

3.3.2.3.3. Analysis types

Large Deflection, Elastic

3.3.2.3.4. Element types

2 noded BEAM 4 elements are used for the tower and blades

3.3.2.3.5. Real constants

2 sets of real constants for the 3-D analysis are defined , one for the tower and another for the blades.

Table 3-3. Real constants

Real Constant Set	Region used	Cross Sectional Area (m^2)	Area Moment of Inertia (m^4)		Thickness along axis (m)	
			Izz	Iyy	Tkz	Tky
1	Tower	0.00216	$0.2059*10^{-3}$	$0.2059*10^{-3}$	0.3	0.3
2	Blades	.0060000	$0.24482*10^{-4}$	$0.24081*10^{-4}$	0.034236	0.27

3.3.2.3.6. Material properties

The material used for the tower is steel, for the blades wood/epoxy is used.

Table 3-4

Mat No.	Region used	E (N/m^2)	υ	ρ (kg/m^3)
1	Tower	210 $*10^9$	0.28	8000
2	Blades	12 $*10^9$	0.3	500

3.3.2.3.7. Boundary conditions and loading

The only constraints applied to the models are on the blades at the root, and on the tower at the base. In these spots all degrees of freedom are constrained.

The loading acting on the structure, blades and tower is imported from a series of ANSYS loading files. These files are created by the FORTRAN program '*WindForces*'. The loads include the aerodynamic forces considering wind shear. This program calculates thrust and drag forces that act on the different stations on the blades and tower. Their values are expressed in the global co-ordinate system of the wind turbine.

The model is subjected to 158 load steps. Each load step corresponds to the force the wind creates on the turbine at a given hour. In each load step, the forces are applied to the nodes on the model. The wind forces considered are those from the start to shut down of the turbine at intervals of one hour, the maximum wind speed of the wind spectrum is considered.

All the data is managed by a series of codes. A flow chart with their relationship and data management is shown in Figure 3-9. The results are stored on a data file, ready to be analysed by the finite element package ANSYS.

The centrifugal and inertial forces are directly included by the package ANSYS.

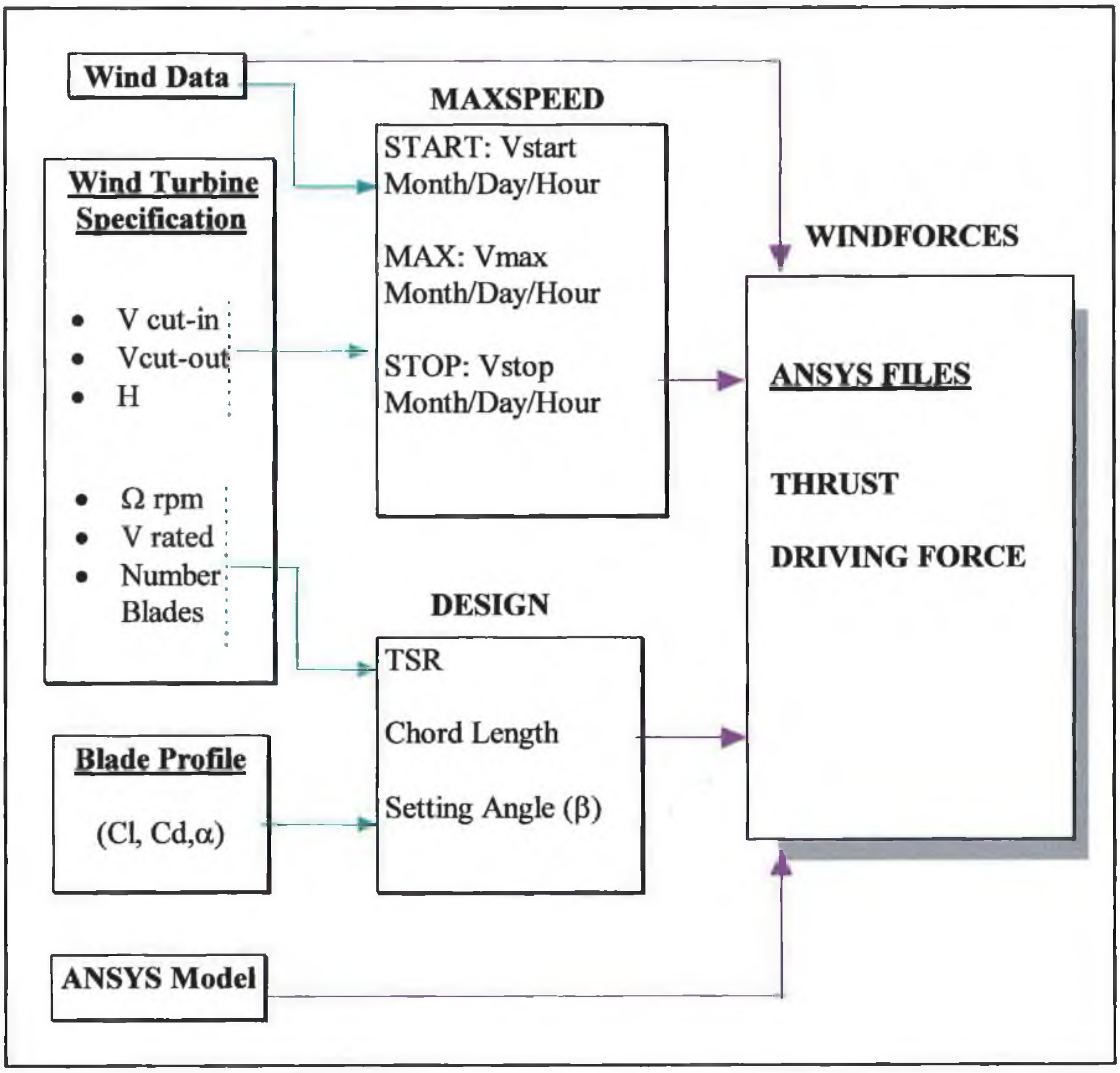
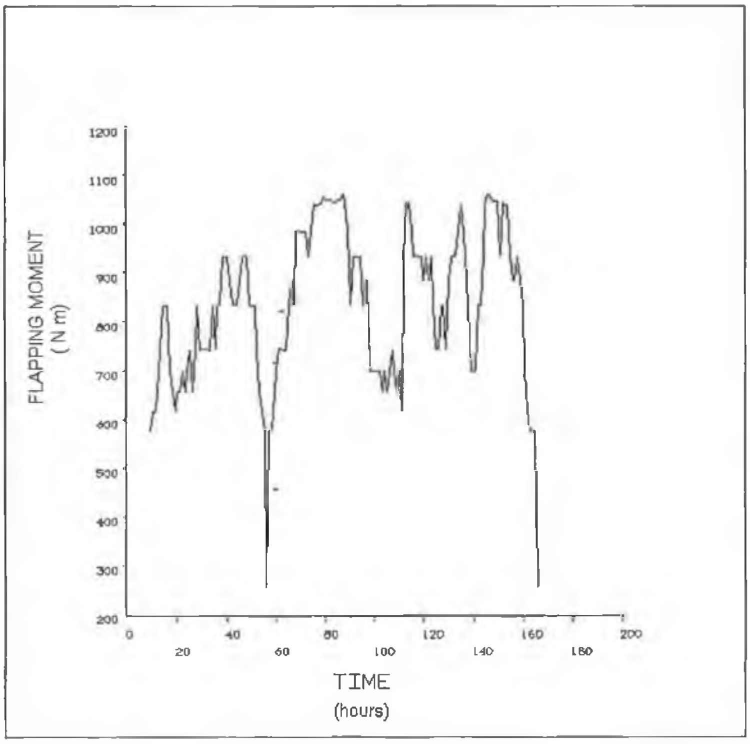


Figure 3-9. Data Flow for Aerodynamic Design Implementation

3.3.3. Time History of the Stresses

The ANSYS output provides the forces and reactions at each node of the model. The root blade is the section of interest as it is where the highest stresses develop. Figure 3-10 shows the output for the flap bending moment at the root blade. In this figure a time history is presented where each hour represents a different load step. Analysis of the loading revealed that centrifugal forces were the highest.



Max. value: 1061 Nm
Min. value: 255.7 Nm

Figure 3-10. Time history of flapping moment at blade root.

Plotting the flapping moment for the wind speeds ranges results in Figure 3-11.

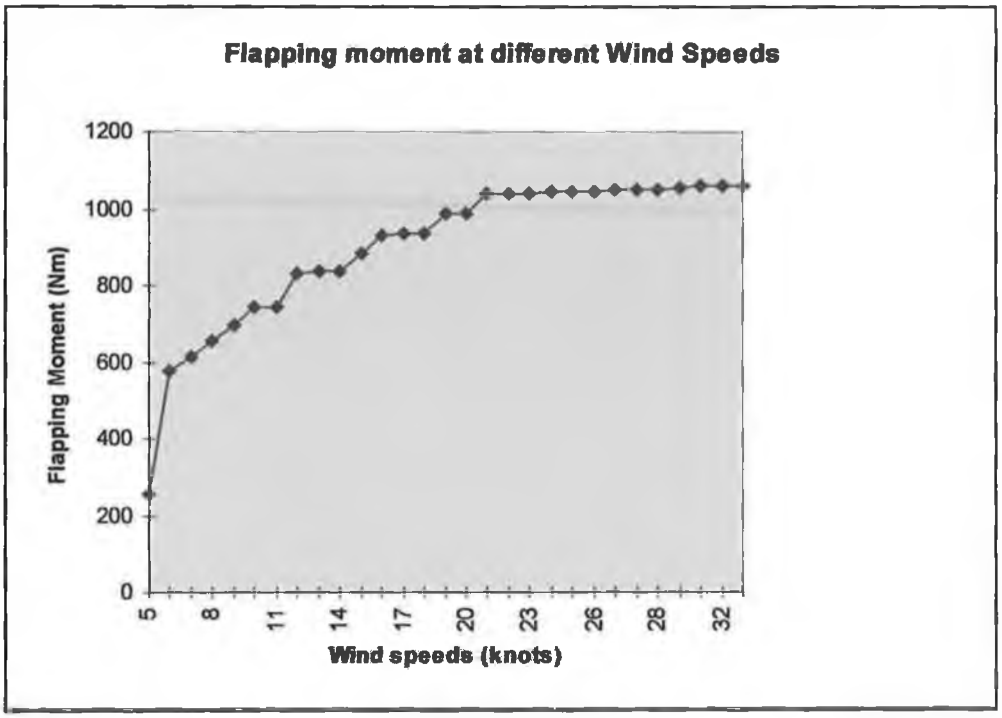


Figure 3-11. Flapping moment at different Wind Speeds

As it was anticipated, the flapping moment increases with the wind speed. When the rated wind speed (22knots) is reached, the flapping moment stabilise in a constant value. As the blade flexes in flapping, the centrifugal force starts to balance the bending moment due to the wind (see Figure 3-12). When the wind turbine rotates at 200 RPM (at rated wind speed) the resulting moment due to centrifugal and aerodynamic forces reaches a constant value.

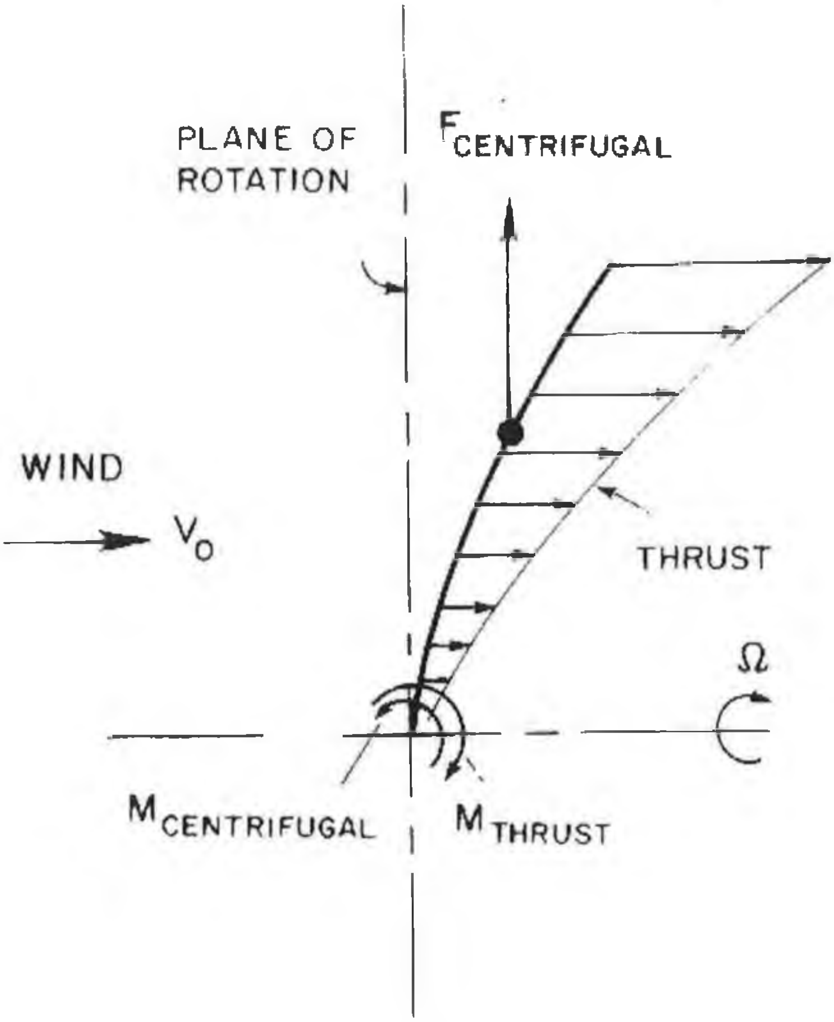


Figure 3-12. Forces and Moments acting on a rotating blade

The tip deflections of the vertical blade in the in-and-out of plane direction are displayed in Figure 3-13. As it was expected deflection follows the same variation shape with time than the flapping moments did. The deflections are direct proportional to the wind speeds. The maximum deflection is shown in Figure 3-14 and its value is 51.17 cm, corresponding to a wind speed of 33 knots. The minimum deflection is experienced at a wind speed of 5 knots, and it has a value of 12.41 cm.

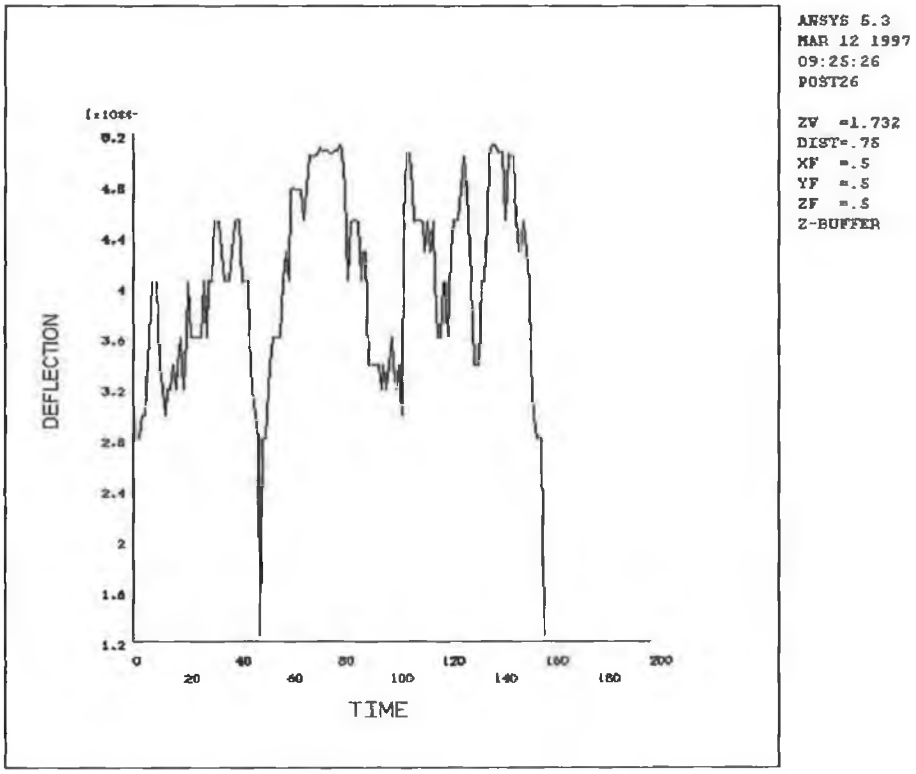


Figure 3-13. Deflections at blade root

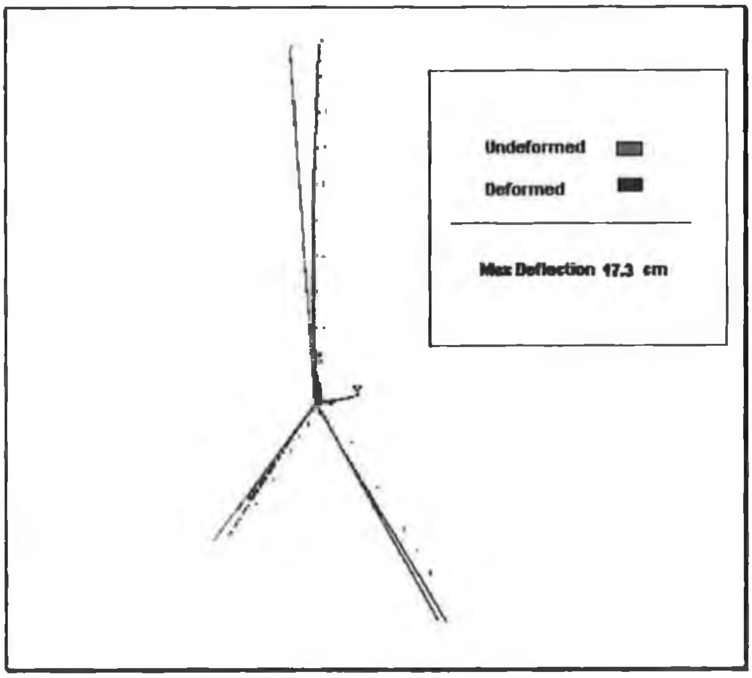


Figure 3-14. Maximum deflection at tip.

Plotting the flapping moment for the wind speeds ranges results in Figure 3-11.

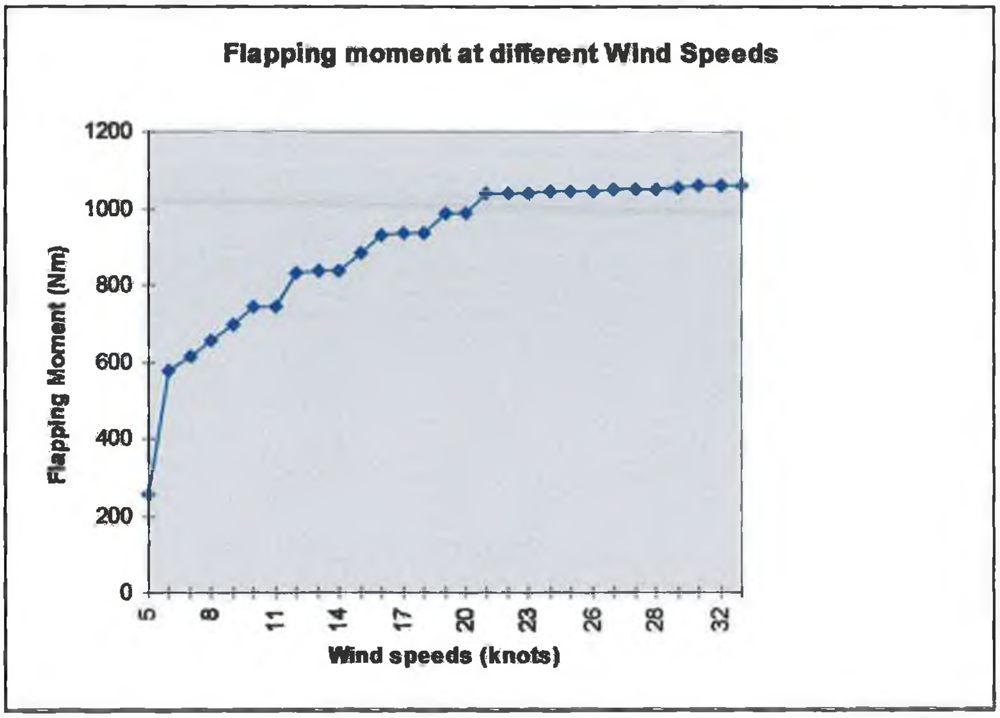


Figure 3-11. Flapping moment at different Wind Speeds

As it was anticipated, the flapping moment increases with the wind speed. When the rated wind speed (22knots) is reached, the flapping moment stabilise in a constant value. As the blade flexes in flapping, the centrifugal force starts to balance the bending moment due to the wind (see Figure 3-12). When the wind turbine rotates at 200 RPM (at rated wind speed) the resulting moment due to centrifugal and aerodynamic forces reaches a constant value.

No stress output is possible for beam elements in the ANSYS Finite Element Code. Consequently, the forces and moments calculated had to be treated during the postprocesing phase. Use of the ANSYS Parametric Design Language was made to account for the equivalent stresses.

The simulation with the ANSYS program provides 158 final load files. Each file corresponds to an average hour wind speed, and contains the stresses at different positions of the blades and tower. The section of interest is the root blade, and in this way a stress spectrum is obtained at this critical position. Figure 3-15 shows the stress history for the run-period under consideration. It illustrates a time history of the mean and alternating Von-Misses stresses felt by the turbine blade at the blade root at each hour. Each stress range in the spectrum represents Ω*60 cycles at that stress level; where Ω states for the rotational speed of the rotor. This type of cycling correspond to the cycles Type I introduced previously in section 2.4. Figure 3-16 displays a representation of the Type I cycles for a wind speed input at rated speed during one hour.

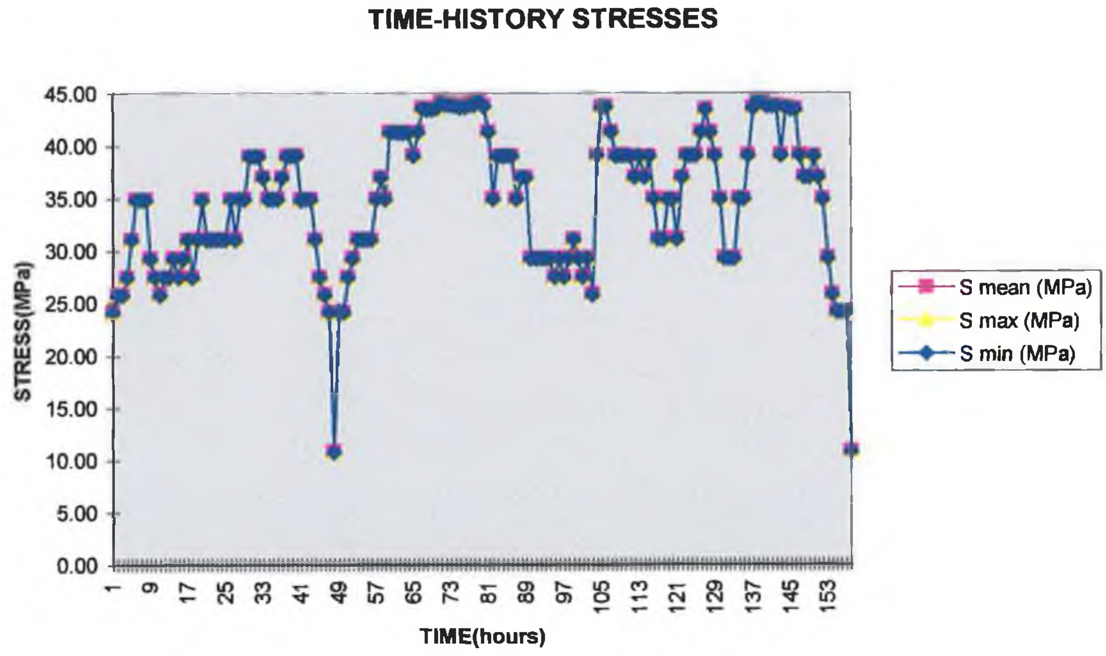


Figure 3-14. Graph showing how the mean, maximum, and minimum stresses at the blade root vary with time. It is observed that for the model considered the three of them have nearly the same value.

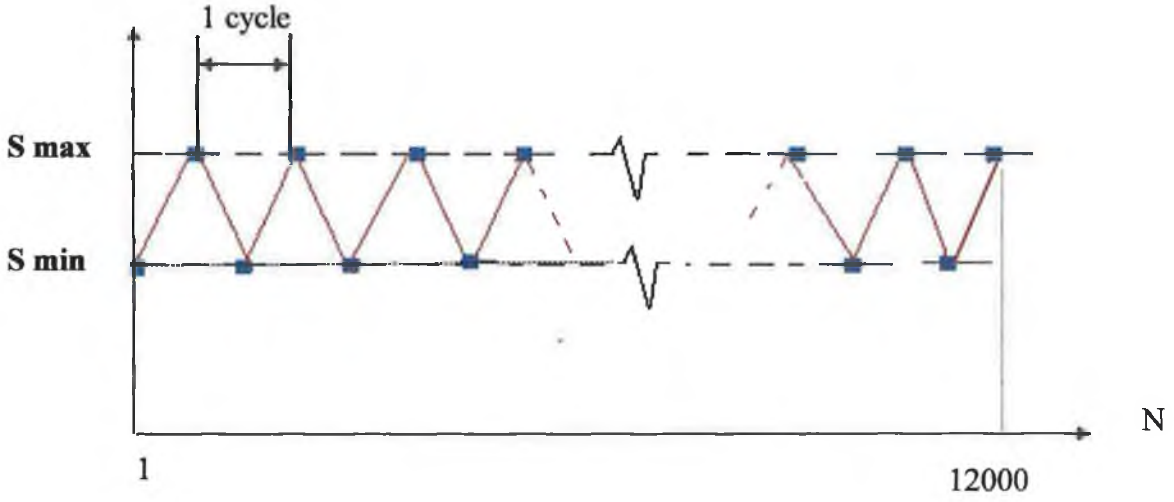


Figure 3-15. Stress Cycles felt at the root blade during 1 hour

A listing of the mean and alternating at the wind speed range of operation is also presented. Their values are graphed in Figure 3-16.

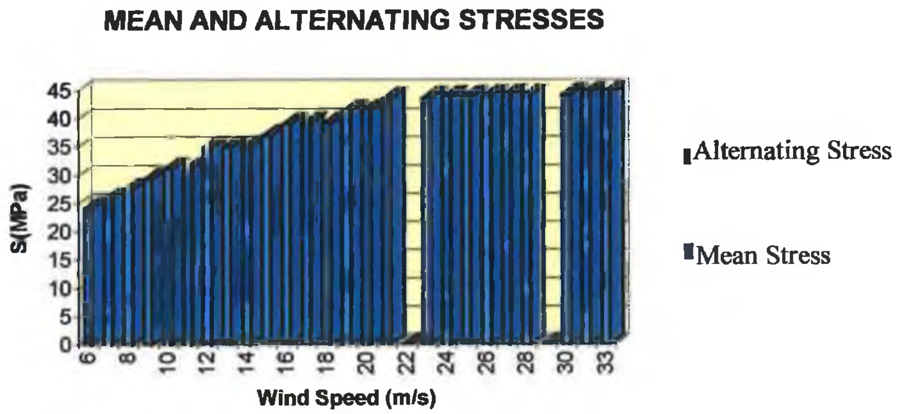


Figure 3-16. Mean and Alternating Stresses at different wind speeds

Wind Speed (knots)	S mean (MPa)	S alt (MPa)
5	10.76	0.02
6	24.11	0.02
7	25.79	0.02
8	27.47	0.02
9	29.27	0.02
10	31.06	0.02
11	31.09	0.03
12	34.87	0.03
13	34.91	0.03
14	34.95	0.03
15	36.99	0.03
16	39.00	0.04
17	39.05	0.04
18	39.10	0.04
19	41.26	0.05
20	41.31	0.05
21	43.45	0.05
22	-	-
23	43.58	0.06
24	43.64	0.07
25	43.71	0.07
26	43.79	0.07
27	43.86	0.08
28	43.94	0.08
29	-	-
30	44.10	0.09
32	44.27	0.10
33	44.36	0.11

Table 3-5. Mean and Alternating stresses at blade root for different wind speeds.

Figure 3-14 shows that maximum, minimum and mean stresses basically coincide in a cycle. This causes alternating stresses be low. As it was predicted, Figure 3-16 shows that the magnitude of mean and alternating stresses are directly proportional to wind speed. However, the alternating stresses are very low compared to the mean values. The maximum alternating stress only reaches 0.11 MPa, while the mean stresses range from

10 to near 45 MPa. It is expected that this kind of stable cyclic loading (Type I) will not effect the fatigue life.

The reason why cycles occurring once per revolution are so low is because the main load acting on the blades is the high centrifugal forces. These are mainly stable during the running of the wind turbine as the rpm stay nearly constant (200 rpm). Consequently, the stresses felt by the blade are nearly constant during one revolution. Oscillation of the mean value is caused by the gravity and wind shear effect. Because of the light weight of the blades (6.3 kg) the gravity loading reversal (1 MPa) is not critic. This finding contrast with large scale wind turbines where gravity is a primary fatigue load. [26],[10]

Figure 3-14 also shows the stress variations due to wind speed changes (Type II cycles). The maximum difference between stress peaks reaches 33.63 MPa. This magnitude of stress cycles is significant enough to effect the fatigue life of the machine. A method to account for the stress cycles due to changes in wind speed is implemented in this project. The code developed is based on the rainflow counting algorithm technique[34].

3.3.4. Stress Spectrum Determination

Once that the stress history has been identified, its information has to be treated to transform it into a stress spectrum with relevant information to the fatigue analysis.

First, the types of cycles defined in section 2.4. must be identified (Type I, II, III), and the number of cycles that are experienced at each stress level must be counted.

The final spectrum will contain relevant information about each stress cycle: maximum stress, minimum stress, cyclic stress, average stress, stress ratio, number of cycles at each stress level, and type of cycles .

3.3.5. Counting Fatigue Cycles

As explained in section 2.4. the fatigue cycles that a wind turbine component experiences can be classified into three types. The total number of cycles is the sum of the three of them.

Considering a stress spectrum corresponding to a run of the wind turbine (from startup to shutdown), the cycles are counted in the following way:
Type I cycles are calculated as the run duration multiplied by the average rotor speed.
Type II cycles are accounted using a rainflow algorithm.
Type III cycle is one.

For the GMIT wind turbine these values are the following
Run duration (from startup to shutdown)= 158 hours
Average rotor speed = 200 rpm =12000 rev per hour
and therefore,

TypeI cycles = Rotor_speed * Run_period= 1896 * 10^3

TypeII cycles = 38

TypeIII cycles =1

3.3.5.1. Cycles Type I

Each stress cycle identified in the histogram represents one hour of running of the wind turbine. Each hour represents 12000 cycles at the same stress characteristics (range and mean). Table 3-6 displays the stress levels at each wind speed, with the corresponding number of cycles. Figure 3-17 shows the same information three dimensionally.

Wind Speed (knots)	S mean (MPa)	S alt (MPa)
5	10.76	0.02
6	24.11	0.02
7	25.79	0.02
8	27.47	0.02
9	29.27	0.02
10	31.06	0.02
11	31.09	0.03
12	34.87	0.03
13	34.91	0.03
14	34.95	0.03
15	36.99	0.03
16	39.00	0.04
17	39.05	0.04
18	39.10	0.04
19	41.26	0.05
20	41.31	0.05
21	43.45	0.05
22		
23	43.58	0.06
24	43.64	0.07
25	43.71	0.07
26	43.79	0.07
27	43.86	0.08
28	43.94	0.08
30	44.10	0.09
32	44.27	0.10
33	44.36	0.11

Table 3-6. Stresses for Cycles Type I

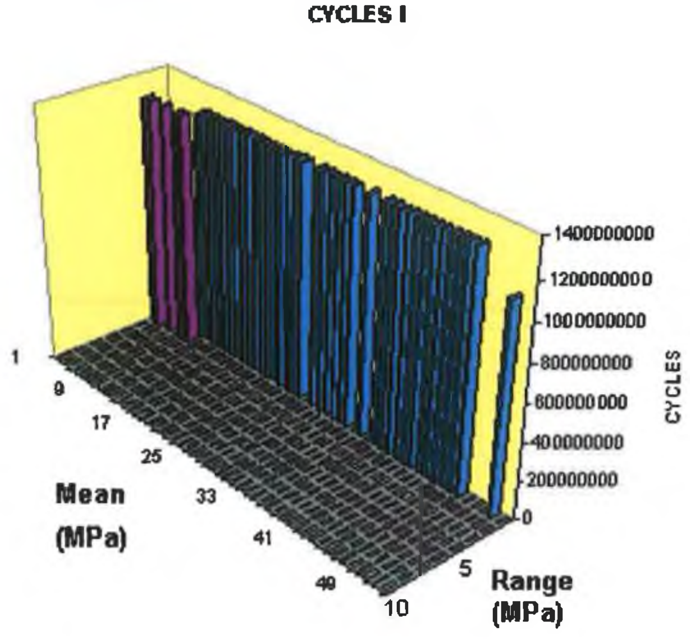


Figure 3-17. Results of a rainflow analysis for Type I cycles of the GMIT wind turbine

The tall column in the figure shows the many lower stress range cycles a wind turbine experiences. As they are low amplitude cycles, they will cause negligible fatigue damage.

Analysis of the stresses presented in Table 3-6 show the following;

- ◊ mean stress is directly proportional to wind speed
- ◊ as the wind speed increases, the cyclic amplitude increases slightly

3.3.5.2. Cycles Type II

Type II cycles represent the variation in mean or alternating stress due to a change in wind speed. To account for this kind of cycles the rainflow algorithm is implemented.

A rainflow computer code was developed using the FORTRAN code. This program is based on the 'ASTM' approach [34]. This code identifies each stress cycle and determines the mean and alternating stress level for each stress cycle in the histogram.

It is assumed that small stress cycles do not effect the fatigue life [37], and consequently they are disregarded. Then, the ASTM code[11] is used to count the number of stress cycles in the data. It determines the mean and the peak-to-peak (also referred as range) alternating stress level for each stress cycle in the histogram. Finally, each stress cycle is mapped into a cycle count matrix. The stress cycles are sorted into bins, that are functions of mean stress and alternating stress levels.

The following is a list of the stress cycles Type II accounted by the rainflow algorithm.

S_{MIN} (MPa)	S_{MAX} (MPa)	S_{RANGE} (MPa)	S_{ALTERN} (MPa)	S_{MEAN} (MPa)
41.36	44.47	3	1.5	42.92
34.98	39.03	4	2	37
34.93	37.01	2	1	35.97
27.48	29.29	1	0.5	28.39
27.48	31.08	3	1.5	29.28
27.48	29.29	1	0.5	28.39
37.01	39.03	2	1	38.02
37.01	39.03	2	1	38.02
31.11	34.89	3	1.5	33
31.11	43.7	12	6	37.4
29.29	43.5	14	7	36.4
39.14	43.63	4	2	41.39
37.01	39.03	2	1	38.02
25.8	43.7	17	8.5	34.75
27.48	29.29	1	0.5	28.39
27.48	31.08	3	1.5	29.28
25.8	34.89	9	4.5	30.34
31.08	34.89	3	1.5	32.99
31.11	34.93	3	1.5	33.02
34.98	39.03	4	2	37
10.77	39.03	28	14	24.9
34.98	37.01	2	1	35.99
39.09	41.3	2	1	40.19

Table 3-7. Stresses for Cycle Type II

The Type II cycle counting performed by the rainflow algorithm is presented in Figure 3-18. This type of stress cycling is responsible for the fatigue damage because of their high ranges, however they are in minority.

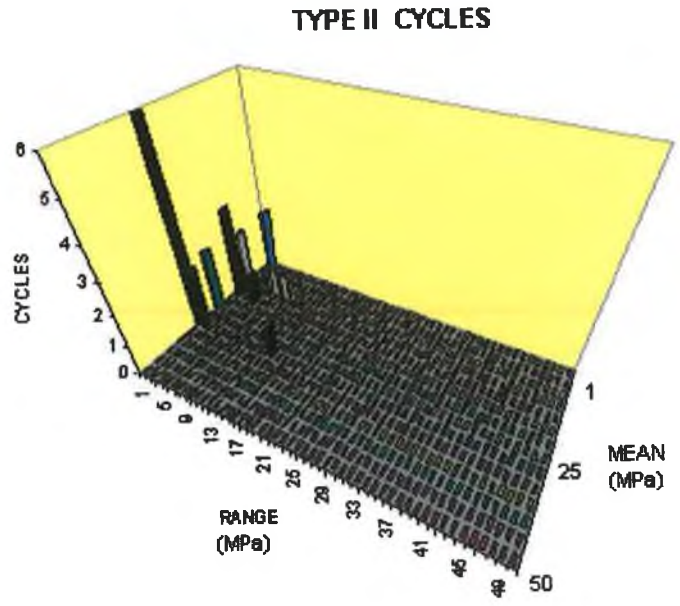


Figure 3-18. *Results of a rainflow analysis for Type II cycles of the GMIT wind turbine*

3.3.6. Stress Spectrum

The sequence of stresses calculated for the wind turbine blade was presented in Table 3-6 and Table 3-7. Now, its relevant information for the fatigue analysis must be displayed in the stress spectrum of Table 3-8.

A fatigue load spectrum is developed, in which the stresses during a run period are shown. They are arranged depending on the type of cycle: Type III corresponds from the maximum peak to minimum valley in the spectra; Type II corresponds to changes in wind speed (the counting is performed using the rainflow counting algorithm). Finally Type I corresponds to the cyclic loading during one rotor revolution. A listing of the wind speed, loads - maximum, minimum, cyclic (amplitude) , and average (mean) - and the R-ratio are presented in the spectrum.

The information displayed in the spectra will be used to calculate the allowable fatigue stress for wind turbine design according to the S-N Linear Damage Method.

Table 3-8. Calculated stress-spectrum, arranged in Type of cycling

Smin (MPa)	Smax (MPa)	Scyc (MPa)	Savg (MPa)	si	N	R	Type
10.00	44.00	17	27	0.99	1	0.227273	III
43.00	44.00	1	44	0.99	1	0.977273	II
38.00	39.00	1	39	0.88	2	0.974359	II
34.00	39.00	3	37	0.88	1	0.871795	II
34.00	37.00	2	36	0.83	1	0.918919	II
27.00	29.00	1	28	0.65	2	0.931034	II
27.00	31.00	2	29	0.70	1	0.870968	II
38.00	39.00	1	39	0.88	1	0.974359	II
36.00	39.00	2	38	0.88	2	0.923077	II
31.00	43.00	6	37	0.97	1	0.72093	II
29.00	43.00	7	36	0.97	1	0.674419	II
39.00	43.00	2	41	0.97	1	0.906977	II
36.00	37.00	1	37	0.83	4	0.972973	II
36.00	39.00	2	38	0.88	1	0.923077	II
25.00	44.00	10	35	0.99	1	0.568182	II
27.00	29.00	1	28	0.65	1	0.931034	II
27.00	31.00	2	29	0.70	1	0.870968	II
25.00	34.00	5	30	0.76	1	0.735294	II
31.00	34.00	2	33	0.76	3	0.911765	II
38.00	39.00	1	39	0.88	2	0.974359	II
34.00	39.00	3	37	0.88	1	0.871795	II
38.00	39.00	1	39	0.88	1	0.974359	II
10.00	39.00	15	25	0.88	1	0.25641	II
34.00	37.00	2	36	0.83	1	0.918919	II
39.00	41.00	1	40	0.92	1	0.95122	II
43.00	44.00	1	44	0.99	4	0.977273	II

Table 3-8 (Continuation)

V wind (knots)	Smin (MPa)	Smax (MPa)	Scyc (MPa)	Savg (MPa)	si	N	R	Type
5	10.74	10.77	0.02	10.76	0.24	18000	0.997	I
6	24.09	24.12	0.02	24.11	0.54	55800	0.998563	I
7	25.77	25.81	0.02	25.79	0.58	28800	0.998563	I
8	27.45	27.49	0.02	27.47	0.62	49500	0.998549	I
9	29.25	29.29	0.02	29.27	0.66	142800	0.998531	I
10	31.03	31.08	0.02	31.06	0.70	43200	0.998503	I
11	31.06	31.11	0.03	31.09	0.70	54000	0.998383	I
12	34.84	34.90	0.03	34.87	0.78	43200	0.998436	I
13	34.88	34.94	0.03	34.91	0.79	54000	0.99831	I
14	34.92	34.98	0.03	34.95	0.79	88800	0.998176	I
15	36.95	37.02	0.03	36.99	0.83	114000	0.998136	I
16	38.96	39.04	0.04	39.00	0.88	102600	0.998089	I
17	39.01	39.09	0.04	39.05	0.88	79800	0.997944	I
18	39.06	39.14	0.04	39.10	0.88	81900	0.997791	I
19	41.21	41.30	0.05	41.26	0.93	60000	0.997747	I
20	41.26	41.36	0.05	41.31	0.93	60000	0.997587	I
21	43.40	43.50	0.05	43.45	0.98	60000	0.997539	I
22	0.00	0.00	0.00	0.00	0.00	0	0	I
23	43.52	43.64	0.06	43.58	0.98	36000	0.9972	I
24	43.58	43.71	0.07	43.64	0.98	36000	0.997021	I
25	43.64	43.78	0.07	43.71	0.98	24000	0.996836	I
26	43.71	43.86	0.07	43.79	0.99	48000	0.996645	I
27	43.78	43.94	0.08	43.86	0.99	12000	0.996448	I
28	43.86	44.02	0.08	43.94	0.99	48000	0.996245	I
29	0.00	0.00	0.00	0.00	0.00	0	0	I
30	44.01	44.19	0.09	44.10	0.99	12000	0.995822	I
31	0.00	0.00	0.00	0.00	0.00	0	0	I
32	44.17	44.38	0.10	44.27	1.00	12000	0.995378	I
33	44.25	44.47	0.11	44.36	1.00	24000	0.995148	I
Spectrum: 16.08					**0.23**	**1388438**	**0.997835**	

3.4. Fatigue Allowable Determination

Once the stress spectrum is identified calculation of the fatigue allowable for a design life is straight forward. The S-N linear damage method is used for calculating the effect of spectrum loading on fatigue strength. The cyclic stress is assumed to be the damage mechanism.

3.4.1. Problem Description

The blade is manufactured from ply-wood composite. It will be assumed that its properties are similar to those of Khaya described in section 2.7. The design spectrum for the blade is composed of the cycles in Table 3-8, and the stress ratios in each level are the same as the load ratios listed in this table. The spectrum represents 158 hours of operation (6 days and 14 hours). The blade is to be designed for a 25-yr lifetime running continuously.

3.4.2. Load Data

The stress spectrum presented in Table 3-8, is divided in different stress levels. The following information must be subtracted from the spectrum for each stress level to calculate the fraction of life consumed by the spectrum.

I	number of stress levels in one spectrum
S_i	stress parameter in the cycle upon which fatigue damage is primarily dependent at level i
n_i	number of cycles applied at S_i

3.4.3. Analysis Data

The laboratory fatigue data for the wood material was specified in section 2.7. The S-N curves of Figure (2-2) corresponds to equation (2-3). The empirical exponent α is been calculated to be equal to -0.0422.The curve shown in Figure 2-5 corresponds to an R-ratio of 0.1 whereas the average R-ratio in Table 3-8 is 0.997835. The empirical coefficient S_l is determined using Figure 2-6.

Its slope is calculated as:

$$\frac{Scyc}{Savg} = \frac{1-.997835}{1+.997835} = 1.1 * 10^{-3}$$

The stress cycle parameters at the intersection of this R-ratio line and the fatigue strength line for 10^7 cycles to failure of the specified material are

Scyc = .0858 MPa

Savg = 78 MPa

Smax = 78.0858 MPa

3.4.4. Allowable Stress Calculation

The S-N curve for the average fatigue strength of laboratory specimens with an R-ratio of 0.99875 then becomes

$S_{max}= 78.0858(N/10^7)^{-.0422} = 154.16\ N^{-0.0422}$

from which S_l=154.16 MPa

For the required 25-year design life, the number of cycles are:

N_f= 25 yr * 8760 hr/yr * 138843 cyc/158 hr = 192.446*10^6 cycles

From Table 3-8

$$\sum_i^I n_i s_i^{-1/-0.0422} = 263562 cycles$$

$$\sum_i^I n_i = 1388438 cycles$$

Substituting these factors calculated into Equation 2-6

$$S_{\max\max} = S_l \left[N_f \frac{\sum_1^I n_i s_i^{-1/\alpha}}{\sum_1^I n_i} \right]^{\alpha} = 154.16*(192.446*10^6*263562/138843)^{-0.0422} = 67\ \text{MPa}$$

This fatigue allowable accounts for the effect of the fatigue spectrum. It represents the average fatigue strength of laboratory specimens. As explained in section 2.6, this value should be modified by one or more correction factors to account for scatter in the laboratory test data and several conditions that can reduce fatigue strength in full scale structures below that of laboratory specimens. A value of one is assumed for these modifying factors. The study carry out by Ansell, Bond, Bonfield and Hacker [9]on Khaya composite blades, shows that wood composites are notch-insensitive and do not show a size effect when subjected to axial fatigue loads.

3.4.5. Safety Factor

Making use of the values found for the maximum allowable stress, and the maximum stress found in the spectrum, the value of the safety factor for fatigue can be estimated.

$$\boxed{N = S_{maxmax} / S_{max} = 67/42 = \mathbf{1.52}}$$

A safety factor higher than unity determines that the structure is safe against fatigue failure. However due to the uncertainty of wind speed, there is always a probability of failure. Higher safety factors decrease this probability.

3.5. Conclusions

A fatigue analysis methodology, based on the S-N approach, has been applied to determine the fatigue life of the GMIT wind turbine facility. The analysis has been focused on the blades, as they are the most critical components.

The methodology employed in this project seeks to define the fatigue life of the blades by defining a fatigue stress allowable for a desired design life. In order to ensure that life, all the stresses must be kept under the fatigue allowable.

The characteristics of the wind turbine have been specified. The design life has been set in 25 years.

The fatigue stress allowable depends on the specification of the wind turbine under consideration and its operational characteristics. These factors are introduced by calculating the effect that a stress spectrum of the wind turbine has over the endurance limit of the material. The method developed by Spera [26] is used in this project to account for the influence of the stress spectrum on the fatigue allowable. Application of this method involves the definition of a stress spectrum. The stress spectrum contains information about the magnitude of stress levels that occur during a start-run-stop cycle of the wind turbine, and the number of cycles for each of the stress levels identified.

The stress spectrum was determined following a process, implemented for this project, based on the European Standards Fatigue Scheme presented in section 1.8. The procedure implemented combines information from a Wind Model and a Wind Turbine Model for the GMIT wind turbine. The Wind Model contains information about the wind speed spectrum during the start-run-stop cycle. The Structural Model comprises an Aerodynamic Model and a Structural Model. The aerodynamic model consist on the blade aerodynamic characteristics which allows the calculation of the aerodynamic forces acting on the blades. The structural model of the wind turbine contains information about the geometry, operational characteristics and material properties of tower and blades. The information is combined making use of the Finite Element Analysis Code ANSYS. On a time history basis, ANSYS outputs the forces and moments experienced by the blades during the start-run-stop period under consideration. Making use of the ANSYS Parametric Design Language this loading is combined with the material properties to compute the stresses. Once the stress levels have been identified the number of occurrence of each of them must be accounted.

The number of cycles at each stress levels are calculated by adding two different kind of cycles: Type I, occurring once per revolution, and Type II, due to changes in mean wind speed. Calculation of Type I is straight forward as it only depends on rotational speed. Calculation of Type II involves the implementation of a rainflow algortithm.

Once the stress spectrum is identified. Its information is combined with relevant fatigue material data to define the fatigue allowable. The material properties are assumed to be similar to those of Khaya composites, whose behaviour and fatigue characteristics are well documented [27].

Application of the methodology to the GMIT wind turbine yields a fatigue allowable higher than the stresses felt by the blades under normal operation. It is expected that the turbine does not fail during the 25 years design life. However, due to the high uncertainty of the wind, there is always a probability of failure. Higher safety factors will decrease this probability. Improved blade designs and setting of operational characteristics of wind turbines based on fatigue could increment this factor. Insights in the blade design will be given in chapter 4.

Attention should be given to the model considered for the wind turbine as characteristics have been disregarded that could modify the magnitude of the stresses felt by the blades. These are the conning effect, and the tower shadow effect. Conning of the blades reduces the stresses. The bending due the aerodynamic forces is balanced by the moment of the centrifugal forces. During normal running, depending on the type of conning (fixed or variable), the blade stresses could be scarcely higher than those created by the centrifgal forces acting alone. On the other hand, tower shadow increments the cyclic loading of the blades during one rotor revolution. Tower shadow refers to the effect produced by the blockage to the wind each time the blade passes behind the tower. The wind speed felt by the blade is modified in a factor that depends on the tower structure. If this factor is significant a cyclic loading is acting on the blade.

The relevance of these factors will be determined during the experimentation phase. Stress measurement in the blades will reveal if these effects were relevant and should be considered.

Chapter 4. Optimisation of Blade Design against Fatigue

The purpose of this chapter is to optimise the fatigue life of the wind turbine blade in the GMIT installation. The original wind turbine blade is a wooden thick blade. Various design alternatives are developed. These designs are based on hollow section blades. The dimensions of the airfoil profile are not modified as they optimise blade performance. Design alternatives include modification of thickness values and addition of internal ribs. The finite element code ANSYS is used to evaluate the designs. Evaluation is based on safety factor increment and stress reduction from the original model.

4.1. Problem Description

4.1.1. Introduction

The original design of the blade in the GMIT wind turbine consists of a thick wood blade. The blade profile is the NACA 4412. The blade and chord length have been calculated to optimise the aerodynamic performance of the blade at the rated rotational speed of the rotor of 200 rpm. Their values are reported in Table 4-1. The section remains constant along the blade. A plane view of the original design is shown in Figure 4-1.

Table 4-1

rotor length: 2.8 m	blade length: 2.1 m
chord length: 0.27 m	hub blade clearance: 0.7 m

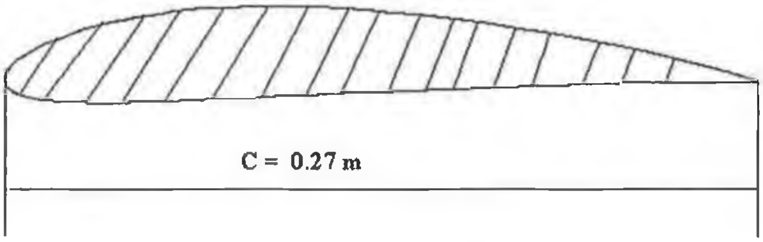


Figure 4-1. NACA profile. Original design.

In chapter 3 a fatigue analysis was carried out on this blade. The safety factor found was 1.52. The maximum stress acting on the blade was 44 MPa.

4.1.2. Scope

3 design alternatives are considered, these are:

- hollow blade (Figure 4-2)
- hollow blade with 1 rib (Figure 4-3)
- hollow blade with 2 ribs (Figure 4-4)

For each of them three models with different values of thickness (5, 8, and 10 mm)have been considered.

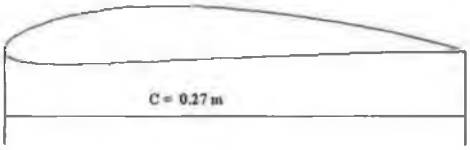


Figure 4-2. Hollow blade

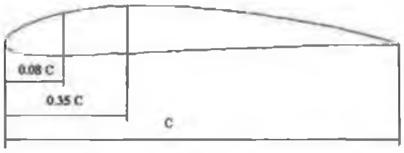


Figure 4-3. Blade with one rib

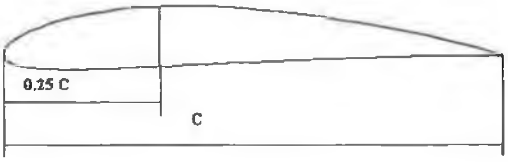


Figure 4-4. Blade with two ribs

4.1.3. Analysis Requirements

The geometry of the blade is specified in Table 4-1, relevant material properties are given in section 2.6 The loading data corresponds to the pressure distribution on the blade for an angle of attack of 6^0 when rotating at rated speed.

4.2. Analysis Specification

4.2.1. Modeling assumptions

(i) Large deflection
(ii) Elastic behaviour
(iii) Wind flow is simulated by applying a pressure distribution along the blade.

4.2.2. Analysis code and revision

The finite element program used is ANSYS revision 5.3 , running on a PII 233 Hz. PC.

4.2.3. Analysis types

Large Deflection, Elastic.

4.2.4. Element types

8 noded SHELL93 elements are used for the blades.

4.2.5. Real constants

The real constants used for the 3-D blade analysis are defined .

Table 4-2

Real Constant Set	**Shell thickness (m)**
1	$5*10^{-3}$
2	$8*10^{-3}$
3	$10*10^{-3}$

4.2.6. Material properties

The material used for the blades is wood/epoxy.

Table 4-3

Mat No.	Region used	E (Pa)	υ	ρ (kg/m^3)
1	Blades	$12 *10^9$	0.3	500

4.2.7. Boundary conditions and loading

The blade is constrained at the root. In this section all degrees of freedom are constrained.

The loading consist on a pressure distribution along the surface of the blade. The airfoil pressure distribution is shown in Figures 4-5 and 4-6, it corresponds to an angle of attack of 6^0. In addition gravity and an angular velocity of 21 rad/sec are applied.

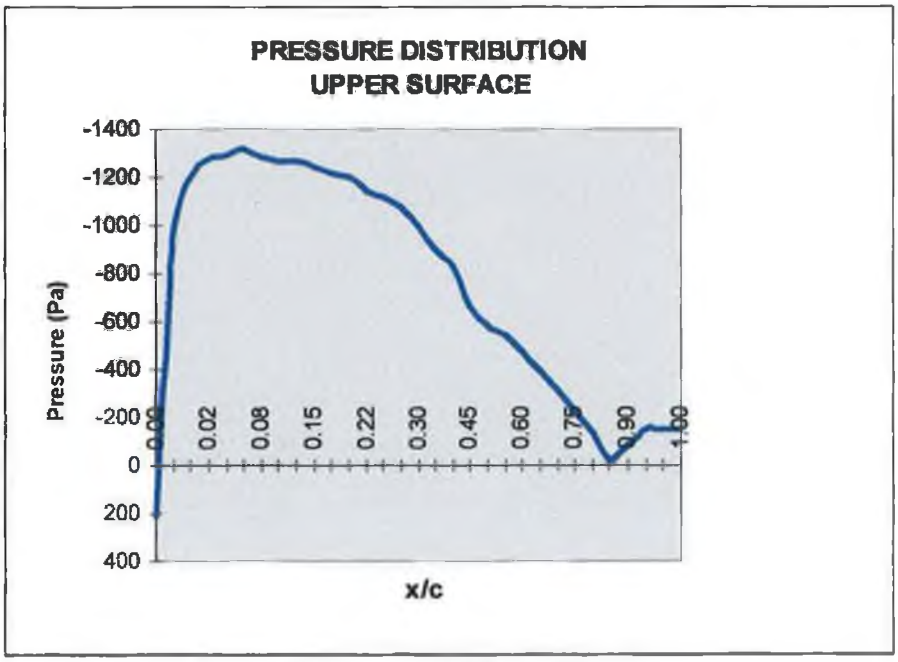


Figure 4-5. Pressure distribution in the upper surface of the airfoil , for an angle of attack of 6^0.

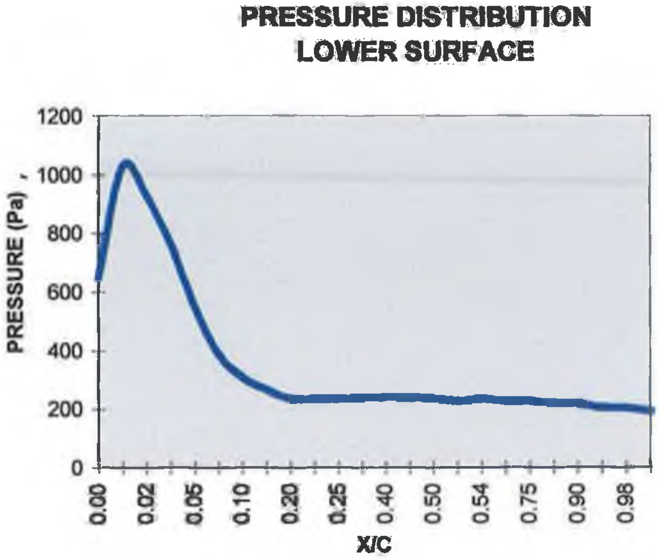


Figure 4-6. Pressure distribution in the lower surface of the airfoil , for an angle of attack of 6^0.

4.3. Analysis Results

4.3.1. Summary of Principal Results.

The stress distribution has been computed along the blade, and shown in Figure 4-7. The hot spots are identified in position 1 and 2 where most critical stresses are located.

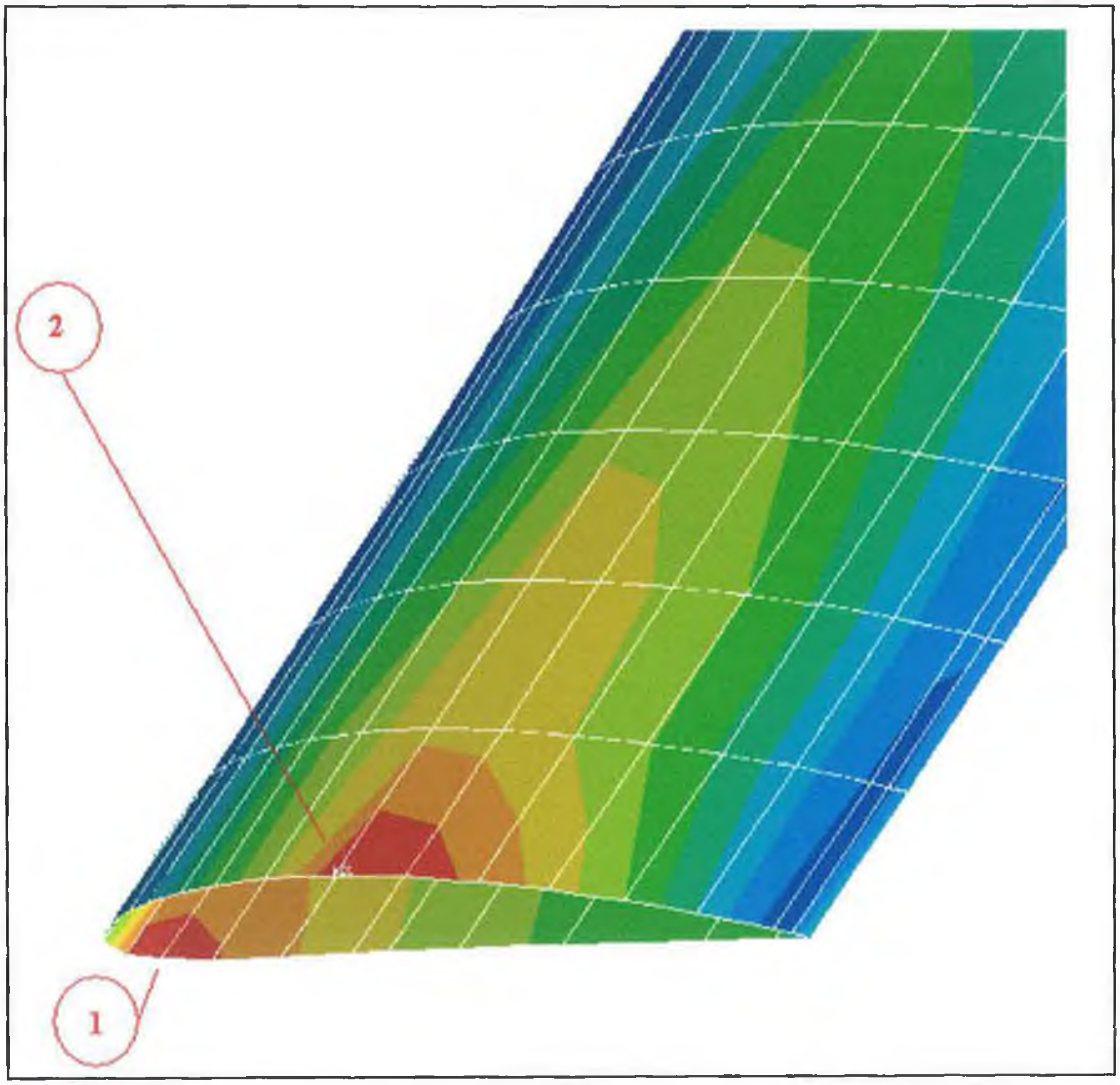


Figure 4-7. Equivalent Stresses at the blade root. (Von Misses Stresses)

The results of primary interest are shown in the table below. These are the maximum stresses in tension which are used to calculate fatigue life.

Table 4-4. Wooden models. Hollow Blade

Thickness	**Hollow Blade**					
mm	**Mass (kg)**	Mass reduction (%)	**Stress (MPa)**	Stress reduction (%)	**SF**	SF increment (%)
10	5.81	7.78	17.17	60.98	**3.9**	156.56
8	4.65	26.19	19.86	54.86	**3.37**	121.71
5	2.9	53.97	27.34	37.86	**2.4**	57.89

Table 4-5. Wooden models Stiff blade with 2 ribs.

Thickness	**Stiff blade with 2 ribs**					
mm	**Mass (kg)**	Mass reduction (%)	**Stress (MPa)**	Stress reduction (%)	**SF**	SF increment (%)
10	6.39	-1.43	15.02	65.86	**4.46**	193.42
8	5.11	18.89	17.05	61.25	**3.92**	157.89
5	3.19	49.37	22.9	47.95	**2.92**	92.11

Table 4-6. Wooden models. Stiff blade with 1 ribs at middle

	Stiff blade with 1 ribs at middle					
Thickness mm	**Mass (kg)**	Mass reduction (%)	**Stress (MPa)**	Stress reduction (%)	**SF**	SF increment (%)
10	6.14	2.54	15.6	64.55	**4.29**	182.24
8	4.92	21.9	17.78	59.59	**3.77**	148.03
5	3.05	51.59	24.05	45.34	**2.78**	82.89

4.3.2. Conclusions

Analysis of the designs shows that stresses reduced dramatically when considering hollow blades against thick blades. The stress reduction varies from 37.86% , for a 5 mm blade, to 65.86% for 10 mm thick blades.

In hollow blades a proportional relation between thickness and stress reduction is observed. This is also observed in designs containing ribs, however the reduction of stress is lower for the same thickness.

Stress reduction increments further when adding ribs to a hollow blade (for a 5 mm thickness blade, the stresses reduce 7% more when adding the first rib). However the increment rate reduces as the number of ribs increases (stresses reduce only 3% more when considering a second rib). Values found for designs with two ribs were similar to those having only one rib. In addition, adding ribs has a higher effect in thinner blades ; when adding one rib to a hollow blade, stresses are reduced a 5% more for a 5 mm blade than a 10 mm blade.

Additional analysis reveals that for designs with a same mass reduction those designs containing ribs have higher stress reductions and consequently higher safety factors, than those that do not. Mass reduction is important because results in a decrease of gravity forces, that as was mentioned in chapter 2, causes a cycle loading once per revolution (Type I cycles).

All the safety factors have incremented considerably. The original design had a safety factor of 1.52. The new design safety factors range from 2.4 to the more conservative 4.6.

It is concluded that the use of hollow blades has a positive effect in designing against fatigue. In addition, the use of rib stiffeners allows a reduction in the thickness of the hollow blade without reducing its strength.

Chapter 5. Conclusions

All rotating machines including wind turbines are generators of fatigue. Every revolution of its components produces a load cycle. Each of these cycles causes a finite amount of damage, resulting in a reduction in the component fatigue life. Fatigue life is been identified as the major cause of wind turbine failure. To estimate fatigue life, load and cycle estimation in conjunction with linear damage rules and material fatigue data are used.

Rotor blades are the key component in designing against fatigue. Therefore, a fatigue analysis is performed on the rotor blades. However, the same methodology is applicable to the other wind turbine components. The root blade is the critical section of the blade, where the maximum stresses are experienced.

The objective of the overall project is the application of a fatigue methodology to predict the fatigue life of the GMIT wind turbine installation, and address design optimisations to the original model.

In order to assess the fatigue life of the wind turbine a methodology had to be identified. Two different approaches for fatigue life prediction have been follow by diverse researches: (1) the S-N approach, and (2) the Fracture Mechanics Method. The former bases its approach in the crack-propagation state. The latter bases its analysis on the nominal stress in the region of the component being analysed.

The methodology selected follows the S-N approach. In this methodology the fatigue life of the wind turbine is based on the determination of a fatigue allowable for a desired design life. To ensure that life, all stresses must be kept below the fatigue allowable. To estimate the fatigue allowable for this life, the magnitudes of the loadings (mean and

The fatigue analysis involves the definition of two elements:

1. the load and consequent stress spectra in the critical components of the wind turbine
2. and their allowable fatigue stress for a design life.

To identify the load spectra the GMIT wind turbine was modelled on an aerodynamic and structural basis. The finite element code ANSYS was used to determine the load and stress spectrum. Aerodynamic, gravitational and centrifugal forces were considered in the analysis. As it was anticipated, the root blade is the critical spot in the blade, where the maximum stresses are found.

Analysis of the loads shows that the maximum stresses are caused by centrifugal forces. Further analysis of the stress spectrum reveals the following:

- ◊ Mean and alternating stresses are directly proportional to wind speeds
- ◊ The stress amplitude increases slightly with wind speeds.
- ◊ Alternating stresses occurring once per revolution (Type I cycles) are very low.

The reason why cycles occurring once per revolution are so low is because the main load acting on the blades is the high centrifugal forces. These are mainly stable during the running of the wind turbine as the rpm stay nearly constant (200 rpm). Consequently, the stresses felt by the blade are nearly constant during one revolution. Oscillation of the mean value is caused by the gravity and wind shear effect. Because of the light weight of the blades (6.3 kg) the gravity loading reversal (1 MPa) is not critic. This finding contrast with large scale wind turbines where gravity is a primary fatigue load. [26],[10]

When the magnitude of the stresses are known, the number of times they are experienced must be calculated. The number of cycles at each stress levels are calculated by adding two different kind of cycles: Type I, occurring once per revolution, and Type II, due to changes in mean wind speed. Calculation of Type I is straight forward as it only depends on rotational speed. Type II cycle counting is performed by the implementation of the 'rainflow-counting' algorithm.

The stress-spectrum contains information about the stress levels and number of cycles of each of them.. Following Spera's Methodology the stress spectrum information is combined with relevant fatigue material data to define the fatigue allowable. The material properties are assumed to be similar to those of Khaya composites, whose behaviour and fatigue characteristics are well documented [27]. The fatigue requirement for the GMIT is determined as a design life of 25 years.

The allowable fatigue life was found to be 67 MPa for the wooden blade. The fatigue allowable is higher than the stresses felt by the blades under normal operation. It is expected that the turbine does not fail during the 25 years design life. However, due to the high uncertainty of the wind, there is always a probability of failure. Higher safety factors will decrease this probability

Diverse design alternatives were analysed to increment the fatigue life of the blades for the GMIT wind turbine. The blade consist on a thick NACA 2214 airfoil with constant chord along its length.. The design alternatives consist on hollow blades combined with rib stiffeners. All the designs developed improved the strength of the blade, and consequently its performance against fatigue. All the safety factors incremented in the new designs. The original design had a safety factor of 1.52. The new design safety factors range from 2.4 to the more conservative 4.6.

Analysis of the designs with the finite element code ANSYS showed that stresses reduced dramatically, by 37.86% or more, when considering hollow blades. Stress reduction increments further when adding ribs to a hollow blade. However the increment rate reduces as the number of ribs increases. Values found for two ribs designs were similar to those having only one rib.

In addition for a same design shape, increment in thickness yields higher stress reduction. In hollow blades increment of the thickness reduces the stresses dramatically. In blades with ribs the increment rate is smoother.

In general, designing against the fatigue loads that a wind system will have to survive during its design life, will include keep load levels low, avoid stress concentrations caused by holes, burrs, sharp corners, etc., in addition there are considerations of corrosion and galvanic action that can precipitate or aggravate crack formation.

Studies of large horizontal-axis windmills have shown that primary fatigue loads are caused by centrifugal forces and gravity [23] . Reducing their effect will increase the life of the structure. Reducing the weight of the blades will decrease both forces centrifugal and gravity. The most important effect is the reduction of the reversal cyclic stress caused by gravity for each revolution of the rotor. Factors affecting the weight of the blades, include material selection, blade profile, and thickness for hollow blades.

Another way of reducing fatigue loading consist on modifying the wind turbine operational characteristics. A method of doing so consist on the arrangement of the rotor allowing conning. Coning consist on the fastening of the blades to the hub in such a way that the blades axes make with the rotation axis of the rotor an angle lower than 90^0. This arrangement allows the aerodynamic force to be compensated by the moment of the centrifugal forces during normal running, in such a way that the stresses at the blade are reduced.

On the other hand, tower shadow increments the cyclic loading of the blades during one rotor revolution. Tower shadow refers to the effect produced by the blockage to the wind each time the blade passes behind the tower. The wind speed felt by the blade is modified in a factor that depends on the tower structure. If this factor is significant a cyclic loading is acting on the blade. This cyclic loading can decrease the fatigue life of the wind turbine.

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APPENDIX I

FORTRAN PROGRAMS

I.1 Introduction

This unit describes the programs developed to calculate the forces that apply on a wind turbine.

These calculations are based on the Glauert Blade Element Theory, explained in Chapter 4 of the report.

All the programs have been implemented using FORTRAN 90, and the code source is provided for all of them.

I.2 Flow Chart

The following flow chart (fig I.1) is an overview of the data handling and results carried out by the different programs.

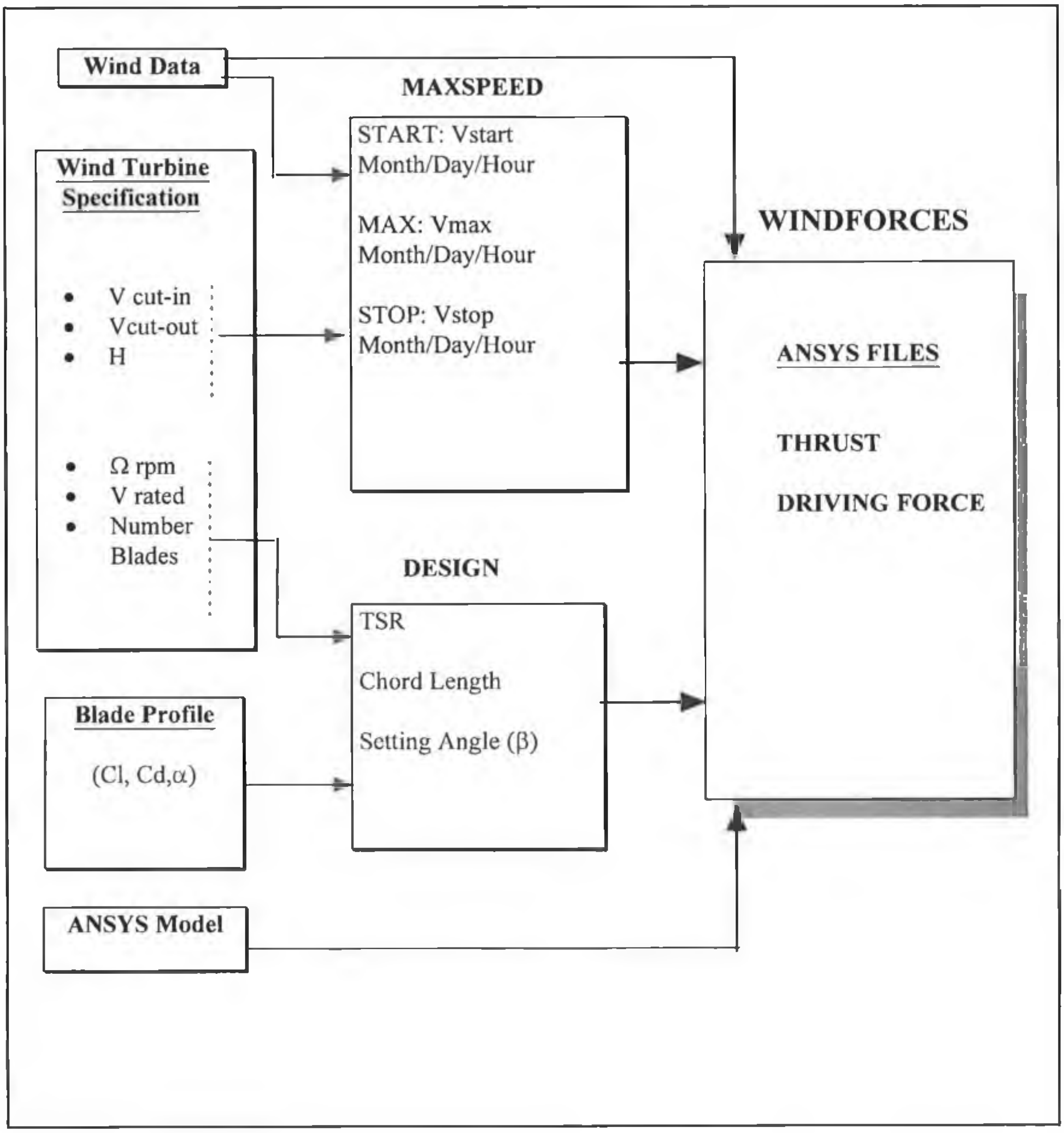

Fig. I..1

The Wind Velocities are entered from a data file.

The Wind Turbine Specification are entered by the user.

The program 'MAXSPEED' provides the period start-run-stop of study.

The aerodynamic design is performed by the program 'DESIGN'. This program outputs the optimum chord and setting angle at the different stations considered on the blade.

The results provided by both programs plus the wind data file and the node coordinates used for the ANSYS model are inputs for the main program 'WINDFORCES'. This program calculates the forces to apply to the ANSYS model, and outputs the results as a series of results files, one per hour, formatted to be loaded in the ANSYS program automatically.

Appendix I.3

PROGRAM MAXSPEED

1. **Period with Maximum Wind Speed. From Start up to Shut down. Program MAXSPEED.**

    1.1 Introduction
    1.2 Program Features
    1.3 Input Data
    1.4 Output Data

2. **Code Source.**

3. **Results.**

1. Period with Maximum Wind Speed. From Start up to Shut down.

Program MAXSPEED

1.1 Purpose

The main aim of the program 'MAXSPEED' is to find the maximum wind velocity occurred in a year. It also obtains the date and time a specific wind turbine will start-up and will stop for that maximum wind speed recorded.

The specification required from the wind turbine must be entered by the user, and it includes the cut-in velocity, the cut-out velocity, and the nacelle height.

1.2 Program Features

In its actual structure, the program 'MAXSPEED' consists of a main program and two subroutines.

The pupose of this structure is to allow future improvements on the programs; as modifications on the subroutines can easily be performed without affecting the main program.

The subroutines implemented in the program 'MAXSPEED' are the following:

MaxVelocity:	This subroutine finds out the maximum wind speed from a data file. The output parameters are:

text1: file name with the wind speeds.

ms: maximum wind speed recorded.

nm,nd,nh: month, day, and hour when the maximum velocity is recorded.

ipoint: record number (line) of the data file where the maximum wind velocity is recorded.

SpeedConv: this subroutine convers the cut-in velocity of the wind turbine from m/s to knots.
In addition, it takes into account the nacelle height in the calculation of the start-up velocity for a reference height of 10 m.

The input parameter are the following:

nh: nacelle height.
nsp: start-up velocity (m/s) at the nacelle height.

The output parameters are:

nout: start-up velocity (m/s) at 10 m. height.

1.3 Input Data.

The input data for the program are those values entered for the following parameters:

Text1: file name for the wind velocities.
Vcutin: cut-in velocity (m/s) of the wind turbine.
h: nacelle heigh in m.

1.4. Output Data.

The output data are printout on the screen. These include the wind velocity in knots, and the month, day and hour of occurrence for the conditions listed below :

- Maximum Wind Speed: Vmax
- Wind speed at which the wind turbine starts to run: Vstart
- Wind Speed at which the wind turbine stops: Vstop

2. Code for the program 'MAXSPEED'

The FORTRAN 90 source code is shown below.

```
!
! Program to find the range of Velocities where Vmax   is,
!                              from Vcut-in to Vcut-out
!
        Program DataHandle
        integer ndir(24),nspeed(24)
        integer Vmax,day,month,hour
        character (len=25) :: text
        real Vin,Vstop,Vcutin,h,Vstart
        integer icont,icont2
!
        call MaxVelocity(Vmax,day,month,hour,text,icont)
        icont2=icont
        iconfix=icont
        open(unit=31,access='sequential',status='old', file=text)
!
        do 20 i=1,icont-1  ! places the data file in the right record
        read(31,11,err=20,end=998)
20      continue
!
        print *," Enter Cut-in Speed (m/s)"
        read (*,*)Vcutin
        print *,(/"/)
        print *," Enter Height of hub (m)"
        read (*,*)h
        print *,(/"/)
        call SpeedConv(h,Vcutin,Vin)
!
        Vstop=100
        print 12,"Vmax","day","month","hour"
        print *,Vmax,day,month,hour
        do 115 while (icont.lt.365.and.Vstop.gt.Vin)
        read (31,11,err=105,end=998)nst,iyear,imonth,iday,(ndir(j),nspeed(j),j=1,24)
11      format (i2,i4,i2,i2,24(i2,i2))
        i=hour
        do 105 while (nspeed(i).gt.Vin.and.i.lt.24)
        i=i+1
105     continue
        icont=icont+1
        Vstop=nspeed(i)
        if (nspeed(i).lt.Vin)then
        print 12,"Vstop","day","month","hour"
12      format (4(a14))
        print*,Vstop,iday,imonth,i
        print *,(/"/)
        endif
115   continue
```

```
!
!
        close(31)
        open(unit=31,access='sequential',status='old', file=text)
        do 40 i=1,icont2-1              ! places the data file in the right record
        read(31,11,err=20,end=998)
40      continue
!
        Vstart=100.0
        do 215 while (icont2.gt.1.and.Vstart==100.0)
        read (31,21,err=205,end=998)nst,iyear,imonth,iday,(ndir(j),nspeed(j),j=1,24)
21      format (i2,i4,i2,i2,24(i2,i2))
        if (icont2==iconfix)then
        i=hour
        else
        i=24
        endif
        do 205 while (nspeed(i).gt.Vin.and.i.gt.1)
        i=i-1
205     continue
        if (nspeed(i).lt.Vin) then
        Vstart=nspeed(i)
        print 12,"Vstart","day","month","hour"
        print *,Vstart,iday,imonth,i
        print *,(/"/)
        else
        if (i==1) then
                icont2=icont2-1
          close (31)
                open(unit=31,access='sequential',status='old', file=text)
                do 42 j=1,icont2-1              ! places the data file in the right record
                read(31,11,err=20,end=998)
42              continue
        end if
        endif
215   continue


!
!
contains
!---------------------------------------------------------------------------
        subroutine MaxVelocity (ms,nd,nm,nh,text1,ipoint)
        character (len=25) :: text1
        integer ndir(24),nspeed(24)
        integer nst,Maxspeed,ms,nd,nm,nh
!
        print *," Enter name an path of file of wind speed data"
        print *,(/"/)
        print *," 1: default <c:\beafich\data.txt>"
        print *," 2: different file or path"
        print *,(/"/)
        read *,choice
        print *,(/"/)
```

```
        if(choice==1)then
        text1="c:\beafich\data.txt"
        else
        print *," Enter name an path of file of wind speed data"
        read  *,text1
        endif
        print *,(/"/)
        open(unit=31,access='sequential',status='old', file=text1)
!
        Maxspeed=0
    do 101 icount = 1, 365
        read (31,11,err=101,end=999)nst,iyear,imonth,iday,(ndir(j),nspeed(j),j=1,24)
11      format (i2,i4,i2,i2,24(i2,i2))
        do 100 i=1,24
        if (nspeed(i).gt.Maxspeed)then
        maxspeed=nspeed(i)
        nday = iday
        nmonth = imonth
        nhour=i
    ipoint=icount
        end if
100     continue
101   continue
!
999     close (31)
        ms=maxspeed
        nd=nday
        nm=nmonth
        nh=nhour
        return
        end       subroutine MaxVelocity
!
        subroutine SpeedConv(nh,nsp,nout)
        real nh,nsp,nout
        real zr,zo,a,vi
! nh: height of hub
! nspeed: V cut in in m/s
! Return: V cut in knots, at hub height
        vi=nsp/.515 ! converts m/s to knots
        zr = 10.0
        zo = nh
        a = 1.0/7.0
    vi = vi/(zo/zr)**a       !converts V at h height to 10 m
        nout=vi
        return
        end subroutine SpeedConv
998     end program DataHandle
```

3. Results

The output of the program is shown below.

The input data are those of the Proven Wind turbine WT6000, listed in Chapter 3, section 3.3.1. of the report.

	V (knots)	MONTH	DAY	HOUR
MAX	33	2	10	15
START	2	2	7	8
STOP	3	2	13	23

Appendix I.4

PROGRAM DESIGN

1. **Aerodynamic Design of the Blades. PROGRAM DESIGN**
    - **1.1 Purpose**
    - **1.2 Input Data**
    - **1.3 Output Data**
2. **Code Source.**
3. **Results.**

1. Aerodynamic Design of the Blades. PROGRAM DESIGN

1.1 Purpose

The aim of the program 'DESIGN' is to perform the optimum aerodynamic design of the rotor of any wind turbine, to obtain maximum power for a given specification.
The procedure implemented is based on the Theoretical Fundaments explained in Chapter IV of the report. The approach considered is less rigorous as some simplifications have been made that give reliable results. Some improvements of the program are proposed.

The program 'DESIGN' outputs the chord lengths and setting angle for the different stations along the length of the blade.

The main elements of the programs are explained in the following section.

1.2 Input Data.

The input data for the program are those values entered for the following parameters:

B:	number of blades.
Alpha:	optimum angle of attack for the aerodynamic profile used for the blades (The profile NACA 4412 has been considered, its optimum angle of attack is 6 degrees).
Stat:	Number of stations in which the blade is divided. The lenght chord and setting angle is calculated for each of the stations. (Value entered: 10)

V: Rated wind velocity of the wind turbine (m/s)

Omeg: Nominal Rotational Speed of wind turbine in rpm.

1.3 Program Output.

A list of the results are output on the screen.

For the different stations along the blade the following data are given:

- chord length (m),
- setting angle (degrees).

The tip speed ratio, TSR, is also provided.

2. Code for the Program DESIGN

The FORTRAN 90 source code is shown below.

```
!Program to calculate the cord in the different stations
        program Design
        real c(20),r,pi,D,Ra,span,w,V,alpha,tanfi(20),fi(20),beta(20)
        integer n,B
        character choice
        print*,"enter number of stations"
        print *,"1- 10 equidistant stations"
        print *,"2- other"
        read *,choice
        if (choice=="1") then
        n=10.0
        else
        print *,"number of stations"
        read *,n
        endif
        pi=3.1416
        print *,"Enter diameter of rotor disk "
        read *,D
        Ra=D/2.0
        span=Ra/n
        print *,"Enter omega (rpm)"
        read *,w
        print *,"Enter rated speed (m/s)"
        read *,V
        TSR=(w*2.0*pi*Ra)/(60.0*V)
        print *,"Enter number of blades"
        read *,B
        print *,"enter optimum angle of attack"
        read *,alpha
        r=span
        do 10 i=1,n
        raiz=SQRT((TSR*TSR*R*R/(Ra*Ra))+4.0/9.0)
        print*,raiz
        c(i)=(16.0*pi/(9.0*B))*Ra/(TSR*raiz)
        print*,c(i)
        tanfi(i)=(2.0/3.0)*Ra/(r*TSR)
        fi(i)=atand(tanfi(i))
        beta(i)=fi(i)-alpha
        r=span+r
10      continue
        r=0
        print *," Tip Speed Ratio ", TSR
        do 15 i=1,n
        print 12,"estation",i,"chord length", c(i),"setting angle",beta(i)
12      format(a10,i4,3x,a13,f8.2,a14,f8.2)
15      continue
        print *,"Lenth of span",span
end
```

3. Results

The output of the program is shown below, the data input are those of the GMIT wind turbine listed on Chapter 3 , section 3.2.1. of the report.

The blade profile used is NACA 4412.

TSR: 4.99

Station	Chord (m)	Setting Angle (degrees)
1	2.18	47.76
2	1.09	28.30
3	.73	18.45
4	.55	12.83
5	.44	9.26
6	.36	6.81
7	.31	5.03
8	.27	3.68
9	.24	2.62
10	.22	1.77

Appendix I.5

PROGRAM WINDFORCES

1. Forces on a Wind Turbine. PROGRAM WINDFORCES

- **1.1 Purpose**
- **1.2 Program Structure**
  - **1.2.3 Main Program**
  - **1.2.4 Subroutines**
- **1.3 Input Data**
- **1.4 Program Output**

2. Code Source.

3. Results.

1. Forces on a Wind Turbine. PROGRAM WINDFORCES

1.1 Purpose.

The program 'WINDFORCES' calculates the wind forces that act on a wind turbine.

A series of parameters must be entered by the user. These values are computed from other programs explained in the previous sections.

The results are stored on data files with the format requested by the ANSYS software. A model of the wind turbine has been modeled using ANSYS.

The actual implementation of the program 'WINDFORCES' consider blades with the profile NACA 4412, in future improvements the program will be modify to accept different profiles.

1.2 Structure of the Program.

The program 'WINDFORCES' consists of a main program an several subroutines.

1.2.1 Main Program. WINDFORCES:

The program 'WINDFORCES' computes the aerodynamic forces that act on a wind turbine.

Each run of the program is performed for a series of wind velocity records; these are found in a data file.

The program gives the user two choices; to enter the name of the file or a default name (c:\beafich\data.txt). The latter is the one used in this project, and it has been supplied by the Dublin Meteorological Sevice. It contains the value and direction of the wind velocities recorded in Shannon Aerport in the period of a year.

For each velocity the program calculates the aerodynamic forces to apply on the turbine, in the different nodes of the modes corresponding to the tower and blades.

The node coordenates fr the blades and tower are stored in a data file. The user is again given the opportunity of either entering the name of the file or choosing the default one (c:\beafich\nlist.lis). The latter is an ANSYS data file in which some modifications have been performed.

The results are stored in a data file with the format required by ANSYS file. This format allows the ANSYS software to run the load cases automatically.

1.2.2 Subroutines

The program contains several subroutines: Totday, AngVelocity, and Thrust.

Totday: Function that computes the number of days on a year before a given month.
The purpose of this function is to place the data file on the line required to be read by the program.

AngVelocity: This function gives the value of the rotational speed of the rotor for a given wind velocity.
The values are obtained from the program Rotational Speed.

Thrust: This function calculates both the forces that opposes the wind in the out-of-plane direction, thrust; and the driving forces that makes the blade rotate.

1.3 Program Features

The program 'WINDFORCES' calculates the forces to apply on the geometry of a wind turbine.
The wind velocities are input from a data file, where the wind velocities are recorded on an hourly basis.
The results are stored on a data file with the format required by the ANSYS software.

The theoretical Foundaments are based on Glauert Blade Element Theory explained in Chapter IV of the report. Some simplifications have been performed.

Only the drag force acts on the tower. On the blades the aerodynamic forces have been calculated as two forces one acting on the rotor plane, and the other out of the rotor plane. The calculation method uses standard strip theory. The blade is divided radially into chordwise strips from the tip to the root. For each element, the chord length is entered as input. Their values have been previously calculated by the program 'DESIGN' The setting angle is also entered.

For a first model the chord length and setting angle is considered to be constant along the blade. It's suggested to consider tappering and twisting in future versions of the program.

Note on Simplifications:
No se han condirado los factores de interferencia axial y angular debido a que una de los criterios de disenio para las aeroturbinas de este tamanio consiste el coste y facilidad de manufactura. El incremento en eficiencia de la aeroturbina no compensaria el incremento en el coste.

1.4 Input Data

A list of the input data with explanations of their meaning is given below. Some suggested values used for this project are also supplied.

The most important input parameters are:

text1: file name where the wind velocities are stored.

The wind velocities are stored in knots.

The data are assigned to the following parameters:

ist: number of the meteorological station
iyear: year of record
imonth: month of record
iday: day of record
nspeed (24): array with the wind speed for the 24 hours in a day.

text2: file name where the node coordenates of the model are stored.

Its format corresponds to ANSYS files.

Nodes 1-21: tower
nodes 22- right blade
nodess left blade
nodes up/down blade

The node coordenates are assigned to the following array parameters:

x(i): coordenate x of node i
y(i): coordenate y of node i
z(i): coordenate z of node I

text3: file name where the results are stored. Its format corresponds to ANSYS load step files.

The program gives the user three choices:

1. To write a file for each month.
   In each month file, everyday has 24 load steps to apply on the ANSYS model. They correspond to the 24 hours on a day.

2. To write on the file MaxSpeed, the load steps for the start-run-stop cycle of the turbine under consideration. This cycle contains the maximum wind speed recorded on a year.

3. Another.

Note: To apply a force file as a load step on ANSYS, the file must possess a certain name. The name required is 'Jobname.SX', where 'Jobname' stands for the name of the model considered in the finite element analysis. X stands for the load step number.

D: rotor diameter.

Omega: Rotational speed of the rotor in rpm.

Stat: number of stations in which the blade is deivided. The geometry of the blade at each station must be entered. The number of stations must be equal to the number of blade nodes considerd for the ANSYS model.

chord(i): chord length of the blade at station i; i=1 root, i=10 tip.
These values are computed by the program 'DESIGN'.

If the chordlength along the blade is considerd to be constant, is recommended to apply the value of the chord length for station 8 out of 10.

Beta(I): setting angle of the blade at station i; i=1 root, i=10 tip.
These values are computed by the program 'DESIGN'.
If the setting angle along the blade is considerd to be constant, is recommended to apply the value of the setting angle for station 8 out of 10.

Alpha: Optimum angle of attack for the profile considered. In this case the profile used is NACA 4412, and the optimum value is 4^0.

Cl: Lift coefficient for the blade profile. In this case a constant value is given.
Cd: Drag coefficient for the blade profile. In this case a constant value is given.

TanE: Lift to Drag ratio.

Other parameters:

conv=.515 : conversion constant from knots to m/s.

z: nacelle height in m. We have considered 9 m. as specified by manufacturer.

a=1/7: roughness surface coefficient.

V: wind speed at the different t node heights of the model.

Force:	force acting along the tower nodes.
T:	thrust acting along the blade nodes.

1.5. Program Output

The output of the program 'WINDFORCES' is stored on a series of data file which format corresponds to the one specific to the ANSYS load step files. This format allows the automatic application of the forces on the model when running ANSYS.

In these files the node numbers, the force direction, and force values in newtons are given.

2. Code for the program 'WINDFORCES'.

The FORTRAN 90 source code is shown below.

```
! Program Wind Forces
        integer ndir(24),nspeed(24),node(51),nodedown(51)   !51= number of nodes
        real z(51),x(51),y(51),xdown(51),ydown(51),zdown(51)
        character (len=25) :: text1,text4,text5
        character (len=27) ::text6
        character (len=37) :: text2
        character (len=38) :: text20
        character (len=2) :: text3(99)
        character (len=3) :: text30(99)
        character (len=2):: aday,amonth
        character (len=6):: text7
        character (80) lin(40)
        integer::day(12),stat
        real omeg,l(10),sum1,sum2,sum3,omega
        integer choice, choiceres
        real driving,drivingx,drivingz
        real drivingdown,drivingdx,drivingdz
        character (len=36)textdriv2
        character (len=40)textdriv2d,textdriv22d,textdriv23d
        character (len=37)textdriv20,textdriv22
        character(len=41)textdriv21          ,textdriv23
c
        sum1=0
        sum2=0
        sum3=0
        day=(/31,28,31,30,31,30,31,31,30,31,30,31/)
        text3=(/'01','02','03','04','05','06','07','08','09','10',
        1'11','12','13','14','15','16','17','18','19','20',
        1'21','22','23','24','25','26','27','28','29','30',
   1'31','32','33','34','35','36','37','38','39','40',
   1'41','42','43','44','45','46','47','48','49','50',
        1'51','52','53','54','55','56','57','58','59','60',
   1'61','62','63','64','65','66','67','68','69','70',
   1'71','72','73','74','75','76','77','78','79','80',
        1'81','82','83','84','85','86','87','88','89','90',
   1'91','92','93','94','95','96','97','98','99'/)
    text30=(/'100','101','102','103','104','105','106','107','108',
        1'109','110','111','112','113','114','115','116','117','118','119'
   1,'120',
        1'121','122','123','124','125','126','127','128','129','130',
   1'131','132','133','134','135','136','137','138','139','140',
   1'141','142','143','144','145','146','147','148','149','150',
        1'151','152','153','154','155','156','157','158','159','160',
   1'161','162','163','164','165','166','167','168','169','170',
   1'171','172','173','174','175','176','177','178','179','180',
        1'181','182','183','184','185','186','187','188','189','190',
   1'191','192','193','194','195','196','197','198'/)
```

```
        print *," Enter name an path of file of wind speed data"
        print *,(/"/)
        print *," 1: default <c:\beafich\data.txt>"
        print *," 2: different file or path"
        print *,(/"/)
        read *,choice
        print *,(/"/)
        if(choice==1)then
        text4="c:\beafich\data.txt"
        else
    print *," Enter name an path of file of wind speed data"

        read  *,text4
        endif
        print *,(/"/)
c
        print *," Enter name an path of file of node coordinate"
        print *,(/"/)
        print *," 1: default <c:\beafich\nlist.lis>"
        print *," 2: different file or path"
        print *,(/"/)
        read *,choice
        print *,(/"/)
        if(choice==1)then
        text5="c:\beafich\nlist.lis"
        else
        read  *,text5
        endif
        print *,(/"/)
c
        print *," Enter name an path to store results"
        print *,(/"/)
        print *," 1: default <c:\beafich\beams\month>"
        print *," 2: default <c:\beafich\beams\maxRecord\>"
        print *," 3: different file or path"
        print *,(/"/)
        read *,choice
        choiceres=choice ! variable that will be use later to write in the right  results file
        print *,(/"/)
        if(choice==1)then
        text1 = 'c:\beafich\beams\month'
        else
        if (choice==2)then
        text6='c:\beafich\beams\maxRecord\'
        else
        read  *,text1
        endif
        endif
        print *,(/"/)
c
c
        print *,"Enter name of ANSYS file "
        print *," 1: default 'beams1'"
        print *," 2: different name"
```

```
        print *,(/"/)
        read *,choice
        if (choice==1)then
        text7='beams1'
        else
        read  *,text7
        endif


c
     open(unit=31,access='sequential',status='old',       !file with wind data
    1file=text4)
     open(unit=36,access='sequential',status='old',!ansys load file without
    1file='c:\beafich\origin.s01')                          !wind forces
     open(unit=33,access='sequential',status='old',!file with nodes coordenates
    1file="c:\beafich\nlist.lis")
        open(unit=34,access='sequential',status='old',!file with nodes coordenates
    1file="c:\beafich\ndownlist.lis")
c
c
        do 105 i=1,51                                   !stores the coordenate data of the nodes
        read(33,*)node(i),x(i),y(i),z(i)
105  continue
        do 106 i=21,51                                  !stores the coordenate data of the nodes
        read(34,*)nodedown(i),xdown(i),ydown(i),zdown(i)
        zdown(i)=zdown(i)+9
106  continue
c
c
     do 188 i = 1,40                 ! Read the first 40 lines of ansys file and stores in
     read(36,17)lin(i)         ! lin(i)
17   format(a80)
188   continue
c
c
c
        print *,"Enter omega (rpm)"
        read *,omega
        print *,"10 stations in the blade"
        stat=10
        print *,"Enter chord lengths, 1=root",stat,"=tip"        !chord of the element
        do 1121 ii=1,stat
        print*,"chord",ii
        read*,l(ii)
1121    continue
c
        if (choiceres==1)then
        iday=1 ! contador for days
        imonth=2! contador for months
        do while (imonth.lt.3)       !for memory reasons we do only 1 month ,
c                                                        for 12 months we would write 12 instead of
2
                do while (iday.lt.2)!for memory reasons we do only 1 day ,
```

```
c                                                                     for all month we would
write day(iday)
c                                                                     instead of 2

   read(31,10)nst,nyear,amonth,aday,(ndir(j),nspeed(j),j=1,24)
c                                                                           ! read the records
of 1 day (24hours)

10   format(i2,i4,a2,a2,24(i2,i2))
c
   conv=.515                      ! knots to m/s
c
   do 100 i = 1,24                !for each hour a different file
       omeg=angularvelocity(nspeed(i),omega)
c

       text2 = text1//amonth//'\'//text7//'.s'//text3(i)
13   format(1x,a40)
   open(unit=32,access='sequential',status='unknown',
   1file=text2)
c
       write (32,*)imonth,iday,i
   do 187 kk = 1,3                       !writes for the ansys file in the right format
       write(32,17)lin(kk)               !3 first lines the same
187   continue
c
   write(32,18)i                  !modifies line 4
18   format('_LSNUM=',i4)
c
   do 196 kk = 5,9
       write(32,17)lin(kk)
196   continue
c
   write(32,21)float(i)     !modifies line 10
21   format('TIME,',f13.7)
c
   do 193 kk = 11,39
       write(32,17)lin(kk)
193   continue
c
c
       area=0.135                                             !   calculate forces for the tower
nodes
   do 102 j = 2,21
       vr=nspeed(i)*conv
       zr = 10.0
       z0 = z(j)
       a = 1.0/7.0
   v = vr*(z0/zr)**a
       force=0.5*1.225*v*v*area
       write(32,12)node(j),force
12   format('F,',i7,',FY  ,',F12.6,',  0.000000000')
102   continue
c
```

```
c
c
c        "Blade 1"                                    !calculate forces for the airfoil nodes
c
         inode=0
         do 112 j = 22,31  !luego de 32 a 41 y de 42 a 51
         vr=nspeed(i)*conv
         zr = 10.0
         z0 = z(j)
         a = 1.0/7.0
     v = vr*(z0/zr)**a
c
         inode=inode+1
         T=Thrust(inode,v,z(j),z(2),omeg,l,driving)
         write(32,12)node(j),T
         sum1=sum1+T
112   continue
c
c        "blade 2"

         inode=0
         do 113 j = 32,41  !luego de  42 a 51
         vr=nspeed(i)*conv
         zr = 10.0
         z0 = z(j)
         a = 1.0/7.0
     v = vr*(z0/zr)**a
c
         inode=inode+1
         T=Thrust(inode,v,z(j),z(2),omeg,l,driving)
         sum2=sum2+T
         write(32,12)node(j),T
113   continue
c
c
c        "blade 3"
c
         inode=0
         do 114 j = 42,51  !de 42 a 51
         vr=nspeed(i)*conv
         zr = 10.0
         z0 = z(j)
         a = 1.0/7.0
     v = vr*(z0/zr)**a
c
         inode=inode+1
         T=Thrust(inode,v,z(j),z(2),omeg,l,driving)
         write(32,12)node(j),T
         sum3=sum3+T
114   continue


c
c
```

```
    write(32,17)lin(40)                 !writes in ansys file end line
c
    close(unit=32)
c
100   continue
c
c
                              iday=iday+1                              ! increment 1 day
                              enddo
                    iday=1                                  ! end do iday
                    imonth=imonth+1               !increment 1 month
                    enddo      !end do imonth
          endif !(choice/=2)
c

c
          if (choiceres==2)then

          print*,"Enter month to start"
          read *,startmonth
          print*,"Enter day to start"
          read *,startday
          print*,"Enter hour to start"
          read *,starthour
          print*,"Enter month to stop"
          read *,stopmonth
          print*,"Enter day to stop"
          read *,stopday
          print*,"Enter hour to stop"
          read *,stopthour
          iday=1
          imonth=1
29        read(31,11,err=29,end=498)nst,iyear,imonth,iday,(ndir(j),nspeed(j)
          1,j=1,24)
          do 40 while (imonth/=startmonth)! places the data file in the first day of month
20        read(31,11,err=20,end=498)nst,iyear,imonth,iday,(ndir(j),
    1nspeed(j),j=1,24)
40        continue
          do 41 while (iday/=startday)! places the data file in the first day of month
25        read(31,11,err=25,end=498)nst,iyear,imonth,iday,(ndir(j),
    1nspeed(j),j=1,24)
41        continue
11    format(i2,i4,i2,i2,24(i2,i2))

c
c
          jloadstep=1 ! contador del numero de load steps
          initialhour=starthour
          do 5000 while  (imonth<=stopmonth)
          do 5001 while (iday<=stopday)
          if (iday/=startday.or.imonth/=startmonth)then
          initialhour=1
          end if
          do 2100 i=initialhour,24    !24hours
```

```
        jloadstep=jloadstep+1
        if (jloadstep<=99) then
        text2=text6//text7//'.s'//text3(jloadstep)
        textdriv2=text6//'rotor'//'.s'//text3(jloadstep)
        textdriv2d=text6//'rotordown'//'.s'//text3(jloadstep)
        textdriv22=text6//'DRIVE'//'.s'//text3(jloadstep)
        textdriv23d=text6//'DRIVEdown'//'.s'//text3(jloadstep)
        open(unit=32,access='sequential',status='unknown',file=text2)
        open (43,status="unknown",file=textdriv2)
        open (44,status="unknown",file=textdriv2d)
        open (45,status="unknown",file=textdriv22)
        open (46,status="unknown",file=textdriv23d)
        else
        iloadstep=jloadstep-99
        text20=text6//text7//'.s'//text30(iloadstep)
        textdriv20=text6//'rotor'//'.s'//text30(iloadstep)
        textdriv21=text6//'rotordown'//'.s'//text30(iloadstep)
        textdriv22=text6//'DRIVE'//'.s'//text30(iloadstep)
        textdriv23=text6//'DRIVEdown'//'.s'//text30(iloadstep)
        open(unit=32,access='sequential',status='unknown',file=text20) !beams
        open(unit=43,access='sequential',status="unknown",file=textdriv20)!rotor
        open(unit=44,access='sequential',status="unknown",file=textdriv21)!rotordown
        open(unit=45,access='sequential',status="unknown",file=textdriv22)!rotorDriving
        open(unit=46,access='sequential',status="unknown",file=textdriv23)!rotordownDriving
        endif
c
        omeg=angularvelocity(nspeed(i),omega)
        omeg=omeg*2.0*3.1416/60.0
        !write(32,*)iday,imonth,i,nspeed(i),jloadstep
        !write(43,*)iday,imonth,i,nspeed(i)
        !write(44,*)iday,imonth,i,nspeed(i)
        print*,iday,imonth,i,nspeed(i)
c
        do 2187 kk = 1,3                  !writes for the ansys file in the right format
        write(32,17)lin(kk)               !3 first lines the same
        write(43,17)lin(kk)
        write(44,17)lin(kk)
        write(45,17)lin(kk)
        write(46,17)lin(kk)
2187  continue
c
    write(32,19)i                 !modifies line 4
        write(43,19)i
        write(44,19)i
        write(45,19)i
        write(46,19)i
19    format('_LSNUM=',i4)
c
    do 2196 kk = 5,9
        write(32,17)lin(kk)
        write(43,17)lin(kk)
        write(44,17)lin(kk)
        write(45,17)lin(kk)
        write(46,17)lin(kk)
```

```
2196  continue
c
   write(32,57)float(i)      !modifies line 10
        write(43,57)float(i)
        write(44,57)float(i)
        write(45,57)float(i)
        write(46,57)float(i)
57   format('TIME,',f13.7)
c

        do 2193 kk = 11,22
        write(32,17)lin(kk)
        write(43,17)lin(kk)
        write(44,17)lin(kk)
        write(45,17)lin(kk)
        write(46,17)lin(kk)
2193  continue
        write(32,17)lin(23)
        write(43,17)lin(23)
        write(44,17)lin(23)
        write(45,2294)
        write(46,2294)
2294    format   ('NEQIT,    25')

        do 2293 kk = 24,26
        write(32,17)lin(kk)
        write(43,17)lin(kk)
        write(44,17)lin(kk)
        write(45,17)lin(kk)
        write(46,17)lin(kk)
2293  continue

        write(32,17)lin(27)!omega
        write(43,294)omeg
        write(44,294)omeg
        write(45,294)omeg
        write(46,294)omeg
294     format('OMEGA,  .000000000    ,',f6.0,'000000000 ',
        1',  .000000000    ,     0')

        do 293 kk =28,33
        write(32,17)lin(kk)
        write(43,17)lin(kk)
        write(44,17)lin(kk)
        write(45,17)lin(kk)
        write(46,17)lin(kk)
293   continue
        do 1293 kk =34,39
        write(32,17)lin(kk)
1293  continue
        do 1111 ifile=43,46
        write(ifile,*)'D,     21,UX  ,  .000000000    ,  .000000000'
        write(ifile,*)'D,     21,UY  ,  .000000000    ,  .000000000'
        write(ifile,*)'D,     21,UZ  ,  .000000000    ,  .000000000'
```

```
        write(ifile,*)'D,     21,ROTY,  .000000000   , .000000000'
        write(ifile,*)'D,     21,ROTX,  .000000000   , .000000000'
        write(ifile,*)'D,     21,ROTZ,  .000000000   , .000000000'
        !if (ifile==43.or.ifile==44) then ! thrust
        !do 1110 jnod=22,51
        !write(ifile,131)'D,',jnod,',ROTY,  .000000000   , .000000000'
        !write(ifile,131)'D,',jnod,',  UX,  .000000000   , .000000000'
        !write(ifile,131)'D,',jnod,',ROTZ,  .000000000   , .000000000'
!1110   continue
!       else
        if (ifile==45.or.ifile==46) then  !driving
        do 1112 jnod=22,51
        write(ifile,131)'D,',jnod,',ROTX,  .000000000   , .000000000'
        write(ifile,131)'D,',jnod,',ROTZ,  .000000000   , .000000000'
        write(ifile,131)'D,',jnod,',  UY,  .000000000   , .000000000'
1112    continue
        endif
!       endif
1111    continue
131   format(a3,i8,a36)
c
c                   tower
c
        conv=.515
        area=0.135                    !  calculate forces for the tower nodes
    do 2102 j = 2,21
        vr=nspeed(i)*conv
        zr = 10.0
        z0 = z(j)
        a = 1.0/7.0
    v = vr*(z0/zr)**a
        force=0.5*1.225*v*v*area
        write(32,27)node(j),force
27   format('F,',i7,',FY  ,',f12.6,',  0.000000000')
2102  continue
c
c
        conv=.515
c
c
c        "          Blade 1" !calculate forces for the airfoil nodes
c
        inode=0
        jnode=0
        do 2112 j = 22,31 !right blade
        vr=nspeed(i)*conv
        zr = 10.0
        z0 = z(j)
        zdown0=zdown(j)
        a = 1.0/7.0
    v = vr*(z0/zr)**a
        vdown=vr*(zdown0/zr)**a
c
        inode=inode+1
```

```
        zor=z(2)
        T=Thrust(inode,v,z(j),zor,omeg,l,driving)
        jnode=jnode+1
        zor=zdown(21)
        Tdown=Thrust(jnode,vdown,zdown(j),zor,omeg,l,drivingdown)
        write(32,12)node(j),T
        drivingx=driving*.87
        drivingz=driving*.5
        drivingdx=drivingdown*(-.5)
        drivingdz=drivingdown*.87
        write(43,15)node(j),drivingx
        write(44,15)node(j),drivingdx
15      format('F,',i7,',FX  ,',F12.4,',  0.000000000')
        write(43,14)node(j),drivingz
        write(44,14)node(j),drivingdz
14      format('F,',i7,',FZ  ,',F12.4,',  0.000000000')
        write(43,12)node(j),T
        write(44,12)node(j),Tdown
2112  continue
c
c
c               blade 2
c

        inode=0
        jnode=0
        do 2113 j = 32,41!left blade
        vr=nspeed(i)*conv
        zr = 10.0
        z0 = z(j)
        zdown0=zdown(j)
        a = 1.0/7.0
    v = vr*(z0/zr)**a
        vdown=vr*(zdown0/zr)**a
c
        inode=inode+1
        zor=z(2)
        T=Thrust(inode,v,z(j),zor,omeg,l,driving)
        jnode=jnode+1
        zor=zdown(21)
        Tdown=Thrust(jnode,vdown,zdown(j),zor,omeg,l,drivingdown)
        write(32,12)node(j),T
        drivingx=.5*driving
        drivingz=-.87*driving
        drivingdx=drivingdown*(-.87)
        drivingdz=-.5*drivingdown
        write(43,15)node(j),drivingx
        write(44,15)node(j),drivingdx
        write(43,14)node(j),drivingz
        write(44,14)node(j),drivingdz
        write(43,12)node(j),T
        write(44,12)node(j),Tdown
        sum2=sum2+T
2113   continue
```

```
c
c
c       "blade 3"
c
c
        inode=0
        jnode=0
        do 2114 j = 42,51 !vertical blade
        vr=nspeed(i)*conv
        zr = 10.0
        z0 = z(j)
        zdown0=zdown(j)
        a = 1.0/7.0
    v = vr*(z0/zr)**a
        vdown=vr*(zdown0/zr)**a
c
        inode=inode+1
        zor=z(2)
        T=Thrust(inode,v,z(j),zor,omeg,l,driving)
        jnode=jnode+1
        zor=zdown(21)
        Tdown=Thrust(jnode,vdown,zdown(j),zor,omeg,l,drivingdown)
        print*,vr,z(j),v ,T
        print*,vr,zdown(j),vdown,Tdown
        read*,integ
        write(32,12)node(j),T
        driving=-(driving)
        write(43,15)node(j),driving
        write(44,15)node(j),drivingdown
        write(43,12)node(j),T
        write(44,12)node(j),Tdown
        sum3=sum3+T
2114  continue

    write(32,17)lin(40)              !writes in ansys file end line
        write(43,17)lin(40)
        write(44,17)lin(40)
        write(45,17)lin(40)
        write(46,17)lin(40)
c
        close(32)
        close(43)
        close(44)
        close(45)
        close(46)

2100  continue
c
32      read(31,11,err=32,end=498)nst,iyear,imonth,iday,(ndir(j),
   1nspeed(j),j=1,24)         !j=hour
5001    continue            ! increment 1 day
5000    continue !end do imonth
        endif !(choice=2)
c
```

```
c
c
c
        CONTAINS
c ---------------------------------------------------------------------------------
c
        Function totday(n)
        integer sum,days
        sum=0
        days=0
        do 97 j=1,n-1
        days=day(n-1)
        sum=sum+days
97      enddo
        totday=sum
        return
        end function totday
c
        Function Thrust(knode,V,zp,zorig,omega,l,drive)      !V is wind velocity
        real omega,d,Cl,Cd,tanE
        real l(10),r(10),U(10),dA(10),dr(10),Lift(109),Drag(10),T(10)
        1,W(10),fi(10),driv(10)
        real V ,pi
        integer node,knode
c
        node=knode
        d=1.225 !density
        pi=3.1416
        Cl=0.8
        tanE=0.01 !tanE=Cd/Cl
        Cd=Cl*tanE
        if (node==1) then ! asigna a node el numero de station en el que estamos
        node=10
        else
        node=node-1
        endif
        v=2*V/3 ! for betz theorem, the wind throught the rotor is this one
        r(node)=abs(zp-zorig)!raduius of the element
        dr(node)=(5.7/2.0)/stat      !length (span) of the element
        U(node)=omega*r(node)
        W(node)=sqrt(V*V+U(node)*U(node))
        fi(node)=atand(V/U(node))             !in degrees
        dA(node)=l(node)*dr(node)           ! l=chord
        Lift(node)=.5*d*Cl*W(node)*W(node)*dA(node)
        Drag(node)=.5*d*Cd*W(node)*W(node)*dA(node)  ! Drag force
        T(node)=Drag(node)*sind(fi(node))+Lift(node)*cosd(fi(node))!Thrust Force
        Driv(node)=Lift(node)*sind(fi(node))-Drag(node)*cosd(fi(node))!Driving Force
        Thrust=T(node)
        Drive=Driv(node)
        return
        end function Thrust
c
c
        Function angularvelocity(v,omega)
```

```
integer v
real wa

if (v<=2) then
wa=19.0
else
if (v<=3) then
wa=29.0
else
 if (v<=4) then
            wa=38.0
else
if (v<=5) then
wa=48.0
else
  if (v<=6) then
            wa=57.0
else
            if (v<=7) then
            wa=67.0
else
 if (v<=8) then
            wa=76.0
else
if (v<=9) then
wa=86.0
else
if (v<=10) then
            wa=95.0
else
if (v<=11) then
wa=105.0
else
            if (v<12) then
wa=114.0
else
if (v<=13) then
            wa=123.0
else
 if (v<=14) then
wa=133.0
else
 if (v<=15) then
wa=142.0
else
 if (v<16) then
wa=152.0
else
 if (v<=17) then
wa=161.0
else
 if (v<=18) then
wa= 171.0
else
```

```
         if (v<=19) then
        wa=180.0
        else
         if (v<=20) then
        wa=190.0
   else
         if (v>20) then
        wa=omega
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        endif
        angularvelocity=wa
        return
        end function angularvelocity
498     end       !main program
```

3. Results

A running of the program gives 162 files to apply to each ANSYS model.

Three models have been developed; beam1, rotor, and rotordown.

A sample of one of these files output is shown below.

```
/COM,ANSYS RELEASE  5.3    UP100396        15:41:25    03/24/1997
/NOPR
/TITLE,
_LSNUM=  6
BFUNIF,TEMP,_TINY
AUTOTS,OFF
DELTIM, 1.00000000    , .000000000    , .000000000    ,OFF
KBC,    0
KUSE,    0
TIME,    6.0000000
TREF,  .000000000
ALPHAD,  .000000000
BETAD,  .000000000
DMPRAT,  .000000000
TIMINT,OFF ,STRU
CNVTOL,F   ,-1
CNVTOL,U   ,-1
CNVTOL,M   ,-1
CNVTOL,ROT ,-1
CRPLIM,  .100000000
NCNV,     1, .000000000    ,     0, .000000000    , .000000000
LNSRCH,OFF
NEQIT,    0
PRED,OFF ,,OFF
ERESX,DEFA
ACEL,  .000000000    , .000000000    , 9.800000000
OMEGA,  .000000000    ,  21.0000000000 , .000000000    ,    0
DOMEGA,  .000000000    , .000000000    , .000000000
CGLOC,  .000000000    , .000000000    , .000000000
CGOMEGA,  .000000000    , .000000000    , .000000000
DCGOMG,  .000000000    , .000000000    , .000000000
IRLF,  0

 D,      21,UX  ,  .000000000    , .000000000
 D.      21,UY  ,  .000000000    , .000000000
 D,      21,UZ  ,  .000000000    , .000000000
 D,      21,ROTY,  .000000000    , .000000000
 D,      21,ROTX,  .000000000    , .000000000
 D,      21,ROTZ,  .000000000    , .000000000
F,     22,FX  ,      8.0544,  0.000000000
F,     22,FZ  ,      4.6289,  0.000000000
F,     22,FY  ,   31.599980,  0.000000000
```

```
F,   23,FX ,    2.6449, 0.000000000
F,   23,FZ ,    1.5200, 0.000000000
F,   23,FY ,  1.013302, 0.000000000
F,   24,FX ,    2.9740, 0.000000000
F,   24,FZ ,    1.7092, 0.000000000
F,   24,FY ,  2.256714, 0.000000000
F,   25,FX ,    3.4554, 0.000000000
F,   25,FZ ,    1.9859, 0.000000000
F,   25,FY ,  3.934440, 0.000000000
F,   26,FX ,    4.0295, 0.000000000
F,   26,FZ ,    2.3158, 0.000000000
F,   26,FY ,  6.135888, 0.000000000
F,   27,FX ,    4.6576, 0.000000000
F,   27,FZ ,    2.6768, 0.000000000
F,   27,FY ,  8.901766, 0.000000000
F,   28,FX ,    5.3167, 0.000000000
F,   28,FZ ,    3.0556, 0.000000000
F,   28,FY , 12.250610, 0.000000000
F,   29,FX ,    5.9929, 0.000000000
F,   29,FZ ,    3.4442, 0.000000000
F,   29,FY , 16.191250, 0.000000000
F,   30,FX ,    6.6778, 0.000000000
F,   30,FZ ,    3.8378, 0.000000000
F,   30,FY , 20.728240, 0.000000000
F,   31,FX ,    7.3662, 0.000000000
F,   31,FZ ,    4.2334, 0.000000000
F,   31,FY , 25.864030, 0.000000000
F,   32,FX ,    4.6289, 0.000000000
F,   32,FZ ,   -8.0544, 0.000000000
F,   32,FY , 31.599950, 0.000000000
F,   33,FX ,    4.2334, 0.000000000
F,   33,FZ ,   -7.3662, 0.000000000
F.   33,FY , 25.864030, 0.000000000
F,   34,FX ,    3.8378, 0.000000000
F,   34,FZ ,   -6.6778, 0.000000000
F,   34,FY , 20.728240, 0.000000000
F,   35,FX ,    3.4442, 0.000000000
F,   35,FZ ,   -5.9929, 0.000000000
F,   35,FY , 16.191250, 0.000000000
F,   36,FX ,    3.0556, 0.000000000
F,   36,FZ ,   -5.3167, 0.000000000
F,   36,FY , 12.250610, 0.000000000
F,   37,FX ,    2.6768, 0.000000000
F,   37,FZ ,   -4.6576, 0.000000000
F,   37,FY ,  8.901766, 0.000000000
F,   38,FX ,    2.3158, 0.000000000
F,   38,FZ ,   -4.0295, 0.000000000
F,   38,FY ,  6.135888, 0.000000000
F.   39,FX ,    1.9859, 0.000000000
F,   39,FZ ,   -3.4554, 0.000000000
F,   39,FY ,  3.934440, 0.000000000
F,   40,FX ,    1.7092, 0.000000000
F,   40,FZ ,   -2.9740, 0.000000000
F,   40,FY ,  2.256714, 0.000000000
```

```
F,    41,FX ,     1.5200,  0.000000000
F,    41,FZ ,    -2.6449,  0.000000000
F,    41,FY ,   1.013302,  0.000000000
F,    42,FX ,   -18.4958,  0.000000000
F,    42,FY , 122.331700,  0.000000000
F,    43,FX ,    -3.4690,  0.000000000
F,    43,FY ,   2.270741,  0.000000000
F,    44,FX ,    -4.7434,  0.000000000
F,    44,FY ,   6.176498,  0.000000000
F,    45,FX ,    -6.3083,  0.000000000
F,    45,FY ,  12.319260,  0.000000000
F,    46,FX ,    -7.9880,  0.000000000
F,    46,FY ,  20.824830,  0.000000000
F,    47,FX ,    -9.7172,  0.000000000
F,    47,FY ,  31.724460,  0.000000000
F,    48,FX ,   -11.4682,  0.000000000
F,    48,FY ,  45.027920,  0.000000000
F,    49,FX ,   -13.2276,  0.000000000
F,    49,FY ,  60.739110,  0.000000000
F,    50,FX ,   -14.9880,  0.000000000
F,    50,FY ,  78.859590,  0.000000000
F,    51,FX ,   -16.7450,  0.000000000
F,    51,FY ,  99.390350,  0.000000000
/GOPR
```

Appendix I.6

PROGRAM RAINFLOW

1. **Rainflow Algorithm. PROGRAM RAINFLOW**
    - **1.2 Introduction**
    - **1.3 Input and Output Parameters**

2. Code Source

3. Results

1. PROGRAM RAINFLOW

1.1 Introduction

The program 'RAINFLOW' is designed to calculate the number of cycles that is felt by a component as a result of an irregular variation of load with time. Once that these cycles have been identify, the Palmgren-Miner rule can be apply to estimate the fatigue life of a component.

The implementation of the programme is based on the ASTM Rainflow approach presented in reference 10. Some modifications have been made to adequate it to the present work

The theoretical base for the calculation and implementation of the rainflow algorithm has been presented in section 9.3. of the report.

1.2 Input and Output Parameters

No input parameters are required from the user in this programme, they are assigned by the programmer.

The time-history stresses (Pa) are read from the data file(format F5.2)

'c:\Bea\PROGRAM_FORCES\rainflow\Stress.txt'

The initial set of command prepares the full time series data for counting by selecting peaks and valleys, and discarding "small" stress cycles.

Peaks and valleys in the data record are identify by scanning the values of the stresses for every 3 points, and considering only those points where the direction of loading changes. Then a threshold value is set in the algorithm. When the absolute value of the difference between the maximum and minimum values of a stress cycle is greater than the threshold, the algorithm retains that cycle. When the difference is less than the threshold, the cycle is discarded. The final peak and valleys are recorded in the array stress (k)

Then, the rainflow cycle algorithm is implemented according to the ASTM approach.

Finally, the mean and the peak-to-peak (also referred as range) alternating stress level for each stress cycle in the histogram are determined, and stored .
The following arrays are emplyed:
smin(k),smax(k),srange(k),samplitude(k),smean(k)

These stress levels are stored in a temporary file for post processing:
file='c:\Bea\PROGRAM_FORCES\rainflow\IIreal.txt').

The stress peak and valleys are stored in another file.

,file='c:\Bea\PROGRAM_FORCES\rainflow\Sfinal.txt')

2. Code for the program RAINFLOW

In this section the list of the program 'RAINFLOW' is given. The program is written in FORTRAN 90.

```
Program rainflow
        real event(317),stress(317),stressprov(317)
        real smean(317),smax(317),smin(317),samplitude(317),srange(317)
        integer n,j,npts
        integer x,y
        real  range,xmean,xamplitude
        npts=317
        T=1
        do 15 j=1,317
        stress(j)=0
        smax(j)=0
        smin(j)=0
15      continue
        !file with stresses
        j=0
        open(unit=31,access='sequential',status='old',file='c:\Bea\PROGRAM_FORCES\ra
        inflow\Stress.txt')
        do 100 k=1,npts
        read(31,10)stressprov(k)
        j=j+1
        stress(j)=stressprov(k)
        dif=abs(stress(j)-stress(j-1))
        if (dif<=T) then
        j=j-1
        endif
        if (j>3) then
        j1=j-2
        j2=j-1
        j3=j
        if ((stress(j1)<stress(j2)).and.(stress(j2)<stress(j3)))then
                stress(j2)=stress(j3)
                j=j-1
        else
        if ((stress(j1)>stress(j2)).and.(stress(j2)>stress(j3)))then
                stress(j2)=stress(j3)
                j=j-1
        endif
        endif
        endif
        print *,stress(j)
100     continue
10      format(f5.2)
        close(31)
        npts=j
        kf=0
```

```
        Event(1)=Stress(1)
        l=1
        N=1                          ! Counter N initialize
        j=1                          !       Counter j initialize
1       n=n+1
        j=j+1
2       if (j==npts +1)then
        goto 3
        else
        Event(n)= Stress(j)
        if (n<3) then
        goto 1
        else
        x= abs(event(n)-event(n-1))
        y= abs(event(n-1)-event(n-2))
        if (x.lt.y) then
        goto 1
        else
        range = y
        xmean =(event(n-1)+event(n-2))/2
        xamplitude=range/2
        if (event(n-1).lt.event(n-2)) then
        smin(l)=event(n-1)
        smax(l)=event(n-2)
        else
        smin(l)=event(n-2)
        smax(l)=event(n-1)
        endif
        kf=kf+1
        smean(l)=xmean
        samplitude(l)=xamplitude
        srange(l)=range
        l=l+1
        n=n-2
        event(n)=event(n+2)
        goto 2
        endif
        endif
        endif
3       open(32,access='sequential',status='unknown',file='c:\Bea\PROGRAM_FORCES\r
        ainflow\llreal.txt')
        open(33,access='sequential'.status='unknown',file='c:\Bea\PROGRAM_FORCES\r
        ainflow\Sfinal.txt')
        do 200 k=1,kf
        write(32,30)smin(k),smax(k),srange(k),samplitude(k),smean(k)
200     continue
20      format(5f4.0)
        close(32)
        do 400 k=1,npts
        write(33,10)stress(k)
400     continue
30      format(5f4.0)
        close(33)
        end
```

3. Results

The stresses are stored in temporary files to postprocessing .

Peak and Valley stresses are stored in :

,file='c:\Bea\PROGRAM_FORCES\rainflow\Sfinal.txt')

format (f4.0)

Minimum, maximum, alternating, range and mean are stored in this order in :

file='c:\Bea\PROGRAM_FORCES\rainflow\IIreal.txt').

format (5f4.0)

Appendix I.7

PROGRAM MATRIX

1. **Cycle Counting. PROGRAM MATRIX**
    - **1.2 Introduction**
    - **1.3 Input and Output Parameters**

2. Code Source

3. **Results**

1. PROGRAM MATRIX

1.1 Introduction

The program 'MATRIX' is designed to calculate the number of TypeII cycles [6] that is felt by the turbine blade as a result of an irregular variation of load with time.

This program is intended as a Post-Count Algorithm for the Rainflow Program described in Annexe I.6. This algorithm maps each stress cycle into a cycle count matrix . the algorithm sorts the resulting stress cycle data into bins, that are functions of mean stress and alternating stress levels.

1.2 Input and Output Parameters

The minimum, maximum, alternating, range and mean stresses calculated previously with the Rainflow Program are read from file:

'c:\Bea\PROGRAM_FORCES\Ncycles\IIreal.txt' (format 5f4.0)

Each stress cycle is account in the 50*50 matrix *matriz(col1, col2)* according to its mean and range value.Col1 refers to mean stress and col2 refers to range stress.

The matrix is stored in the following data file for post-processing.

'c:\Bea\PROGRAM_FORCES\Ncycles\N2cycles.txt') format (50i3)

2. Code for the program MATRIX

In this section the list of the program 'MATRIX' is given. The program is written in FORTRAN 90.

```
Program MATRIX
         integer,DIMENSION(50,50):: matriz
         real,dimension(22):: smin,smax,srange,samplitude,smean


         ncyc=22
         open(32,access='sequential',status='old',file='c:\Bea\PROGRAM_FORCES\Ncycles\IIreal.txt')
         open(33,access='sequential',status='unknown',file='c:\Bea\PROGRAM_FORCES\Ncycles\Ncycle
s.txt')
         do 200 k=1,ncyc
         read(32,20)smin(k),smax(k),srange(k),samplitude(k),smean(k)
         imean=int(smean(k))
         irange=int(srange(k))
         col1=imean
         col2=irange
         matriz(col1,col2)= matriz(col1,col2)+1
         PRINT*,matriz(col1,col2)
200      continue
20       format(5f4.0)
         close(32)
         open(33,access='sequential',status='unknown',file='c:\Bea\PROGRAM_FORCES\Ncycles\N2cycl
es.txt')
         col1=1
         do 300 col1=1,50
         write(33,10)(matriz(col1,j),j=1,50)
300 continue
10       format(50i3)
         close(33)
         end
```

3. Results

A 50*50 matrix is been produced, its value stored in the following data file for post-processing:

'c:\Bea\PROGRAM_FORCES\Ncycles\N2cycles.txt'

Each bin of the matrix accounts for the number of times a cycle occurs. A cycle is identify by its mean stress (col1), and its range stress (col2).