ESTIMATION OF FATIGUE LIFE OF STEEL MASTS USING FINITE ELEMENT MODELLING

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The Research Thesis was submitted in partial fulfilment of the requirements for the Degree of Bachelor of Science of Engineering

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DECLARATION

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Dr. H.M.Y.C. Mallikarachchi

ABSTRACT

Estimation of Fatigue Life of Steel Masts using Finite Element Modelling

Fatigue is an important design consideration for tall steel structures. Accurate prediction of fatigue endurance is essential to design the elements subjected to wind and earthquake induced fatigue. The design guidelines given in codes of practices are applicable only to simple shapes and laboratory experimental verification is costly. Therefore, simulation using finite element software is becoming popular.

An attempt is made to couple Abaqus finite element analysis software and fe-safe software to estimate the fatigue life of a structure. First, the accuracy of the techniques and idealizations used in simulation are validated by simulating experiments available in the literature. Standard Uni-Axial fatigue experiments which were conducted at several strain amplitudes showed a closer relationship to simulation results. Moreover sensitivity of fatigue life to surface finish and stress strain dataset importing method in fe-safe software were evaluated. It was found that the surface finish is a highly sensitive parameter and it should be estimated accurately. Elastic plastic block method gave good results while elastic block method with neuter's rule results were poor. This indicates the importance of using elastic plastic block method for low cycle fatigue especially when stress redistribution is high. Simulation result of multi-axial fatigue experiment showed similar results to results obtained from physical experiments.

The verified technique was the applied to estimate the fatigue life of a 64 m tall steel mast with an opening located at the top of a 285 m tall concrete tower. The sensitivity of the plate thickness and shape of the opening of the mast were studied. It was found that small increase in plate thickness rapidly increases the fatigue endurance. This shows the importance of using stiffeners in fatigue prone areas. Comparison of the shape of the opening showed that square shape would have higher endurance than a circular shape of same opening area. However only monolithic sections were studied here and effects on welds and bolted connections are beyond the scope of this research.

Key Words:

Fatigue simulation, Abaqus, fe-safe, mast with an opening

DEDICATION

I dedicate my thesis to my family, friends and teachers. First of all a special feeling of gratitude to my loving parents, Upali Kariyawasm and Swarnalatha Kariyawasam whose good examples have taught me to work hard for the things that I aspire to achieve . My brother Ruchira and sister Ushara were always by my side and they are very special.

I want to dedicate this also to all my friends at the university who encouraged me and made my life at the university an interesting experience with a lot of memories.

Last but not least I dedicate this work to all the teachers who helped me build up my academic life and moral values. I was really lucky to have such supportive teachers and lecturers throughout my academic life. Their encouragements and supports meant a lot for everything I have achieved.

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National Research Council of Sri Lanka funded us to buy required software and a workstation which cost millions of rupees. I want to thank them for the funding which meant a lot.

The lecturers of department of Civil Engineering taught us all civil engineering subject matter well. Those were very useful while doing this research. I want to thank them for all of the subject matter they taught and all other supports and encouragements.

Research project was one of the most interesting works that I did and I found the passion of mine in doing research after doing my first research work. I want to thank everyone who helped in any way possible to make this a success.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Modelling
ULCF	Ultra Low Cycle Fatigue
CAE	computer-aided engineering
C3D8R	8-node linear brick solid elements
3D	3 Dimensional
2D	2 Dimensional
S8R	Eight-node doubly curved thick shell elements

LIST OF SYMBOLS

Symbol	**Description**	**Units**
E	The elastic modulus	Pa
b	The fatigue strength exponent	
c	Fatigue ductility exponent	
F_{max}	Maximum force	kN
F_{min}	Minimum force	kN
F_{rn}	Detailed category	
K	The strain hardening coefficient	
K'	The cyclic strain hardening coefficient	
K_t	Elastic stress concentration factor	
n	The strain hardening exponent	
n'	The cyclic strain hardening exponent	
N_f	Number of cycles to failure	
Ni	cycles required to cause failure under the same amplitude	
ni	the number of stress cycles of the considered amplitude	
N_{in}	Number of cycles to crack initiation	
N_p	Number of cycles to crack propagation	
P_{max}	Maximum load induced	
P_{min}	Minimum load induced	
R	Load ratio	
R	Radius	mm
Ra	Surface roughness	µm
$\Delta\gamma_{max}$	Maximum shear strain range	
$\Delta\varepsilon$	Applied strain range	
$\Delta\varepsilon_n$	Range of strain normal to the maximum shear strain	
$\Delta\varepsilon_p$	Plastic strain range	
ε'_f	Fatigue ductility coefficient	
ε	Total stress	Pa
σ'_f	The fatigue strength coefficient	
σ_m	Mean stress	Pa

1 INTRODUCTION

The infrastructure heights are increasing rapidly with time. Due to the limited land availability the tall buildings are becoming popular. Rapid construction, low weight to strength ratio and many other benefits of steel attracts it as a construction material for tall buildings. The recent expansion of telecommunication sector has increased the use of tall steel towers and masts to support antennas. However these tall steel structures are subjected to dynamic loading such as wind and earthquake induced loading in their lifespan. The wind induced loadings are very significant at greater heights. . These tall steel structures are often slender and hence sensitive to dynamic loading. Therefore dynamic stresses on structural elements of those structures are significant.

A material can fail well below its monotonic strengths when it is subjected to repeated loading. This phenomenon is known as fatigue. Fatigue can happen progressively, even when the applied loads are individually too small to cause failure. In the 19th century, it was considered mysterious that a fatigue fracture did not show visible plastic deformation and this lead to a false belief that fatigue was merely an engineering problem.

A structure may fail with lower number of cycles when it is subjected to higher amplitudes of vibration (low-cycle fatigue) or the same structure may fail with higher number of cycles but under lesser amplitude of vibration (high-cycle fatigue).

Fatigue damage estimation methods given in most codes of practices are for simple structural shapes. On the other hand experimental testing of large structural components for fatigue is costly. Australian code AS-4100:1990 defines a concept called the detailed category (f_{rn}) for different components. Detail category takes in to account many fatigue inducing properties to estimate the appropriate endurance curve. However there are still a number of unidentified potential problems in fatigue design specifications given in codes of practices (Mendis & Dean, 2000). Therefore fatigue modelling through computer software is becoming popular. These finite element software use damage estimating algorithms to estimate the damage initiation and propagation. All fatigue inducing properties such as surface finish, temperature, stress concentrations can be included for accurate estimations.

But Idealizations of loading, material properties, boundary conditions, interactions with other elements that are in the actual event must be done carefully to get numerical results which are closer to actual results.

This thesis presents a simulation technique focusing on accurate prediction of fatigue life of steel structures. First part of the thesis attempts to simulate two experimental tests found in literature for successful verification of simulation results. Finally the verified simulation technique is applied to a selected case study to predict the fatigue endurance.

In this thesis, Chapter 2 explains the literature survey done on fatigue and fatigue simulations. Chapter 3 gives a technical introduction to the software that were used for the analysis. Chapter 4 verifies the simulation techniques against the experimental results available in literature. Chapter 5 presents the case study performed on a selected tall steel mast.

1.1 Objectives

1.1.1 Overall Objective

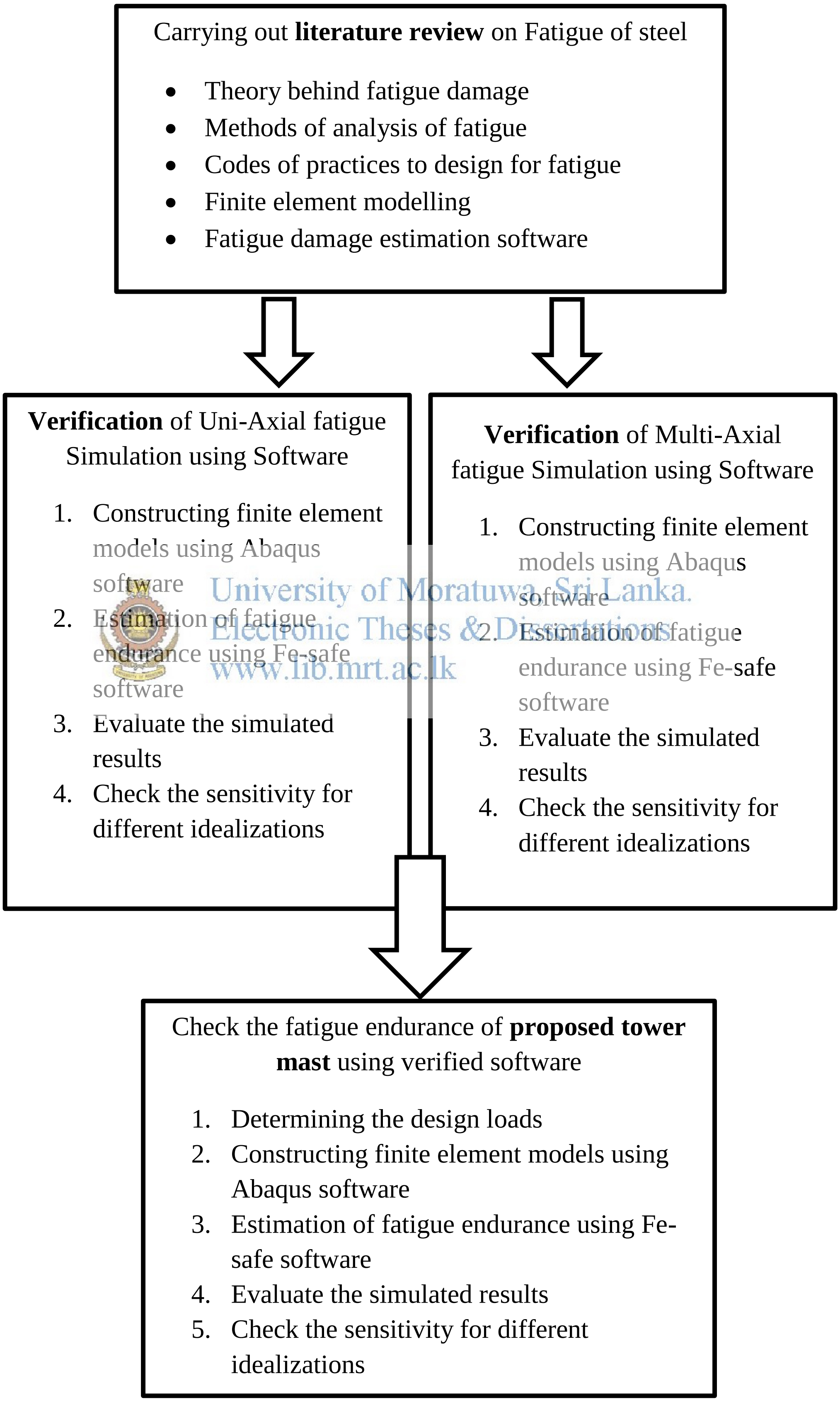
The main objective of this research is to develop a simulation technique that can predict the fatigue life of tall steel structures. This will facilitate design improvement of future steel structures as well as suggest remedial measures for existing structures.

1.1.2 Specific Objectives

- Study the concept behind the fatigue damage
- Study on fatigue inducing loading and how to determine those loading.
- Study finite element modelling with ABAQUS commercial software and couple FE-safe commercial software for fatigue simulations
- Study sensitivity of fatigue inducing parameters such as surface roughness and shape of structure on fatigue endurance of a material.
- Study sensitivity of various fatigue simulation techniques on fatigue endurance of a material.
- Study appropriate material models
- Validate simulated results against physical experiments
- Evaluate vulnerability of a real structure for fatigue damage

1.2 Methodology

1.2.1 **Methodology flowchart**



Carrying out **literature review** on Fatigue of steel

- Theory behind fatigue damage
- Methods of analysis of fatigue
- Codes of practices to design for fatigue
- Finite element modelling
- Fatigue damage estimation software

Verification of Uni-Axial fatigue Simulation using Software

1. Constructing finite element models using Abaqus software
2. Estimation of fatigue endurance using Fe-safe software
3. Evaluate the simulated results
4. Check the sensitivity for different idealizations

Verification of Multi-Axial fatigue Simulation using Software

1. Constructing finite element models using Abaqus software
2. Estimation of fatigue endurance using Fe-safe software
3. Evaluate the simulated results
4. Check the sensitivity for different idealizations

Check the fatigue endurance of **proposed tower mast** using verified software

1. Determining the design loads
2. Constructing finite element models using Abaqus software
3. Estimation of fatigue endurance using Fe-safe software
4. Evaluate the simulated results
5. Check the sensitivity for different idealizations

1.2.2 Description of methodology

Initially literature review was done on fatigue and fatigue simulation using finite element software to get the basic understanding and to determine the exact methodology of research. Literature was done as given below.

- Study on the theories behind fatigue and what other researchers have found on the area.
- Study on the methods of analysis for fatigue.
- Find out the codes of practices that can be used to design for fatigue and the research done on issues of codes of practices.
- Study on finite element modelling using Abaqus FEA software. Different material property, loading and boundary condition idealizations are studied.
- Study on fe-safe simulation techniques and study on other research done using the software.

Then both uniaxial and multi-axial fatigue were simulated as given below.

- Find experiments conducted by other researchers which provide all necessary properties and dimensions.
- Construct finite element models for the experiments chosen from the literature and run the analysis to find out the stress and strain datasets.
- Import the datasets to fe-safe software and perform fatigue analysis.
- Evaluate the simulated results against the results given in the experimental tests chosen.
- Study the sensitivity of different idealizations for fatigue endurance.

Use verified technique to estimate the fatigue endurance of the steel mast of a proposed tower.

- Determine the design wind induced loading.
- Construct a finite element model of the steel mast using Abaqus software and perform analysis to get stress strain datasets.
- Estimate the fatigue endurance of the mast using fe-safe software.
- Check the sensitivity of opening shape and plate thickness for fatigue endurance.

2 LITERATURE REVIEW

2.1 Introduction

The heights of the manmade structures have rapidly increased in the past decades due to urbanization and limited land availability. On one side, these tall structures are slender. On the other hand, the wind velocities are increasing with the height and the effect to the tall structures by the wind is significant. Hence the tall structures are subjected to large amounts of cyclic vibrations in their lifespan. Steel is a preferred material for tall structures as its strength to weight ratio is much less than other materials and other benefits. But one of the main problem with the choice of steel for tall structures is the possibility of fatigue damage. Hence tall steel structures should be designed giving much attention to fatigue.

2.2 Phases of fatigue life

Fatigue failure of materials occur in 3 stages. First the cracks nucleated on microscopically small scale (Crack initiation). Then crack propagates in the direction perpendicular to the direct stresses (Crack propagation). Finally rapid fracture happens nearby the end of the crack (fracture).

Earlier fatigue theories considered the fatigue as a single failure and related engineering stresses in the component to fatigue life. Modern fatigue analysis identifies the 3 stages separately (Figure 2.1). Those phases are analysed as below (STL, 2002)

1. Crack initiation – Assuming Local strains and stresses is the cause
2. Crack propagation- Assuming Stresses in the component is the cause
3. Rapid Fracture- Using Fracture mechanics

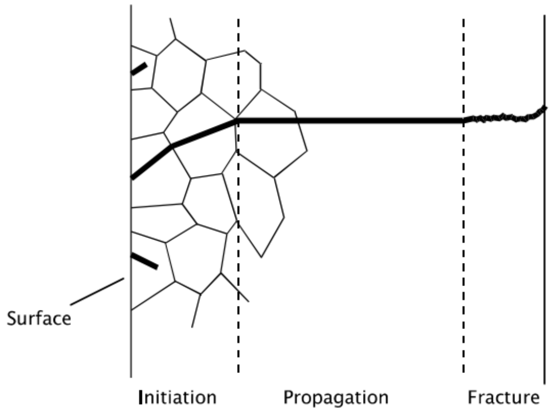


Figure 2.1: Phases of fatigue life

The fatigue life of a component (N_f) is considered as the number of cycles to 1st (N_{in}) and 2nd (N_p) stages stated above since the 3rd stage is a rapid one. The relationship is shown below.

$$Nf = Nin + Np \qquad \text{.............................(2.1)}$$

2.3 Fatigue induce loading on tall structures

Tall buildings are relatively slender hence often flexible. The first few natural frequencies of these structures are relatively low therefore the dynamic stresses generated by dynamic loading will be significant. Dynamic loading such as wind and earthquake induced loading are the main stresses induced in typical tall steel structures and these have to be considered when designing for fatigue.

2.3.1 **Wind induce loading**

Wind is a dynamic and random phenomenon in both time and space. The along wind dynamic effect is determined by gust factor method. This method is used in Canadian and Australian codes. Gust factor relates the peak to mean response in terms of an equivalent static design load. Equivalent static wind load distributions are those loadings that produce the correct expected values of peak load effects, such as bending moments, axial forces in all members, or deflections, generated by the fluctuating wind loading. The effective peak loading distributions associated with the mean wind loading, the fluctuating quasi-static or background response and the resonant response are identified, and combined to give a total effective peak wind loading distribution. The approach can be applied to any type of structure. (Holmes, 2004)

2.3.2 **Earthquake induce loading**

In recent years, much attention is being paid to earthquake loading because of the high seismicity level of many regions where the tall structures were built. Earthquake induced load conditions on steel structures are quite different from other fluctuating loading conditions. Because cyclic loading on structures due to earthquakes involves many fewer cycles (typically less than ten cycles) than conventional low-cycle fatigue and strains that are well in excess of yield. Such conditions can be termed as ultra-low-cycle fatigue (ULCF). (Kanvinde & Deierlein, 2004) Seismic analysis of a structure can be a dynamic analysis or static analysis. In static analysis equivalent static load analysis can be carried out. In dynamic analysis response spectrum analysis or time history analysis can be carried out. The response spectrum analysis method yields much more accurate results than the equivalent static approach and it is essential for flexible structures where dynamic effects are significant. This increase in accuracy is largely due to combining specific vibratory modes from the structure with the spectral accelerations determined for the site.

2.4 Endurance curves (S-N curve)

Endurance curve shows the relationship between the stress level in a component and the number of cycles to failure under that stress. Series of tests of specimen under constant amplitude cyclic loading of different intensities are done to produce these S-N curves. A typical S-N curve is shown in the figure 2.2 below.

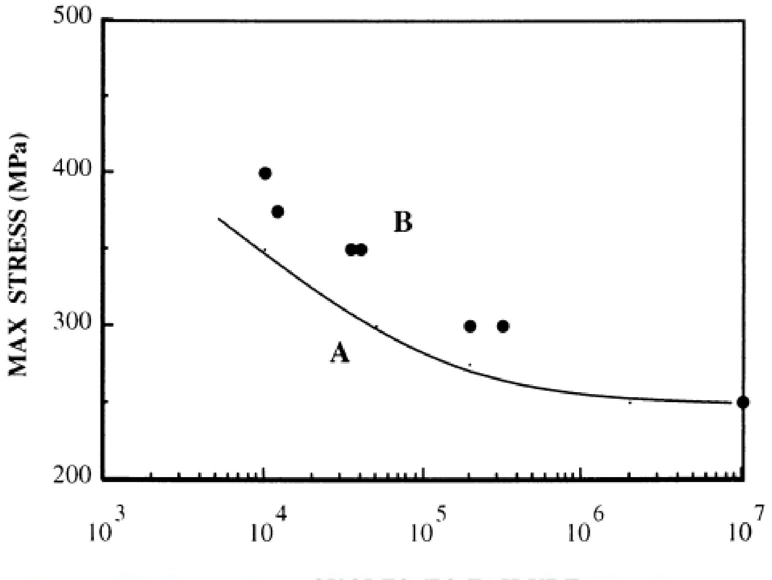


Figure 2.2: An example S-N curve

The number of cycles to failure rapidly reduces with the increasing stress amplitude as shown in the figure below. The slope of this curve reduces with increasing number of cycles to failure and finally it becomes almost parallel to x axis. This stress value is referred to as the endurance limit .If the stress levels are less than the endurance limit it is assume that no failures will occur under any number of cycles. But recent research has showed that this endurance limit is a false phenomenon and every stress level has a certain number of cycles to failure. (Bathias, 1999) Still endurance limit is used for steel as the slope of the curve is negligible.

2.4.1 **Generalised Fatigue data**

Fatigue endurance curves are produced to a certain component should be able to generalise to use for other shapes, different loading histories and other materials.

2.4.1.1 Generalisation for loading

Common structures are subjected to varying loads in their lifespan. The method adopted to use constant amplitude S-N curves to analyse complex loading histories is called the Palmgren-Miner cumulative damage hypothesis or Miner's rule. It assumes that the each successive cycle generates additional damage which accumulates in proportion to the number of cycles until failure occurs. (Holmes, 2004).

Miners rule is given by the following equation,

$$\sum\left(\frac{\boldsymbol{n_i}}{\boldsymbol{N_i}}\right) = \mathbf{1}\ldots\ldots\ldots\ldots\ldots\ \mathbf{(2.2)}$$

Where *ni* is the number of stress cycles of the considered amplitude and *Ni* is the number of cycles required to cause failure under the same amplitude.

If we can estimate the number of cycles and amplitude levels of the designed structure in its lifetime, endurance curves can be used to calculate the miner sum to check whether fatigue failure happens or not. If the loading history is a complex, a method like Rain flow cycle counting can be used considering stress.

2.4.1.2 Generalisation for shape

Fatigue failure of a component often initiate from a place where change of the section is present (holes, grooves and fillet radii). This is because those features produce local stress and strain concentrations. Some local plasticity must occur in the loading history to initiate a fatigue crack. Modern fatigue theorise such as critical location, local stress-strain relate fatigue endurance to local stress concentrations. (STL, 2002). Conventional S-N curve analysis uses a relationship between engineering stresses and fatigue life (Engineering–stress method).

The local stress distribution is different to nominal stress distribution in components with varying section such as shown in figure 2.4. But typical fatigue tests have been performed for smooth cylindrical specimens. Those test results can be used for components with complex local stress distributions by using stress concentration factors. Elastic stress concentration factor K_t is defined as,

$$\mathbf{Kt} = \frac{\boldsymbol{local\ stress\ at\ notch}}{\boldsymbol{nominal\ stress}}\ \ldots\ldots\mathbf{(2.3)}$$

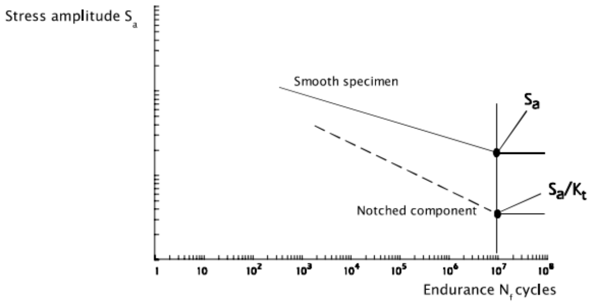


Figure 2.3: SN curves for notched and smooth specimen

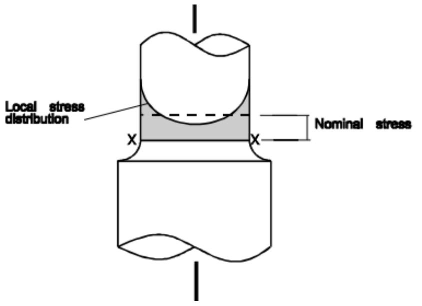


Figure 2.4: Local stress distribution and nominal stress of a component

Stress concentration factors for large number of engineering details have been published. Elastic stress concentration factors can be used to modify the endurance limit as shown in figure 2.3 since there will be little plasticity at the endurance limit stress amplitude. Calculation of notch fatigue strength at a lower amplitude is complex as the plastic stresses will be there. Both local strain and engineering stress fatigue methods contain equations for calculating the effect of notches

2.4.1.3 Generalisation for mean stress

Tests of high mean stresses show shorter fatigue lives. Most standard fatigue tests are done for zero mean stress constant amplitude cyclic vibrations. Mean stress correlation factors are available for load ratios (R) given by,

$$Load\ ratio\ (R) = \frac{Pmin}{Pmax} \ldots\ldots\ldots\ldots\ldots..(2.4)$$

Change of SN curve for different load ratios is shown in the figure 2.5 below,

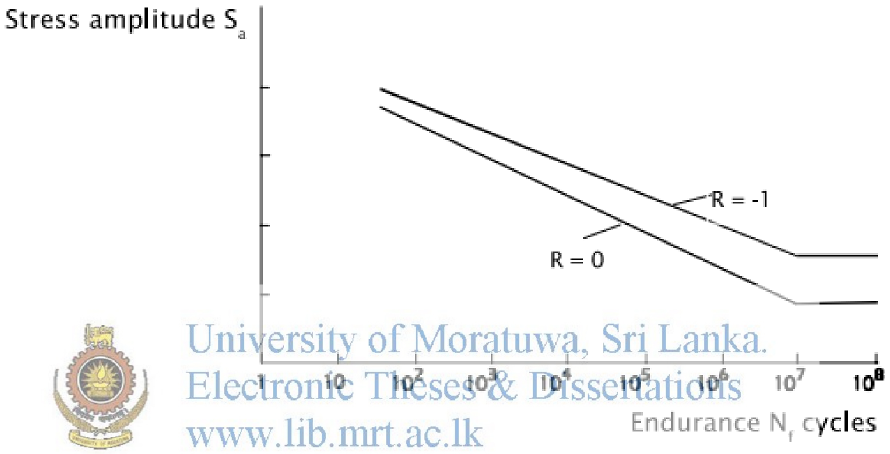


Figure 2.5: SN curves for different load ratios

2.4.1.4 Generalisation for other factors

Crack initiation is a surface phenomenon. Any process which affects the surface will have a significant impact on fatigue strength. They are,

- Quality of the surface finish-ground: machined/rolled/as-forged/as-cast/grinded
- Surface treatment: planting/cladding
- Residual stresses
- Operating environment: temperature/corrosive environment

The cyclic frequency of the applied loading and the waveform can be ignored in many calculations. Smooth specimen test data is almost always obtained from the tests on uniaxial loaded specimens. Special methods must be adopted when these data are used for biaxial stresses.

Laboratory endurance strength ($S_{e'}$) of the materials obtain from S-N diagram (or the likes) are therefore corrected for actual conditions by using correction factors as shown below,

$S_e = K_a x K_b x K_c x K_d x K_e x K_f x S_e$……………….(2.5)

Where,

K_a = Surface Correction factor

K_b = Size Correction factor

K_c =Reliability Correction factor

K_d = Temperature Correction factor

K_e = Stress concentration Correction factor

K_f = Miscellaneous Correction factor

$S_{e'}$ = Endurance Strength of material specimen under laboratory condition

S_e = Endurance Strength of material specimen under actual running condition

(Azeez, 2013)

2.5 Uniaxial strain life fatigue analysis

Local strain life fatigue analysis presumes that the local stress concentration stain life behaviour is similar to a larger uniform with uniform stresses and strains similar to that. Local strain life methods are suitable for Finite element models because the stress strain relationship at all locations are known.

2.5.1 True stress and strain

When a cylindrical test specimen is loaded in tension or compression its length and cross sectional area changes. There are 2 concepts as true stress/strain and engineering stress/strain. They are defined by the equations 2.6 to 2.9 below,

$$\textbf{Engineering stress} = \frac{\textit{Applied load}}{\textit{Original cross sectional area}} \quad \ldots\ldots\ldots.(2.6)$$

$$\textbf{True stress} = \frac{\textit{Applied load}}{\textit{Actual cross sectional area}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.7)$$

$$\textbf{Engineering strain} = \frac{\textit{Total change in gauge length}}{\textit{Original gauge length}}\ldots\ldots,\ldots.\ (2.8)$$

$$\textbf{True strain} = \int \frac{\textit{Instantaneous change of gauge length}}{\textit{Instantaneous gauge langth}} \ldots\ldots\ldots(2.9)$$

True stress strain curve obtained from a single load application is called a monotonic curve.

Ramberg and Osgood proposed true stress strain relationship defined as,

$$\boldsymbol{\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.10$$

Where,

E- The elastic modulus

K- The strain hardening coefficient
n- The strain hardening exponent

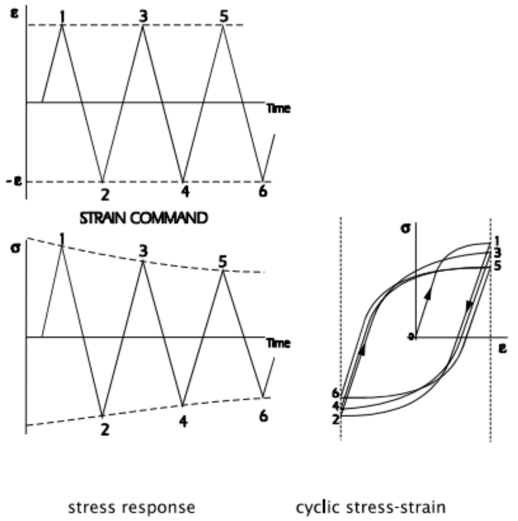


Figure 2.7: Cyclic softening

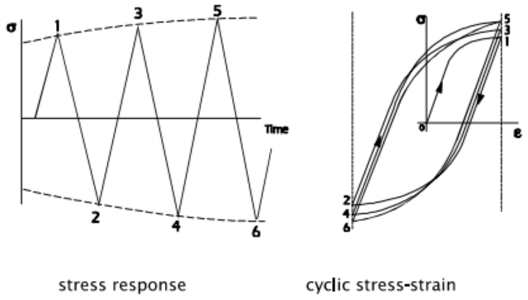


Figure 2.6: Cyclic hardening

When a material is cyclically loaded it hardens (figure 2.7) or softens (figure 2.6) at first but often comes to a stable hysteresis loop in which the same response is shown in all cycles (figure 2.8).

The curve constructed through the tips of the stable hysteresis loops at different strain amplitudes is called the *stable cyclic stress-strain curve*. It is represented by,

$$\boldsymbol{\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}} \text{………} \ \mathbf{(2.11)}$$

Where K' is the cyclic strain hardening coefficient and n' is the cyclic strain hardening exponent. Other symbols have the usual meaning.

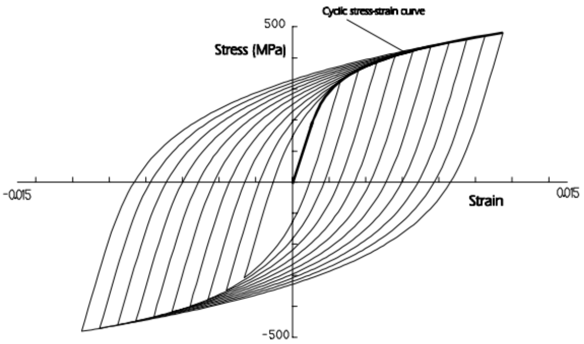


Figure 2.8: Stabilized cyclic response

2.5.2 Low cycle fatigue and high cycle fatigue

When significant plastic straining occurs in a component it is considered as subjected to low cycle fatigue since it fails in lower number of cycle. The fatigue life of the material is less dependent on the stress level but the strain. The analytical procedure used to address low cycle fatigue behaviour is referred to as strain life method. (Hossain & Ziehl, 2012) Manson and Coffin showed that the relationship between plastic strain amplitude and endurance can be expressed as given below,

In high cycle fatigue the stresses and strains are largely confined to the elastic range.

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f(2N_f)^c \quad \text{………..…..…..(2.12)}$$

Therefore the number of cycles to failure is high (typically more than 100,000). However the fatigue endurance in high cycle fatigue is less dependent on the strain but highly dependent on the stress level. The analytical procedure used for these type of fatigue is called as stress life method (Hossain & Ziehl, 2012) Basquin proposed the relationship between elastic stress amplitude and endurance as given below,

$$\frac{\Delta\sigma}{2} = \sigma'_f(2N_f)^b \quad \text{…………………..(2.13)}$$

Combing the 2 equations the total (elastic & plastic) strain-life relationship (figure 2.9) is defined as,

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \quad \text{…..…(2.14)}$$

Local strain-life analysis is a fatigue crack initiation criterion. There are several correlations such as Morrow's mean stress correlation to take account of the mean stress effect.

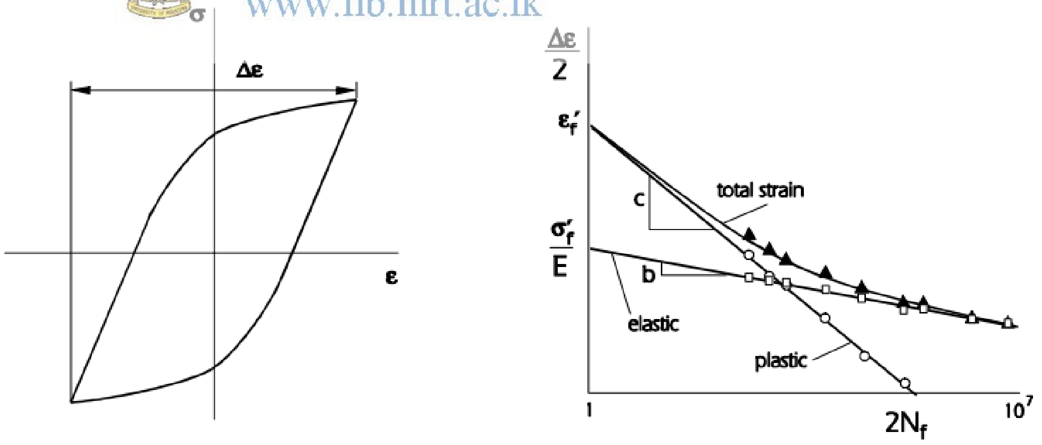


Figure 2.9: Strain life Relationship

The strain excursions of a cyclic strain applied are modelled using the cyclic stress-strain curve and hysteresis loop (figure 2.10) equation. Then actual fatigue cycles in that loading cycle can be identified. Rain flow cycle method too can be used for this. The strain ranges of these fatigue cycles are used in the strain life equations to find the fatigue life for each of the cycle. Then miners rule

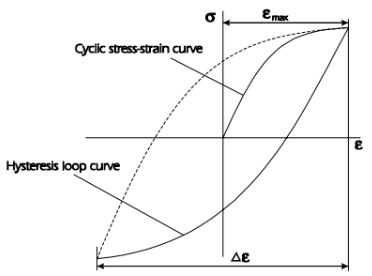


Figure 2.10: Hysteresis loop

can be applied to add the damage of all the fatigue cycles and find the number of cycles of loading the component can survive. Similar method is used in FE-safe software. (STL, 2002)

Morrow's mean stress correction is

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f - \sigma_m}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad \ldots\ldots\ldots\ldots\ \textbf{(2.15)}$$

The hysteresis loop shape is defined by

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \textbf{(2.16)}$$

2.6 Multi-axial fatigue

2.6.1 **Introduction**

Many actual structures experience multi-axial fatigue, bending, torsion as well. Use of uniaxial methods for multiracial fatigue may give overestimates of the life. The fatigue cracks are usually initiated from the surface. Combination of in-plane stresses and out-of-plane stresses on the surface creates tri-axial stress distribution. Multi-axial fatigue theories concentrate on this condition. Different criterions have been proposed by researchers.

2.6.2 **Brown miller combined strain criterion**

The brown-miller equation assumes that the maximum fatigue damage occurs on the plane which experience the maximum shear strain amplitude, and that the damage is a function of both this shear strain and the strain normal to this plane.

Complete Brown-Miller strain-life equation is,

$$\frac{\Delta\gamma_{max}}{2} + \frac{\Delta\varepsilon_n}{2} = 1.65\frac{\sigma'_f}{E}(2N_f)^b + 1.75\,\varepsilon'_f(2N_f)^c \qquad \ldots\ldots\ldots\ldots\textbf{(2.17)}$$

The brown-miller equation gives the most realistic life estimates for ductile metals.

Considering the effects of the mean stress, if morrows mean stress correlation is used with the brown miller equation the equation transforms to,

$$\frac{\Delta\gamma_{max}}{2} + \frac{\Delta\varepsilon_n}{2} = 1.65\frac{(\sigma'_f - \sigma_{n,m})}{E}(2N_f)^b + 1.75\,\varepsilon'_f(2N_f)^c \qquad \ldots\ldots\textbf{(2.18)}$$

Where $\Delta\gamma_{max}$ is the maximum shear strain range and $\Delta\varepsilon_n$ is the range of strain normal to the maximum shear strain. Other parameters have same meanings as the uniaxial strain life equation.

Methods like critical plane method can be used with brown miller equation to consider the critical planes when complex loading is applied. Critical plane method resolve the strain in to number of planes, and calculate the damage in each plane.

2.7 Codes of practices

Calculation of wind induced fatigue according to Australian codes requires calculation of number of stress cycles, stress ranges for each cycle. Finally fatigue analysis can be done according to the AS4100 code using the derived data.

Calculation of the number of cycles: The probability of the wind speed being in a required band may be calculated from hourly mean wind speeds. Most wind data can be fitted to a Weibull distribution. These probabilities can be transferred to number of stress cycles in the design life.

Calculation of stress ranges for each wind speed band: Suitable methods should be used for along wind and cross wind response. AS1170.2 (1989) describes gust factor method which is suitable for along wind response estimation. Cross wind response can be estimated using sinusoidal lock-in and random excitation models. If the structure is too complicated, wind tunnel testing may be required.

Fatigue analysis: Australian code AS4100 defines a concept called the detailed category (f_{rn}) for different components which means the fatigue strength at $2\text{x}10^6$ cycles on the S-N curve. Detail category considers local stress concentration details, size and the shape of the maximum acceptable discontinuity, residual effects, and the welding effects.

The miners rule is used to calculate the combined effect of the all stress ranges found from wind analysis. The following flow chart clearly shows the method used in AS4100. (Mendis & Dean, 2000). See Appendix 3 for the methodology adopted in AS 4100 to estimate the fatigue life.

3 FINITE ELEMENT MODELLING

The simulations were done by constructing the finite element models in Abaqus and importing it to fe-safe fatigue analysis software to estimate the fatigue life. It is very important to use the most suitable material models, parameters and boundary conditions to idealize the actual condition. Fatigue analysis is sometimes called the five box trick which includes material, loading, geometry inputs and analysis and results. (Hossain & Ziehl, 2012) The 3 main inputs for the finite element model is given in Abaqus FEA to analyse and get the stress strain histories for stabilized cyclic response. The fatigue material properties are provided to fe-safe software and the stress strain histories are imported to fe-safe software to analyse fatigue.

3.1 Abaqus FEA

3.1.1 Introduction

Abaqus is a finite element software which is capable of modelling dynamic/static behaviour. There are three core software products that can be used to model structural components.

1. Abaqus /CAE- (complete Abaqus graphical user interface) it is a software application that can be used to both the modelling and analysis.(pre-processing and post-processing)
2. Abaqus/Standard – This is a general-purpose finite element *analyser* with implicit integration.
3. Abaqus/Explicit - This is a special-purpose Finite-Element *analyser* that uses explicit integration to solve highly nonlinear systems with many complex contacts under transient loads.

Abaqus/CAE is divided into 11 modules. Each module defines a logical aspect of the modelling process. The modules help building the model from which Abaqus/CAE generates an input file. It is submitted to the Abaqus/Standard or Abaqus/Explicit analysis product. Then the analysis product performs the analysis, and generates an output database. Eventually the visualization module of Abaqus/CAE shows the results of the analysis.

3.1.2 Material properties

Material properties of monotonic tests cannot be used to simulate cyclic loading conditions. Therefore cyclic properties must be obtained and used for the simulations.

When a material is subjected to cyclic vibrations under fixed strain range elasto-plastic strain an initial softening or hardening behaviour will be shown. After a certain number of cycles of initial hardening or softening (figure 3.1) the material stabilizes, producing a stabilized hysteresis loop (loop closing behaviour). (Abaqus, 2013)

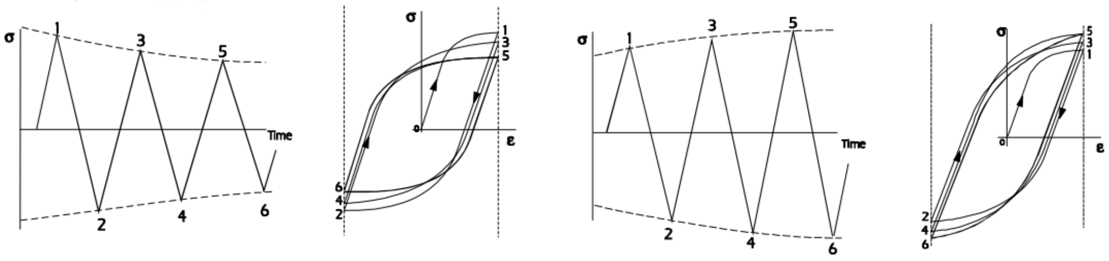


Figure 3.1: cyclic softening (left) and cyclic hardening (right) for a constant amplitude cyclic strain

The stabilized cyclic response is employing much of the fatigue life of the material. Near fracture response again become transient. (STL, 2002)

The material hardening behaviour can be idealized in Abaqus under plastic properties. The 3 main types are isotropic kinematic and combined.

1.) isotropic

The isotropic hardening model is useful for cases involving gross plastic straining or for cases where the straining at each point is essentially in the same direction in strain space throughout the analysis. Therefore this is not suitable for cyclic behaviour. Isotropic hardening describes the change of the elastic range.

2.) Kinematic

The kinematic option uses the linear kinematic model to define a constant rate of cyclic hardening. This is suitable to simulate the inelastic behaviour of material which are subjected to cyclic loading. Kinematic hardening describes the translation of the yield surface in stress space. When temperature dependence is omitted, the evolution law used here is the linear Ziegler hardening law

3.) Combined

The combined feature can be used to define non-linear kinematic hardening and isotropic hardening together. The combination of the isotropic component together with the nonlinear kinematic component can be used to predict shakedown after several cycles. (Cyclic hardening with Plastic shakedown)

. The Bauschinger effect (increase in tensile/compressive yield strength occurs at the expense of compressive/tensile yield strength) and plastic shakedown (plastic deformation ceases after a number of initial cycles and the response goes back to pure elastic with some state of residual stress) can be modeled with both models, but the nonlinear isotropic/kinematic hardening model provides more accurate predictions. (Abaqus, 2013)

It is very important to use proper a kinematic/combined hardening model instead of isotropic model and cyclic material properties instead of monotonic properties to idealize the actual condition.

3.1.3 Boundary condition and loading

Abaqus FEA uses steps to identify the changes in loading, boundary conditions, or when specific output requests are required. The analysis method of the step can also be defined. There are 2 procedure types,

1.) General

The nonlinear effects in the model can be included in general analysis step. The starting condition for each general step is the ending condition from the last general step, with the state of the model evolving throughout the history of general analysis steps as it responds to the history of loading.

There can be 3 sources of nonlinearity

I. Material nonlinearity -
  Nonlinear material behaviours such as nonlinear elasticity and plasticity can be added
II. Geometric nonlinearity
  The nodal displacements are considered to be significant so taken in to account for analysis.
III. Boundary nonlinearity
  The nonlinearities in the boundaries such as contact friction, springs etc are considered.

2.) Linear perturbation

The response in a linear analysis step is the linear perturbation response about the base state.

The loading in finite element models can be either force, pressure, temperature, displacement, or a number of other types. There are different kinds of loading in Abaqus each using a different type of time history. For example, RAMP and STEP define how and when the loading is applied during a given step. Otherwise Amplitude can be defined as well.

Idealisation of actual boundary conditions are very important to simulate the actual condition. Mechanical boundary conditions such as connector displacement, displacement /rotation restraints can be defined.

3.2 FE-safe

Fe-safe is a fatigue analysis software which must be used alongside FEA software to estimate where fatigue crack will occur when fatigue failure happens and the factor of safety on working stresses.

Fe-safe has 2 methods to analyse fatigue when the components are subjected to elasto-plastic vibrations

1. Using elastic FEA(elastic block) results with Neuber’s correlation

   The advantage of this method is that stress histories can be given in the form of loading datasets in fe-safe software itself. But the problem is that the stress redistribution at element nodes are neglected when Neuber’s correlation is used. Therefore this method may predict higher number of cycles to failure than the actual condition when large region of the component being analysed is subjected to plastic stresses.

2. Using elasto-plastic FEA results (elastic-plastic block)

   This method is suitable for any elasto-plastic stress history since the plasticity is taken in to account in the finite element analysis. But stress history cannot be given changed as desired to multiples as in elastic block method. Elasto-plastic FEA should be performed for every stress history required.

The stabilized cyclic response modelled in Abaqus FEA should be properly picked out of the stress strain datasets to perform the analysis.

Fatigue properties of the material can be defined and other fatigue inducing properties such as surface finish, residual stresses should be carefully chosen. Finally the algorithm to perform fatigue analysis is chosen. “Brown-miller equation gives most realistic fatigue life estimates for ductile metals” (Fe-SAFE, 2002,7-20) Brown miller equation is applied to 3d elements in fe-safe using critical plane method. The most damaging plane is identified by applying the equation to planes at 10º intervals between 0º and 180º from the surface of the component. (Fe-safe, 2002)

4 SOFTWARE VERIFICATION

In order to check the fatigue results and modelling techniques of ABAQUS and FE-Safe software, a test should be performed coupling the software to verify the properties and methods used in the simulation. Fatigue testing facilities are not available in Sri Lanka. Therefore other researchers' published tests have been used for modelling. This has been used primarily because the case study fatigue results cannot be verified through laboratory tests.

4.1 Simulation of uniaxial fatigue

Zhou, et al., 2008 have conducted an experimental study on the low cycle fatigue of stainless steel reinforcement bar specimens. An attempt is made to simulate the standard uniaxial fatigue test done by Zhou, et al using Abaqus/FEA and fe-safe commercial finite element software. Experiment is modelled in Abaqus to obtain the maximum stresses and strains under a specified loading condition first. Then the stress-strain data is imported to fe-safe to predict the fatigue behaviour under cyclic loading. The test apparatus and specimen dimensions are given below.

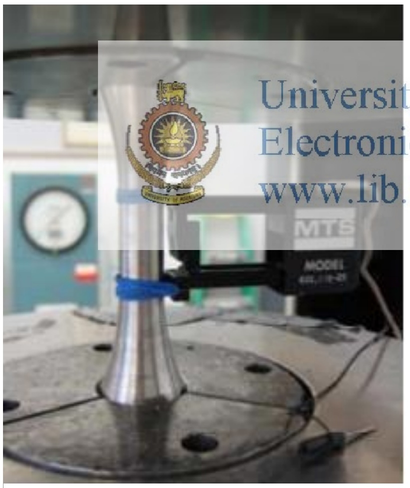


Figure 4.2: Test apparatus

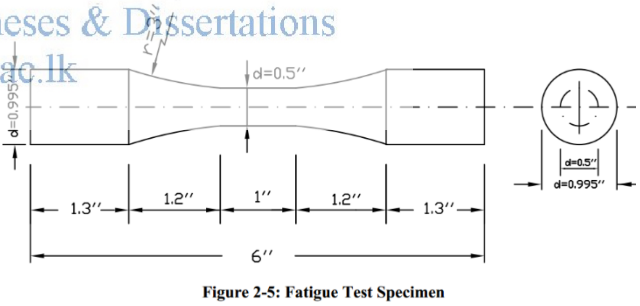


Figure 4.1: Specimen dimensions

4.1.1 Material Properties

The simulation was done for stainless steel 316LN test specimens. The cyclic properties and fatigue properties extracted from the literature are given in Table 4.1:

Table 4.1: Material properties of stainless steel 316LN test specimens

Mechanical Properties	**Cyclic Elastic properties** (Zhou, et al., 2008)	
	Young's modulus (MPa)	Poisson's ratio
	199817	0.33
	Cyclic Plastic properties (J.Shita, et al., 2013)	
	Yield stress(MPa)	Plastic strain
	270	0
	300	0.0025
	330	0.0075
	350	0.0125
	370	0.0175
	400	0.04
Fatigue Properties (Fe-safe, 2014)	B	-0.0835
	C	-0.5142
	ε_f'	0.476
	σf'	703.4

4.1.2 Material model

The hardening model is very important in simulating the fatigue behaviour. The intial transient behaviour is not important since the material comes to stabilzed cyclic response easily. However the stabilized cyclic response is presnt in majority of the fatiguelife. Therefore non-linear kinematic hardening model is used which is similar to that's described in (Staudinger & Reiter, 1997)

4.1.3 Modelling with ABAQUS

Abaqus standard is used for this analysis since the dynamic nature of the forces are negligible.3D20R solid elements with varying mesh size are used in order to model the stainless steel specimen. A finer mesh was used to model the central region to obtain a detail stress distribution.

General static analysis is performed neglecting the geometric nonlinearity. Bottom grip was restrained to move in all degrees of freedom and top grip was allowed to translate along the longitudinal axis of the specimen as shown in figure below.

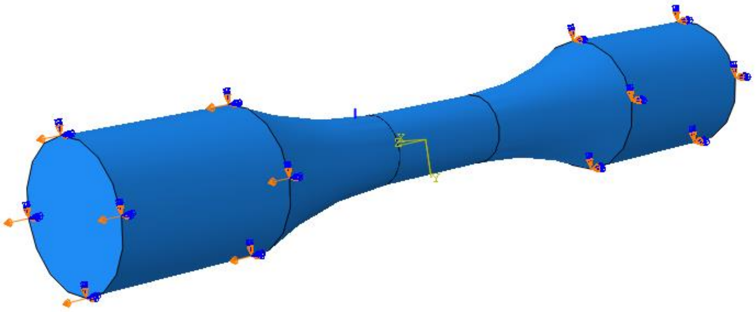


Figure 4.3: Idealized boundary condition in Abaqus

The model was run for different strain levels to construct the stress strain behaviour. Figure 4.4 shows strain distribution for a simulation subjected to 1.77% overall strain. Figure 4.5 illustrates the cyclic stress strain behaviour of a node at the centre of the specimen for the same 1.77% strain amplitude. The strain gauge in the experimental investigation performed by Zhou, et al., 2008 is located between the end points of the middle uniform cylindrical area. Therefore the strain values presented here refers to the same region.

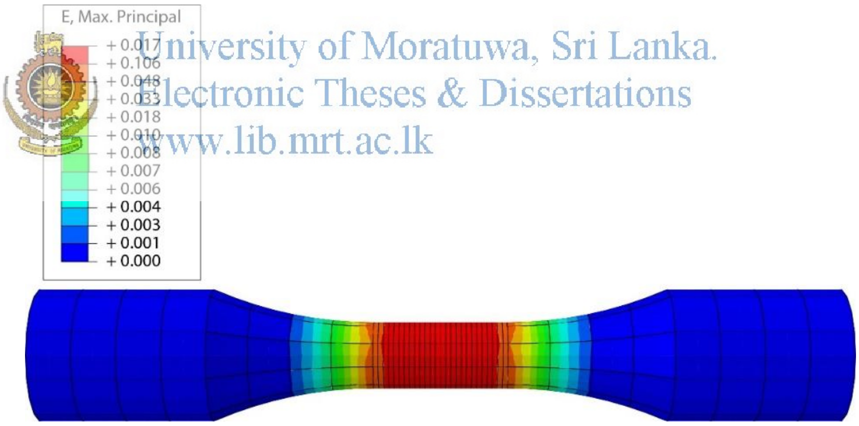


Figure 4.4: Abaqus simulation of 1.77% strain amplitude

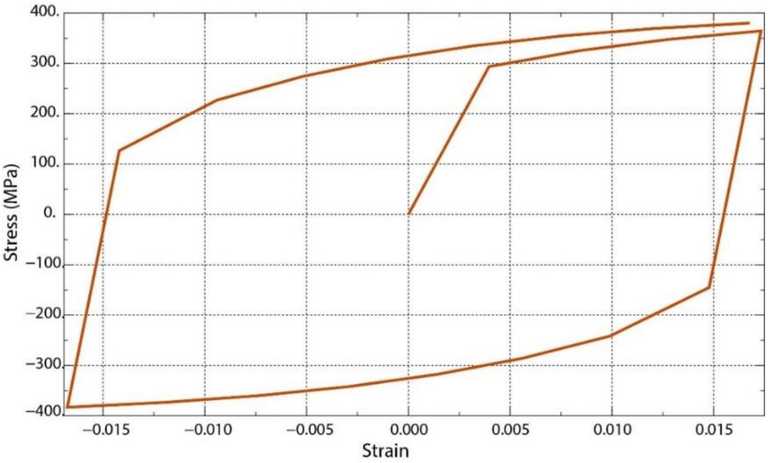


Figure 4.5: Principle stress strain response of an element in the central region

4.1.4 Fatigue analysis using FE-safe

Both the stress and strain datasets for each strain level are imported from Abaqus to the fe-safe software. By default Fe-safe assumes the stress datasets as elastic blocks. Elastic plastic analysis feature in fe-safe requires elastic plastic stress strain datasets for finite elements which is more accurate. Therefore an elastic plastic finite element analysis must be carried out. By combining stress dataset and strain dataset for each increment elastic plastic block was generated. The inbuilt fe-safe material database for S316 stainless steel is used for fatigue simulation and the surface finish was assumed as mirror polished.

Brown-miller equation with morrow's mean stress correlation was selected as the algorithm. Although the loading is uniaxial, uniaxial strain life equations cannot be used in fe-safe for 2D or 3D objects as stress and strains are not uniaxial.

4.1.5 Results and Discussion

Two sets of simulations were performed using an elastic plastic block but varying the surface finish to observe the sensitivity. Another simulation was performed with an elastic block. Table 4.2 compares the results obtained for the simulations against the experimental results obtained by (Zhou, et al., 2008).

Table 4.2: Comparison of fatigue life results

Number of reversals to failure (2Nf)				
Strain amplitude (%)	Experimental result (Zhou, et al., 2008)	Abaqus and fe-safe simulation		
		Using Elastic Plastic block		Elastic block with Neuber's rule
		Mirror polished	Rough(Ra-2um)	Mirror polished
0.99	1322	1198	552	54487
1.28	791	616	336	42369
1.5	576	411	225	35483
1.77	413	292	162	31438
2.1	293	216	120	28763
2.4	225	162	90	27064

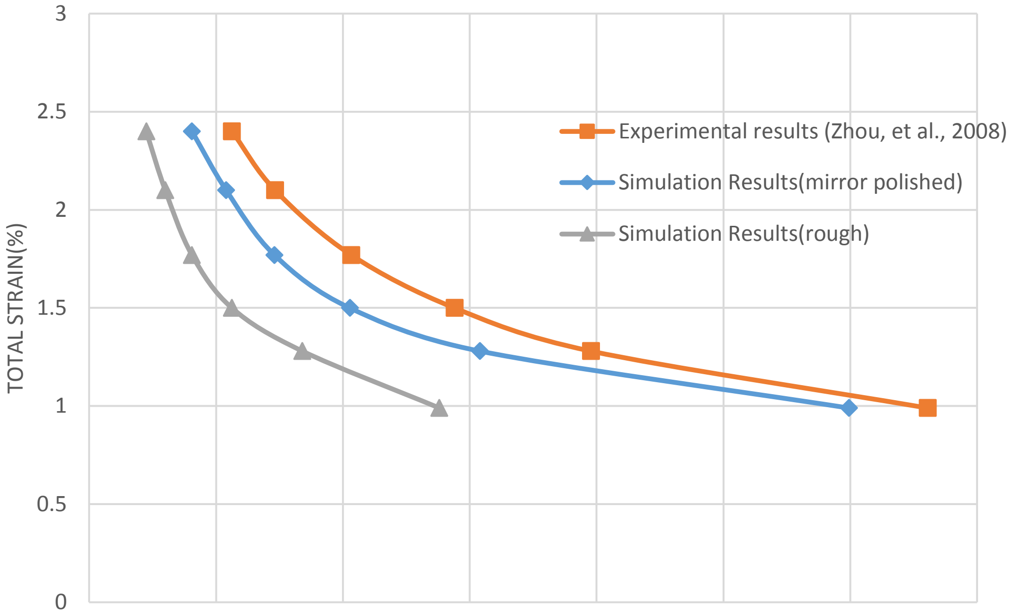


Figure 4.6: Comparison of S-N curves of simulation and experimental results

As shown in the Figure 4.6 the mirror polished surface finish which is the actual condition in the original test gave the closest behaviour to tested results. The simulation is within 25% range of the actual values. The original experimental results indidate that there is a 10%-20% variation of the experimental curve presented here. Therefore the simulation results is in an accpetable range.

The rough surface finish that is present in type 316 rebars (Kalpakjian, 6th edition) will give fatigue limits in the range of half that was for mirror polished. This indicates the surface finish is a primary factor for fatigue life of a material. As shown in Table 4.2 the simulation with an elastic block with Neuber's rule gaves large fatigue lives which are not acceptable. The reason as explained in 4.1.4 is neuber's rule being valid only when stress redistribution is insiginifcant. In this experiment whole central region of the speciemn is subjected to plastic stresses. Therefore elastic-plastic stress block method is preferred.

4.2 Simulation of multi-axial fatigue

Glodež & Knez have conducted an experimental study on the fatigue behaviour of high strength steel crawler crane arms. An attempt is made to simulate the experimental fatigue test done by Glodež & Knez using Abaqus/FEA and fe-safe commercial finite element software. Experiment is modelled in Abaqus to obtain the maximum stresses and strains under a specified loading condition first. Then the stress-strain data is imported to fe-safe to predict the fatigue behaviour under cyclic loading. The test apparatus and specimen dimensions are given in figure 4.7.

The simulation was done for S1100Q test specimens. The cyclic properties and fatigue properties extracted from the literature are given in the table below.

Table 4.3: Material properties of S1100Q test specimens

Mechanical Properties	**Cyclic Elastic properties**	
	Young's modulus (MPa)	Poisson's ratio
	194889	0.3
	Cyclic Plastic properties	
	Yield stress(MPa)	Plastic strain
	875	0
	1000	0.015
	1100	0.0766
Fatigue Properties (Fe-safe, 2014)	b	-0.0997
	c	-0.978
	ε_f'	9.93
	σf'	2076Mpa

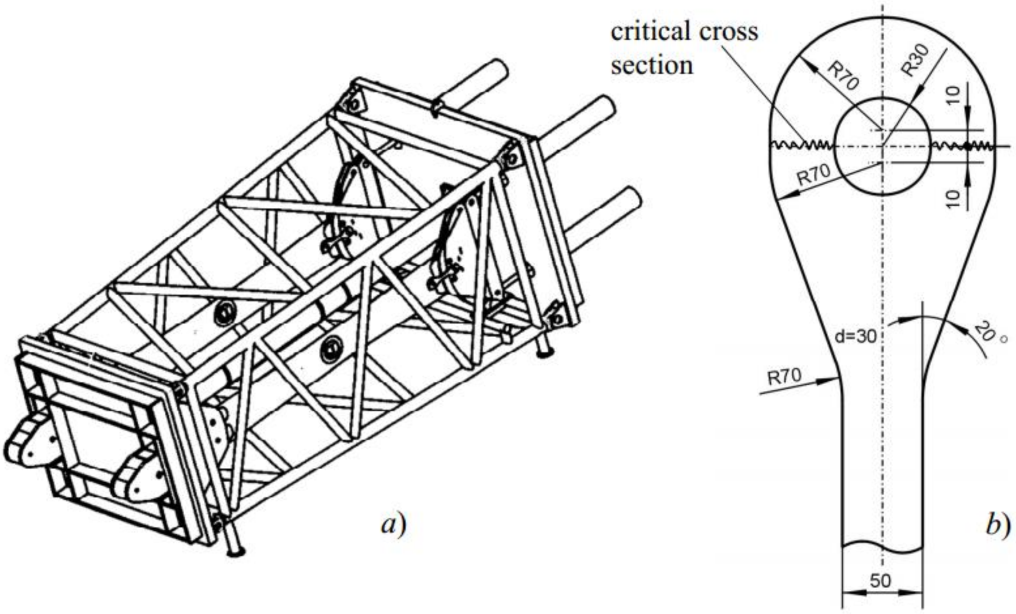


Figure 4.7: Fatigue testing machine (a) and testing bar (b)

4.2.1 Modelling with ABAQUS

Abaqus explicit is used for this analysis since the dynamic nature of the forces are significant while modelling the interaction with the bolt. The bolthole was idealized as analytical rigid shell assuming rigidity (figure 4.8). C3D8R: 8-node linear brick solid elements with varying mesh densities are used in order to model the specimen (figure 4.9). A finer mesh was used to model the central region around the opening to obtain a detail stress distribution.

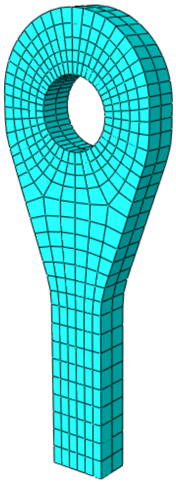


Figure 4.9: Mesh of the crane bar

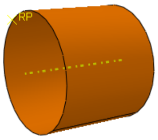


Figure 4.8: Analytical rigid shell for bolthole

Dynamic explicit analysis is performed considering the geometric nonlinearity. The bolt is restrained in all degrees of freedom. Surface to surface contact of Hard and frictionless contact using penalty contact method was used between the bolthole surface and bolt. The load expected in the bar was applied from the bottom end as shown in the figure 4.7 below.

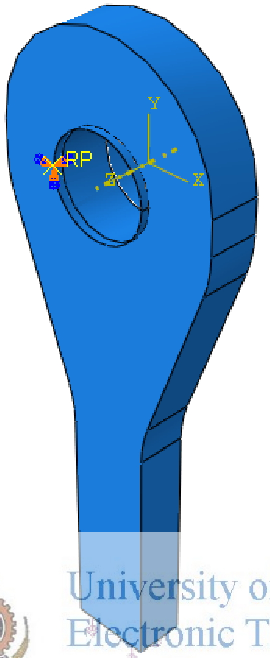


Figure 4.10: Loading and boundary conditions

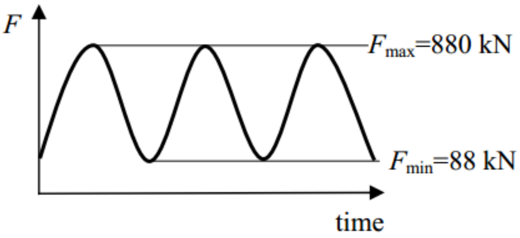


Figure 4.11: Applied cyclic loading

The applied cyclic load is shown in the figure 4.8. This was applied as a periodic type amplitude with relevant parameters. Since the stabilized cyclic properties are given. The model comes to stabilized cyclic response in one cycle.

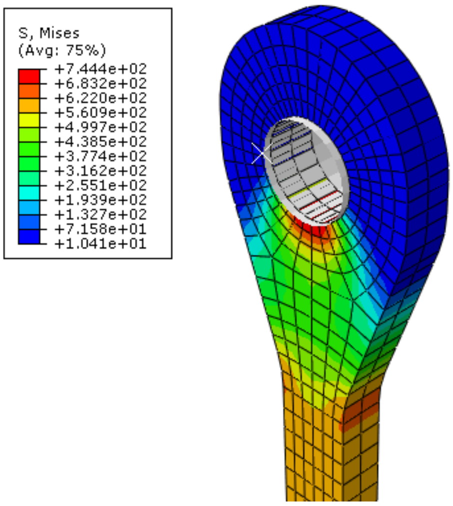


Figure 4.13: Misses stress distribution at the highest loading level

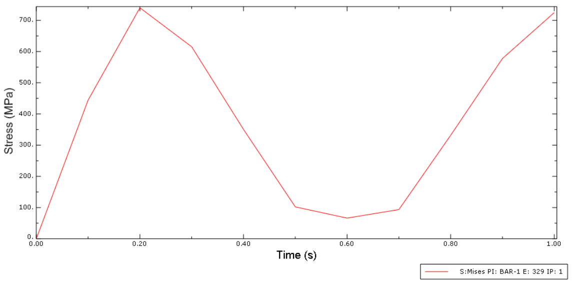


Figure 4.12: Stress variation of a node just below the bolt hole

4.2.2 Fatigue analysis using FE-safe

Both the stress and strain datasets for each strain level are imported from Abaqus to the fe-safe software. An elastic plastic finite element analysis was carried out. The fatigue material properties given by Glodež & Knez, 2007 was used for the analysis. Surface finish was assumed as fine machined (4 um< Ra < 16um). See Appendix 1

Brown-miller equation with morrow’s mean stress correlation was selected as the algorithm.

4.2.3 Comparison of Results

Table 4.4: Results of the simulation and experiments

Experimental Results				FEA results
Test 1	Test 2	Test 3	Test 4	29979
38029	26727	24795	29036	

The results indicate that there is a closer relationship with simulated results and experimentally ested results. But it should be noted that the variations of surface finish idealisation can change the results by large amounts.

5 CASE STUDY

5.1 Introduction

Proposed tower is a 350m tall tower located in Colombo Sri Lanka.The tower mast at the top is reinforced concrete at lower half and steel at the its' upper half. The steel mast is 64.1m tall and it is made out of tubular sections (figure 5.1). The section shape and size change in 3 stages.

There are openings at all these stages. Out of these the openning at the bottom which is subjected to highest stress level and largest in size is valnerable to fatigue failure under cyclic loading.

Since the structure is at 300m height the wind induced vibrations are significant. There is a probability that the wind induced vibrations can cause fatigue. In order to check its vulnerability to fatigue and to compare the sensitivity to thickness, shape of the openning different finite element models are checked for fatigue.

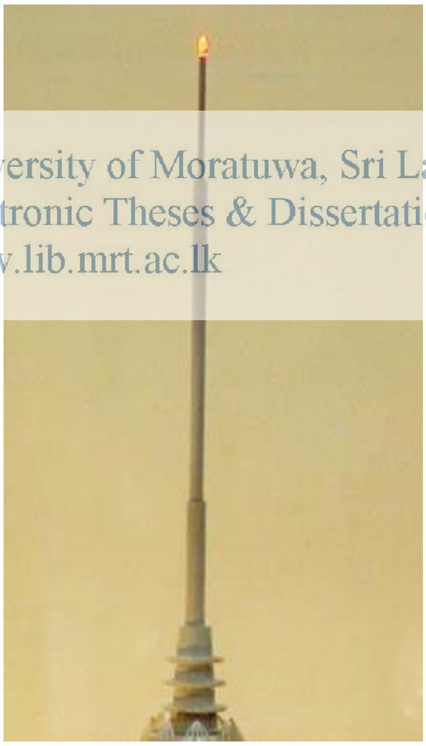


Figure 5.1: Proposed shape of the Steel tower

5.2 Dimensions and properties

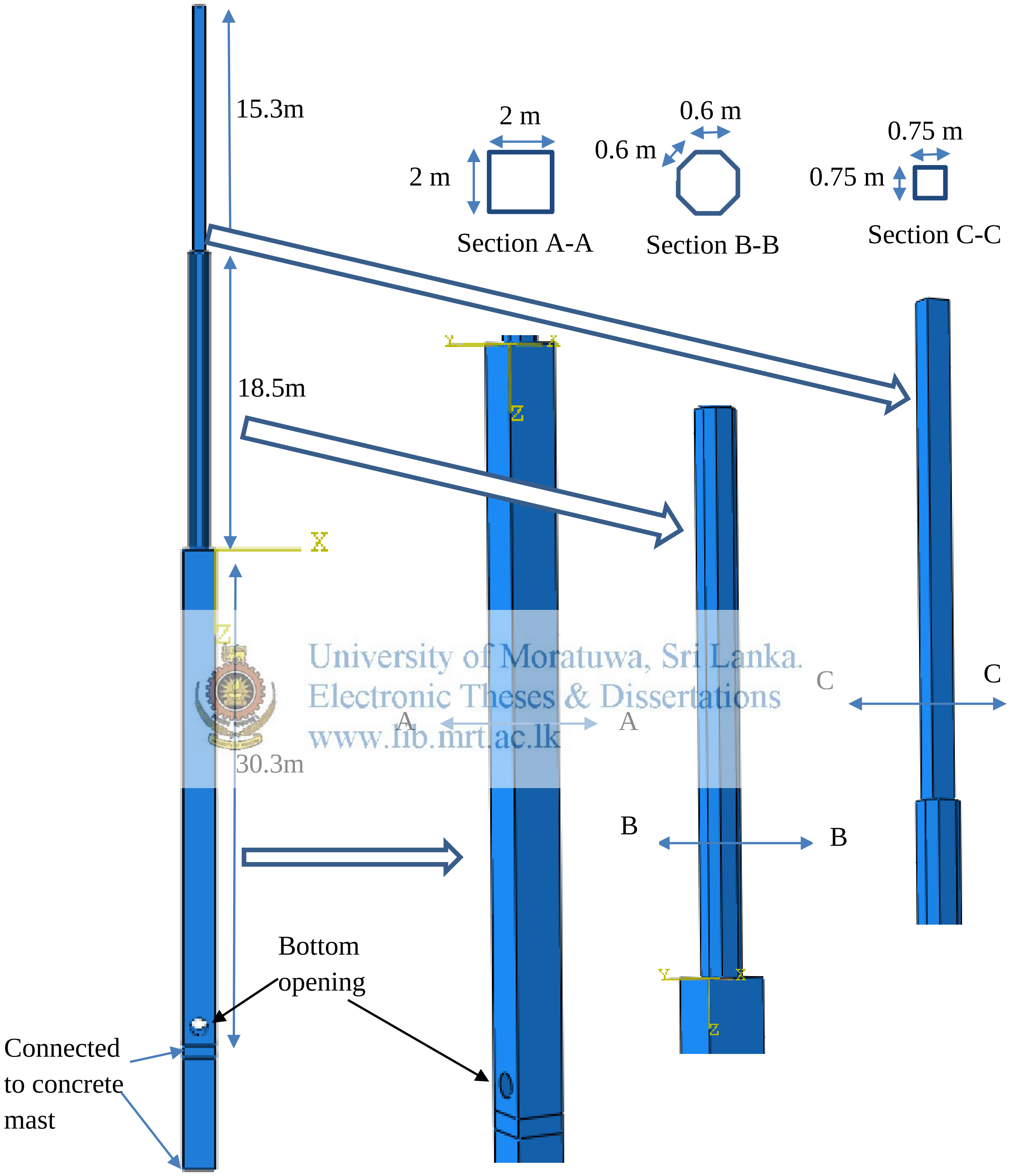


Figure 5.2: Dimensions and the shape of the steel mast

Table 5.1: Material properties

density	
Cyclic elastic properties ((Hachim, et al., sep 2012)	
Young's modulus	200Gpa
Poisson's ratio	0.3
Yield strength	$372Nm^{-2}$
BS 5950-1:2000:Table 9 $335Nm^{-2}$ (40mm<thickness<63mm)	
Fatigue properties ((Fe-safe, 2014)	
B	-0.122
C	-0.598
ε_f'	0.182
σf'	1081

The maximum stresses are lower than $300Nm^{-2}$ in all the simulations. Hence elastic analysis can be performed.

5.3 Finite element modelling

The finite element model of the tower is constructed as shown in the figure 5.2 by merging 3 uniform parts. Different shapes of openings and different thicknesses are introduced to check the sensitivity. Abaqus standard was used with General static analysis neglecting the geometric nonlinearity.

5.3.1 Loading and boundary conditions

The gust factor was found to be 1.77 and design wind pressure is 2.6kNm-2. (See Appendix 2) Hence application of 4.6kNm-2 uniform pressure will generate equivalent stresses on the elements.

The pressure is applied on windward side as a uniform pressure load. Boundary condition at the connection to the concrete mast is idealized as a connection restraining all 3 translational degrees of freedom. The loading and boundary conditions applied on the FE model is shown in the figure 5.3.

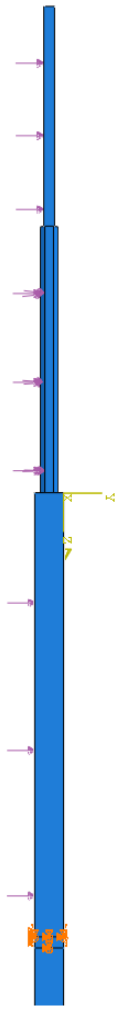


Figure 5.3: Loading on the mast FE model

5.3.2 **Mesh**

S8R: Eight-node doubly curved thick shell elements with varying mesh densities are used in order to model the steel mast. A finer mesh was used to model the area near the opening to obtain a detail stress distribution as shown in the figure 5.4 below.

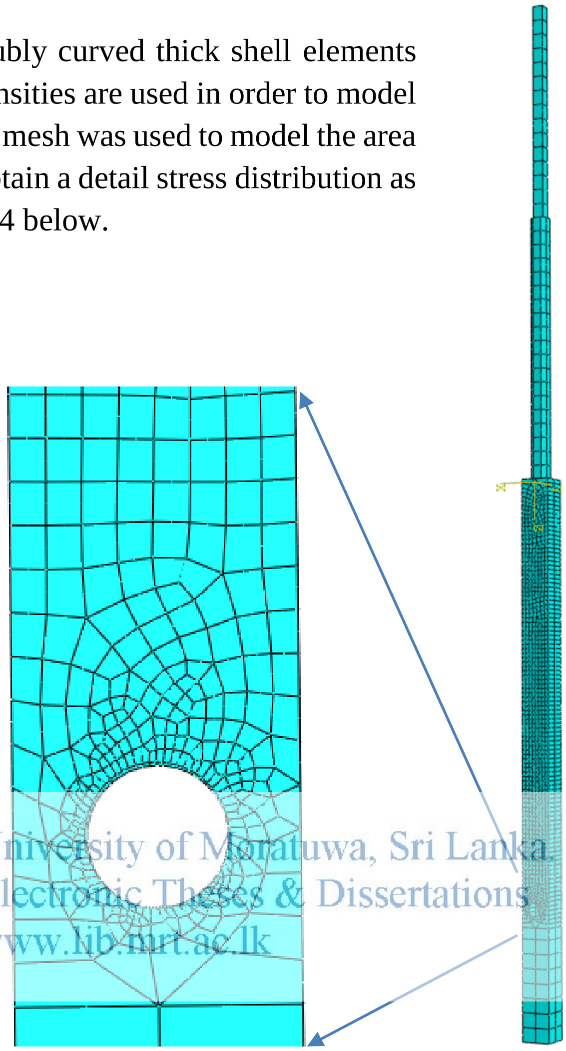


Figure 5.4: Finite element mesh of the mast

5.4 Fatigue analysis

Elastic fatigue analysis can be performed because all stresses are within elastic range. Therefore loading can be changed as desired in the fe-safe software itself unlike in elasto-plastic analysis.

The surface finish of the steel plates are assumed as fine machined (4< Ra< 16) with no residual stresses. BS 4360 G50A inbuilt material which is equivalent to S355 material has been chosen as material properties for analysis.

The fatigue analysis is done using brown miller equation with morrow’s mean stress correlation.

5.5 Results and Discussion

In order to evaluate the sensitivity for opening shape, two shapes of openings (circular and square) of same area are compared. The diameter of the circular opening is 1m whereas the side length of the square opening is 0.89m.

In order to evaluate the sensitivity for thickness around the opening, two thicknesses 30mm and 40 mm were compared.

The design wind induced stress distributions are shown below.

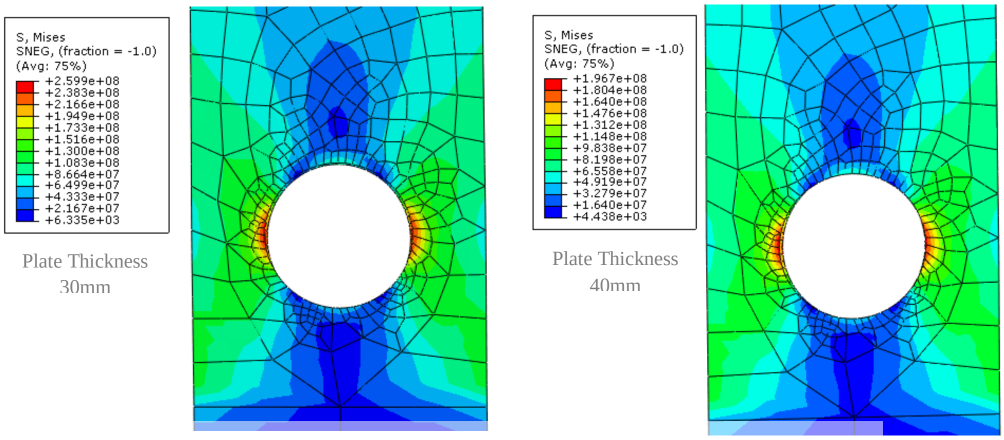


Figure 5.5: Stress distribution around the circular opening

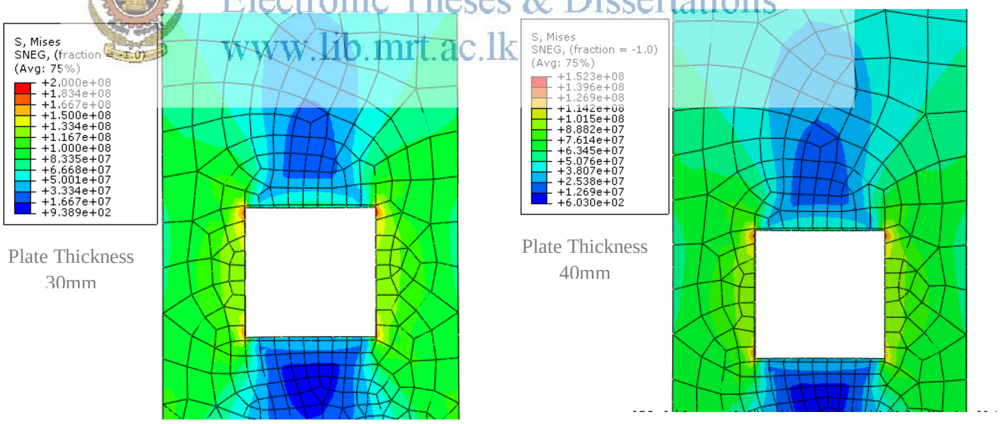


Figure 5.6: Stress distribution around the square opening

The results indicate that there are higher stresses around the circular opening (figure 5.5) than in the square opening (figure 5.6) of same area with same plate thickness. Although corners of square openings create higher stress concentrations, the bending stress increase due to larger opening dimension in the centre level of circular opening has predominated.

Around the circular opening, lowest stresses are noticed at the top and the bottom edges while highest stress concentrations are at the side edges.

Around the square opening, lowest stresses are noticed along top and the bottom edges while highest stress concentrations are along the side edges near the corners.

When the plate thickness is reduced by 25% the maximum stress levels around the opening is also reduced by nearly same value (24%) in both shapes. Adding a stiffener with higher thickness around the opening will create same effect. It will reduce the stress level by the same percentage as the thickness increase given that the stresses are within the elastic range.

The results of the fatigue analysis are shown here.

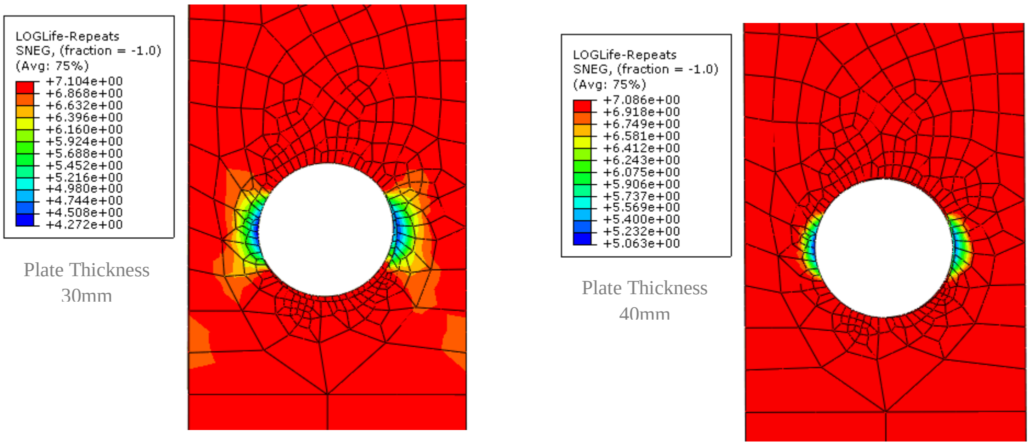


Plate Thickness 30mm

Plate Thickness 40mm

Figure 5.7: Distribution of number of reversals to failure around the circular opening

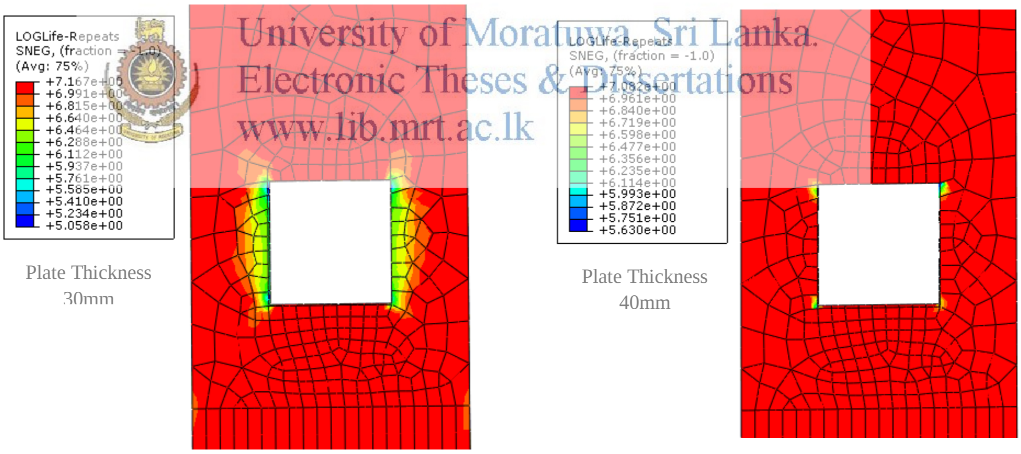


Plate Thickness 30mm

Plate Thickness 40mm

Figure 5.8: Distribution of number of reversals to failure around the square opening

Table 5.2: Minimum number of reversals to failure for combinations considered

No of reversals to failure($2N_f$)	Thickness 30mm	Thickness 40mm
Circular opening	18,367	113,161
Rectangular opening	60,051	426,693

The fatigue analysis results indicate highest stress concentrated areas (figure 5.5 & figure 5.7) having lowest endurance (figure 5.7 & figure 5.8). This is clear by the fact that the plate used is of same properties everywhere around the opening.

Although the maximum stress around the opening is reduced by the same percentage (33%) as the plate thickness increased, the endurance has increased by around 500-600% in both of the opening shapes (table 5.2). This indicates the importance of adopting stiffeners in the areas with stress concentrations such as openings corners etc.

The endurance in the square opening is almost 230-270% higher than in the circular opening for both thicknesses (table 5.2). This indicate the importance of choosing a proper shape for openings of steel structures which are subjected to dynamic vibrations. If the corners of the rectangular opening are smoothed more endurance can be expected.

By considering all above aspects we can assume that the fatigue life of the opening can be improved by adopting a rectangular opening with minimum dimension across horizontal direction with smooth corners and stiffeners along the edges.

6 CONCLUSION

The simulations done to verify uniaxial fatigue and multi-axial fatigue gave successful results which are closer to experimental results. This shows the fatigue simulation technique used is acceptable.

Moreover uni-axial fatigue sensitivity analysis indicated that surface finish is a highly sensitive parameter. The surface finish of a same material is varying depending on the machining or moulding method. Hence the surface finish of the exact material to be used in the site should be measured before simulations. Comparison of the results of the dataset importing methods indicated that elastic block method gives poor results. Although elastic plastic dataset importing method requires finite element simulations for each and every strain amplitude, it gives closer results to the experiment results. The endurance of multi-axial fatigue simulation is closer to the average of the experimental endurance values. Hence the techniques used can be expected to give acceptable results for both uni axial and multi axial fatigue.

The case study done on the steel mast shows highest stress concentrations around the opening. It was found that for same opening area, rectangular shape induce less stress than circular shape. This shows that the effect of larger horizontal opening dimension at the centre level in circular opening is more significant than the stress concentration induced at the corners of square opening. Hence a rectangular opening shape with least possible dimension in the horizontal direction would give the highest endurance. The plate thickness comparison showed that even a small increase in the plate thickness rapidly increases the endurance of the mast. This indicates the importance of using stiffeners in the areas prone to fatigue damage. The highest stresses in this mast are seen near the edges of the opening hence stiffeners with higher plate thickness along the edge of the opening is recommended. Altogether rectangular shape with least possible dimension in horizontal direction with stiffeners along the edges will enhance the fatigue life of the mast. Smoothening the corners of the opening will also enhance the fatigue life. However it should be noted that only monolithic sections are considered in this study and the effects of welds and bolted connections were ignored.

7 RECOMMENDATIONS FOR FUTURE RESEACH

In this study, the fatigue life of the mast was checked only for one wind speed which is the 1 in 500 year return period wind for which the tower is designed to withstand. But there will be different wind speeds and they will induced different cyclic stress amplitudes. These will also make contributions to the fatigue life. Hence fatigue life at different wind speeds should be found and they should be combined using the miners rule to find out the fatigue design life (in years) of the structure. This require the wind data distributions for 300m level at the mast location. Estimation of fatigue life in years will help the designer optimize the plate thickness and opening shape.

This study is focused on the fatigue life induced by the plate because of the hole. But there are more fatigue inducing details such as connections. These connections are often the main stress concentrations and they are highly vulnerable to fatigue damage. Hence it is recommended to simulate fatigue for the connections as well. Fatigue analysis of welds can be done using the verity feature given in the fe-safe software. Fatigue analysis of bolts will require very fine details. Hence it is recommended to use sub-modelling tool which is available in Abaqus software. It will enhance the computational efficiency.

The fatigue analysis for case study has been performed for wind induced fatigue. The earthquakes which are recently seen in Nepal and the nearby area of Sri Lanka indicate that there Sri Lanka has some probability of earthquakes. Hence the mast should be designed for earthquake induced fatigue as well.

There are many tall steel structures and large span steel bridges in Sri Lanka. Fatigue simulations have not been done for them yet. Hence performing fatigue simulations for those existing structures will help improve the safety of Sri Lankan citizens.

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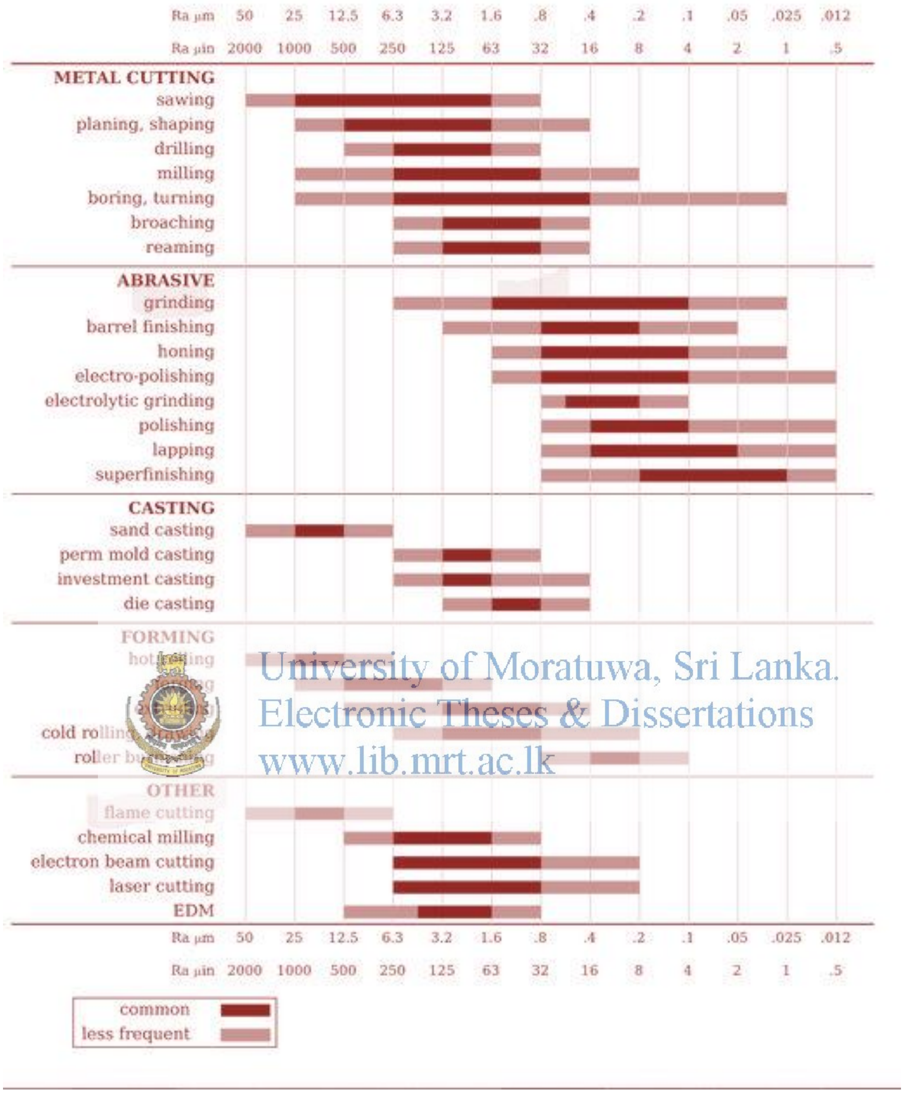
APPENDIX

APPENDIX 1: Surface roughness values for different materials



Source (Kalpakjian, 6th edition)

APPENDIX 2: Wind Load calculation for the mast

The dynamic analysis procedure set out in the AS 1170.2 -1989 enables the determination of wind forces on the overall structure. The wind force calculation is as follows.

7.1.1.1 Wind load calculation

Design hourly mean wind speed
$V_z = V M_{(\mathrm{z,cat})} M_{\mathrm{s}} M_{\mathrm{t}} M_{\mathrm{i}}$

For the site of the project (at 325m: mid height of the mast),

- Basic wind speed, V

V= 38.00m/s
(Post disaster speed for Sri Lanka Zone III (Wijeratne & Jayasinghe, 1998))

- Hourly mean wind speed multiplier, $M_{(\mathrm{z,cat})}$

Terrain category = Category 1
(Exposed open terrain with few or no obstructions)

$M_{(\mathrm{z,cat})} = 1.07$

- Shielding multiplier, M_{s}

$M_{\mathrm{s}} = 1.00$
(Without shielding)

- Topographic multiplier, M_{t}

$M_{\mathrm{t}} = 1.00$
(Up wind slope is less than 0.05)

- Structure importance multiplier, M_{i}

$M_{\mathrm{i}} = 1.1$
(Structure which have special post disaster function)

$V_z = 38 \times 1.07 \times 1.00 \times 1.00 \times 1.1$
$V_z = 44.7\,\mathrm{m/s}$

Dynamic wind pressure, q_z

$$q_z = 0.6V_z^2$$

$$q_z = 0.6 \times 44.7^2$$

$$q_z = 1.2 \text{ kN/m}^2$$

Hourly mean drag force, F_d acting at z = 325m

$$F_d = C_d q_z A_z$$

Drag coefficient, C_d

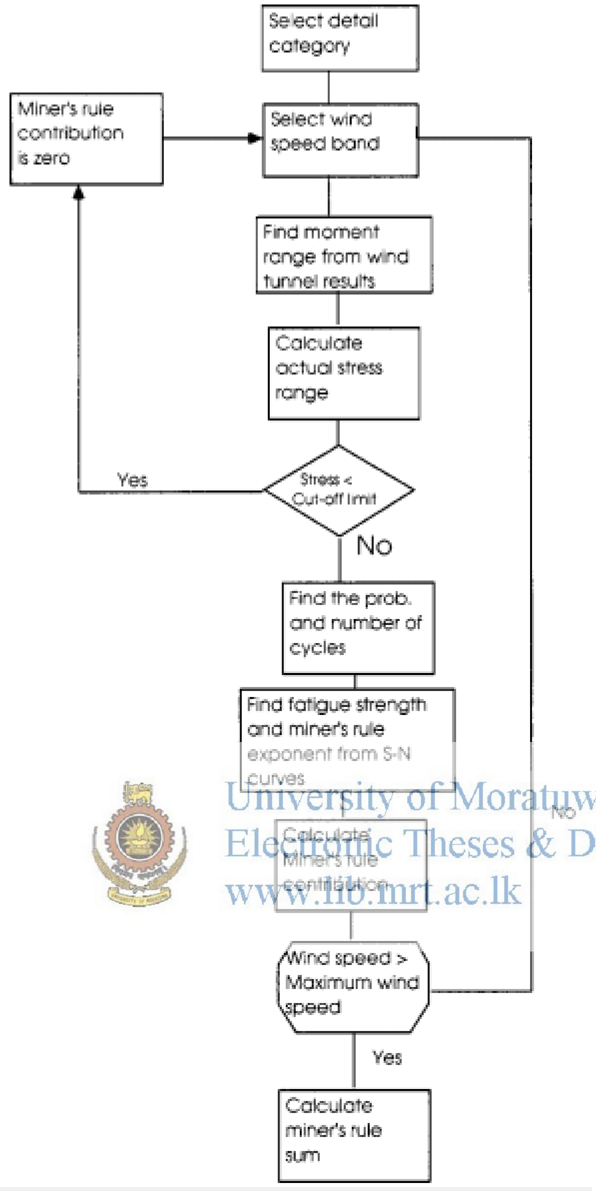
$$C_d = 2.2$$

Drag force per area = 2.2×1.2

= 2.6 kN/m^2

Wind force was applied on the structure as an area load.

APPENDIX 3: Fatigue design methodology used in AS4100:1990



Source: (Mendis & Dean, 2000)