WIND-STRUCTURE INTERACTION ON TRANSMISSION TOWER

FATIN HANANI BINTI FAUZI

CIVIL ENGINEERING
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By

FATIN HANANI BINTI PAUZI

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Universiti Teknologi Petronas
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
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Approved:

AP Ir. Dr. Mohd. Shahir Liew
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Fatin Hanani binti Pauzi

ABSTRACT

Electrical transmission line is a medium to carry power loads from one station to another station, therefore; it is one of the most important projects in power business. To maintain the reliability and safety of the structure, the dynamic and static load acting on transmission structure should be thoroughly studied before an efficient design may be obtained. High standard of design to cater effect of wind load must be implemented to preclude any structural failure which will interrupt the national grid supply of power. The main objective of this study is to identify the behavior of electrical transmission tower due to lateral wind forces. In addition, this study aims to evaluate current design practice adopted by Tenaga Nasional Berhad (TNB) on its adequacy and in optimization of their design. The study begins with comprehensive research and literature review on behavior of transmission tower and conductor under wind loads. A 132kV electrical transmission tower is identified for the purpose of analysis. The calculation of design wind loads are in accordance with American Society of Civil Engineers (ASCE) 7-05 *Minimum Design Loads for Building and Other Structures*. The electrical transmission tower is assumed located at mountainous area with a wind speed of 38 m/s and assessed as a global structure under normal situation as well as under broken conductor situation. As the outcome of the analysis, a design assessment of the transmission tower is provided. Subsequently, the reliability of TNB current practice of design and the design adequacy is evaluated.

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INTRODUCTION

1.1 Background of Study

The electric power industries in Malaysia have been developing power transmission system to cater for rapid growth of the power demand. Tenaga Nasional Berhad (TNB) is the entity that is responsible to supply electricity to its customers mainly publics in Peninsular Malaysia with the least disruption to the system. Transmission line is a medium to carry power loads from one station to another station; therefore it is one of the most important projects in power business. Any interruption in transmission line system would affect the country's economic growth.

Power transmission lines in TNB grid system span from densely populated metropolitan areas to isolated country-side far from the nearest civilization across country in Malaysia. High voltage power transmission lines transmit electricity from hydro or thermal generating stations to consumers of electricity via conductors supported on steel tower structures and concrete foundation. In Malaysia, transmission towers are either of the lattice steel configuration comprising of angles and plates with bolted connections or single tubular poles housed vertically with arched tubular arms welded to the attachments on the tower main body.

TNB grid is comprised of a backbone of 275kV loop linking generating stations in all corners of the country. A 500kV power line supports the high load centers on the western coast of Peninsular Malaysia. For electrification of suburban and isolated areas, spur lines of 132kV are provided.

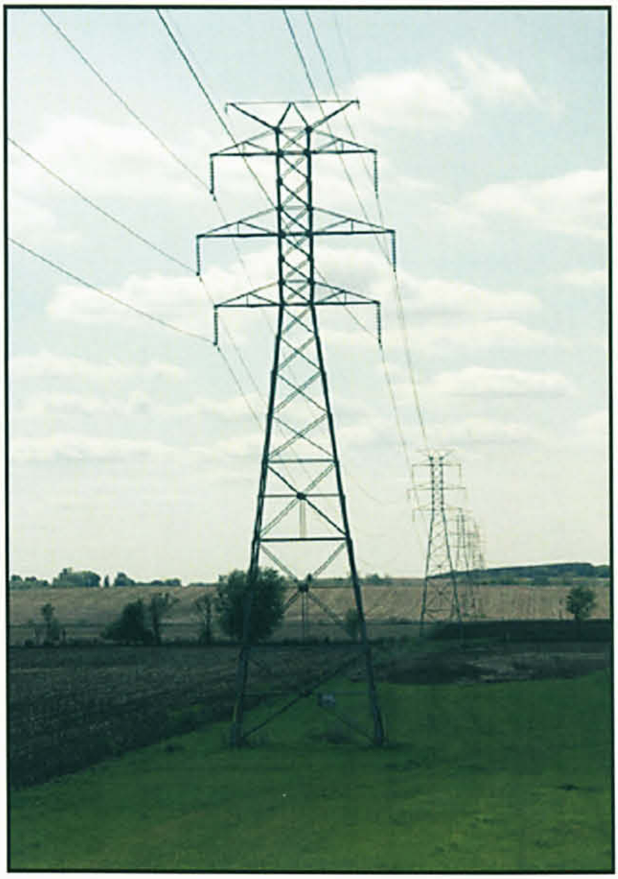


Figure 1: Transmission towers located at isolated area

Transmission towers and their associated foundations are designed to withstand the forces resulting from wind blowing on the faces of tower steelwork and conductors, the angle pull resulting from its position on the alignment of the line route, weight of conductors and accessories, loading condition during breakage of some specified numbers of conductors and loading condition during installation.

1.2 Problem Statement

In order to maintain a balance between demand and supply at all times, it is essential for transmission towers and conductors to function continuously, consistently, and uninterrupted. The structural reliability and the integrity of transmission towers and conductors play an important role to provide a safe, reliable, and economical operation of the grid system. Therefore, a high standard for design must be implemented to prevent any structural failure even when the structure is subjected to severe loading conditions.

The design of the transmission towers is highly sensitive to geographical topography and location of the transmission tower. The transmission towers and conductors may be located in the remote area or may be located in the metropolitan area. Different location may lead to a different field condition.

Two analytical methods may be employed to restrain the hazards faced by transmission tower structures under actual field conditions. First, a conservative design using standard design guidelines. The second approach is a proper in-depth study of the behavior of the transmission towers and conductors under various loading conditions. The second method is more reliable since it considers the behavior of the transmission tower under static and dynamic loads, while the first method may facilitates a design which may be overly conservative.

Before an efficient design may be obtained, the designer must thoroughly studied and fully understood the effect of dynamic loadings on transmission towers and conductors since the structures are more sensitive to dynamic loads than to static loads.

Wind loads on structures are characterized as dynamic loads, hence it is important to design a transmission structures to resist wind loads. Wind loads acting on a transmission tower in two ways; act directly on the transmission tower and act on the conductor. The wind loads act on the conductor will be transmitted to the transmission tower, thus this case is more severe than the wind loads acting on tower itself.

1.3 Objectives

The objectives of the study are as follows:

- To study wind-structure interaction of a high voltage electrical transmission tower.
- To survey on the existing typical design standard of high voltage electrical transmission tower.
- To identify the secondary effects of wind loads.
- To benchmark and recommend best practices in the design method.
- To evaluate current methodology of designing high voltage electrical transmission tower in Malaysia.

1.4 Scope of Study

The scope of this study is confined to:

- Focus only on wind-structure interaction of latticed steel high voltage electrical transmission tower.
- Calculation of load shall be in accordance with the latest ASCE 7-05 Minimum Design Loads for Buildings and Other Structures as the code of practice.
- Analysis is done on dynamic effect of wind forces for 132kV HVAC transmission tower.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Electric energy is transmitted from one substation to another through overhead transmission lines. Overhead transmission lines play an important role in the operation of a reliable electrical grid power system. In Malaysia, these transmission lines operate at voltages of 500kV, 275kV and 132kV with different dimensions of steel transmission tower. A typical transmission lines consist of foundations for the transmission towers, lattice steel transmission towers, insulators and overhead electric conductors. Transmission line systems are considered as slender structure from the definition of the code and, therefore, they are wind sensitive because the natural frequency of vibration is less than 1 Hertz. The responses of structures to wind loads may involve a wide range of structural actions including resultant forces, bending moments, cable tensions, as well as deflections and accelerations [1].

In the field of transmission line structural design, the Electric Power Research Institute (EPRI) has sponsored research studies directed towards the implementation of new safety concepts for the design of transmission line structures (e.g. Criswell and Vanderbilt, 1987). Parallel research and development efforts in this field have also been undertaken by the ASCE Task Committee on Structural Loadings (Task Committee on Structural Loadings, 1991) and the IEC Technical Committee 11 (IEC, 1991). Currently, many electrical power suppliers worldwide have benchmarked their design standards against EPRI. In addition, EPRI is associating closely with ASCE on the structural loadings related to transmission line tower.

2.2 Tower Failures Due To Wind Load

Wind loading is one of the important considerations in the design of transmission tower. Many cases of transmission tower failures are due to extreme wind conditions. Investigation of transmission tower failures in the Americas, Australia, South Africa, and many other utility organizations has reported that more than 80% of the majority of all weather related line failures were the results of high intensity winds (HIW), ranging from fully mature tornadoes to various forms of downbursts and microburst that are associated with the occurrence of thunderstorms [2].

Electrical transmission towers are a vital component to the national power grid network, thus the reliability and safety of these towers are essential to minimize the risk of in-service tower failure that may led to disruption of power supply causing large monetary losses to business. Therefore, the dynamic and static load acting on transmission structure should be thoroughly studied before an efficient design may be obtained.

Records of transmission tower failures have encouraged enhancements in design and analysis of transmission tower. However, to date most retrofitting practices for transmission towers have employed only static approaches such as increasing member section area or shortening effective member length by additional members [3].

Although tower loads especially wind loads have lots of dynamic component, there are lack of dynamic assessments in current design practice. The two reasons that lead to this deficiency are the comparative difficulty of dynamic analysis and the extremely high cost of dynamic field testing.

Existing studies on retrofitting transmission towers are given as follows. One of the retrofitting methods proposed by Albermani et al. [4] is to strengthen existing towers by adding diaphragm and constraining the out-of-plane deformation of each face of transmission tower, and verified the performance both experimentally and numerically.

Battista et al. studied dynamic behavior of transmission tower under action of wind and installed non-linear pendulum-like dampers (NLPD) to reduce dynamic response of the transmission tower [5]. J. –H. Park et al. [6] in his journal wrote that for wind loads with a lot of dynamic components, enhancing energy dissipation capacity by incorporating a static retrofit could improve wind-resistant performance of the transmission tower effectively through the suppression of dynamic response amplification.

2.3 Wind Load Theory

Purushothaman Nair (2006) is very definite: "Wind or the movement of air near the surface of the earth is caused fundamentally by variable solar heating of the atmosphere. The wind velocity at any point exhibits both short and long period varies with time. The short period wind is resulted from wind flow turbulence, while the long period wind is due to large storm systems or seasonal climatic events. At any given time, the wind velocity field also exhibits complex spatial variations."

A wind load is dynamic in nature because wind pressure, direction, and duration of wind are constantly changing. Wind loads vary around the world. Meteorological data collected by national weather services are one of the most reliable sources of wind data. Figure 2 shows the basic wind speed of several locations within Peninsular Malaysia.

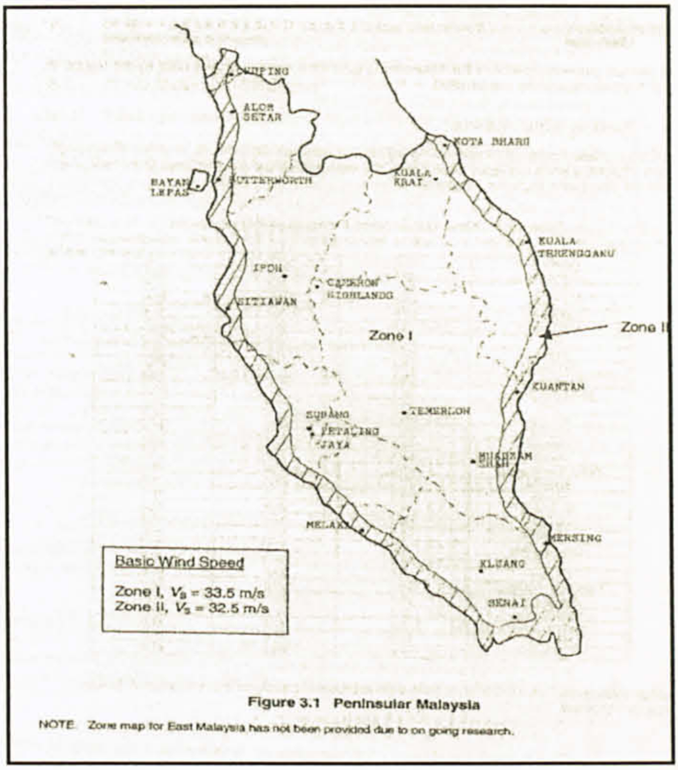


Figure 2: Basic wind speed of Peninsular Malaysia

2.3.1 Wind Load on Conductors

Transmission line conductors are long, flexible, and wind sensitive structures. The conductors are continuously exposed to the forces of wind. The wind loads act on the conductors will be transmitted to the supporting transmission tower. These loads are more than the loads due to the wind acting directly on the tower itself. Hence, it is essential to have an accurate and reliable prediction of wind loads that are transferred from conductors to the towers.

Wind loads on conductor with spans of around 300 m account for 60 to 80% of the total wind load effect on the support tower structure. The wind force is usually assumed to be acting horizontally, i.e. along-wind and across-wind. However, depending on local terrain, wind forces acting in oblique angle must be considered. Also, different wind directionality must be taken into account for the conductors as well as for the tower itself.

The maximum wind velocity does not occur simultaneously along the entire span and reduction coefficients are, therefore, introduced in the calculation of the load transferred to the towers. The major part of the loads on electrical transmission tower arises from the conductor. The dead load from the conductors is calculated by using the so-called weight span (*see Figure 3*).

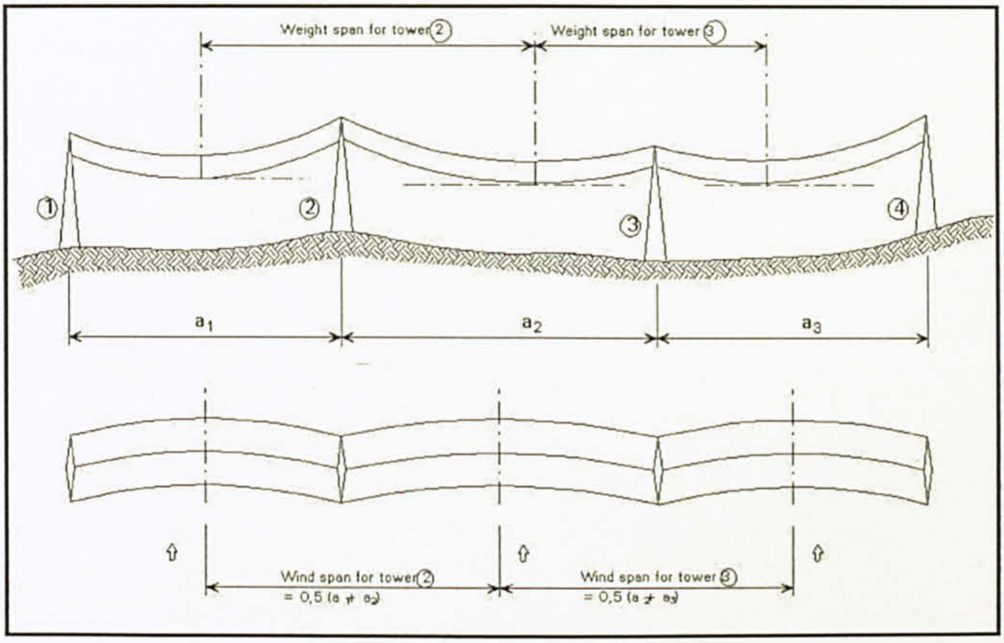


Figure 3: Weight span and wind span

Weight span may be different from the wind span used in connection with the wind load calculation. The average span length is usually chosen between 300 and 450 meters. The wind span is simply half the back span length plus half the forefront span length while the weight span is the distance between the low point in the back span and the low point at the forefront span.

2.3.2 Secondary Effect of Wind Load

Other phenomenon related to secondary responses of the conductors which is beyond the scope of this report includes the following:

i. ***Vortex shedding*** is an unsteady flow that takes place in special flow velocities (according to the size and shape of the cylindrical body). In this flow, vortices are created at the back of the body and detach periodically from either side of the body. Vortex shedding is caused when a fluid flows past a blunt object. The fluid flow past the object creates alternating low-pressure vortices on the downstream side of the object (see Figure 4). The object will tend to move toward the low-pressure zone.

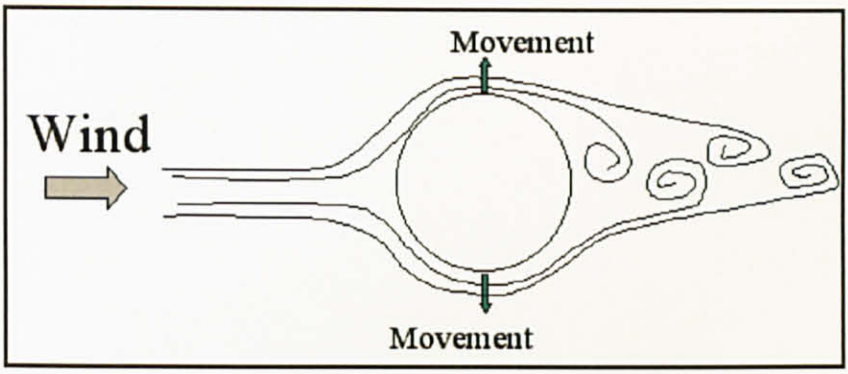


Figure 4: Vortex shedding behind a circular cylinder

Vortex-induced oscillations generated by vortex shedding are very common in high-voltage overhead transmission lines. The vortex-induced oscillations generally caused by winds with speeds of 2 to 10 m/s. Although such vibrations are barely perceptible due to their low amplitudes (less than a conductor diameter), they are, however, extremely important since they may lead to conductor fatigue.

ii. ***Galloping*** (or dancing) is a dynamic condition that occasionally occurs in transmission line ground wires and conductors. Galloping generally occurs with a moderate wind. The wires move at amplitudes ranging from a few feet to more than the full sag. Spacing of phase conductors may sometimes be dictated.

    Galloping may cause one or a combination of the following: (a) flashover or direct contact between phases or between phase and ground wire, resulting in line outages and possible conductor damage; (b) excessive conductor sag due to inelastic stressing; (c) failure or wear damage of the ground wire or conductor support hardware; and (d) failure in the supporting structure.

iii. ***Fluttering*** is distinguished from gallops by its high-frequency (10 Hz), low-amplitude motion. To control flutter, transmission lines may be fitted with tuned mass dampers (known as Stockbridge dampers) clamped to the wires in close proximity to the towers [7] [8]. The use of bundle conductor spacers can also be of benefit [9].

2.4 Steel Lattice Transmission Tower Theory

A transmission tower has, in general, three duties to perform [10]:

1. It must have strength to resist wind pressure on its various members.
2. It must have strength to withstand certain external loads due to cables, guys, etc.
3. It must have strength to sustain its own weight.

The lattice tower is made up of a basic body, body extension, and leg extensions. The basic body is used for all the towers regardless of the height. Body and leg extensions are added to the basic body to achieve the desired tower height.

For transmission lines with 100kV voltage or more, the use of steel lattice structure is nearly always found advantageous because they are:

- Easily adaptable to any shape or height of tower.
- Easily divisible in sections suitable for transport and erection
- Easy to repair, strengthen and extend.
- Durable when properly protected against corrosion.

The members of latticed steel electrical transmission tower are generally designed as trusses. The members are generally subjected to tension or compression with minimal bending forces. All other external forces causing the electrical transmission tower to be in torsion will be counteracted by the two force member in the form of tension or compression.

Height of the tower peak above the cross arms is based on shielding considerations for lightning protection. The width of the tower base depends on the slope of the tower leg below waist. The overall structure height is governed by the span length of the conductors between structures.

By far, the most common structure is a four-legged tower body cantilevering from the foundation. Figure 5 shows a typical four-legged tower. The advantages of this design are:

- The tower occupies a relatively small area at ground level.
- Two legs share the compression from both transverse and longitudinal loads.
- The square or rectangular cross-section (four legs) is superior to a triangular tower body (three legs) for resisting torsion.
- The cross-section is very suitable for the use of angles, as the connections can be made very simple.

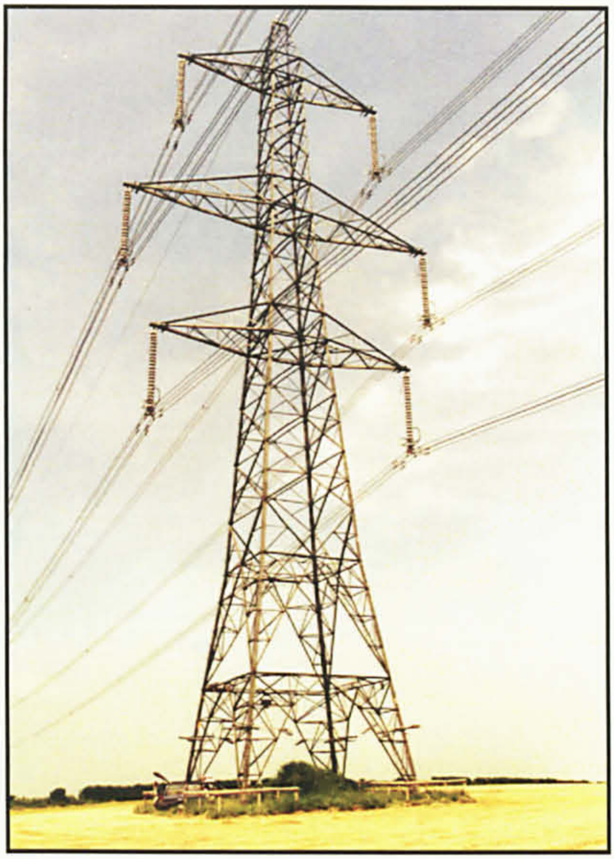


Figure 5: A 4-legged lattice electrical transmission tower

2.4.1 Analysis of Steel Lattice Transmission Tower

A lattice tower is analyzed as a space truss. Each member of the tower is assumed pin-connected at its joints carrying only axial load and no moment. The structural analysis is carried out on the basis of a few rough assumptions:

- The tower structure behaves as a self-contained structure without support from any of the conductors.
- The tower is designed for static or quasi-static loads only.

In a simplified calculation, a four-legged cantilevered structure is often assumed to take the loads as follows:

- Centrally acting, vertical loads are equally distributed between the four legs.
- Bending moments in one of the main directions produce an equal tension in the two legs of the other side. The shear forces are resisted by the horizontal component of the leg forces and the brace forces.
- Torsional moments mostly produce shear forces in the tower body faces, i.e. in the braces.

These assumptions do not reflect the real behavior of the total system, i.e. towers and conductors, particularly well. However, they provide a basis from simple calculations which have broadly led to satisfactory results.

CHAPTER 3
METHODOLOGY

3.1 Introduction

The methodology to conduct this study can be divided into three phases including literature review, analysis of 132kV transmission tower and evaluation on current practice. Each of the methodology used is described in details.

3.2 Literature Review

The study was initiated with comprehensive research and literature review to get detailed understanding of transmission structure and response of the transmission tower due to wind loads. Literature search on the subject was carried out on published books and articles from journals and research papers. The literature includes the cases of tower failures due to wind, method of retrofitting, and wind loads theory. Apart from that, in depth research has been made on common configurations of towers along transmission line, the loads acting on transmission structure, the design of steel lattice tower, and the design standards and codes of practices as well.

3.3 Analysis of a 132kV Transmission Tower

The author had identified a four-legged 132kV lattice transmission tower for the purpose of analysis, which is a common type of tower configuration in TNB grid system within Peninsular Malaysia. The static design parameters, truss and conductor configurations, and conductor loads are identified from TNB Design Standard.

Based on survey of codes of practices which includes American Society of Civil Engineers (ASCE) and British Standard (BS), the author decided to focus only on ASCE 7-05. From the code, the dynamic effect of wind acting on transmission tower is identified. The code from ASCE 7-05 provides 3 methods of analysis which are Simplified Procedure, Analytical Procedure, and Wind Tunnel Procedure.

3.3.1 American Society of Civil Engineers, ASCE (7-05)

According to ASCE, the design wind loads for buildings and other structures shall be determined according to one of the following procedures:

1. Method 1 – Simplified procedure for low-rise simple diaphragm buildings
2. Method 2 – Analytical procedure for regular shaped building and structures
3. Method 3 – Wind tunnel procedure for geometrically complex buildings and structure

Nevertheless, only **Method 2 – Analytical Procedure** is used in this report. Wind loads for buildings and structures that do not satisfy the conditions for using the simplified procedure can be calculated using the analytical procedure provided that it is a regular shaped building or structure, and it does not have response characteristics making it subject to across-wind loading, vortex shedding, instability due to galloping or flutter, or does not have a site location that require special consideration.

The step of analytical procedure, describe in ASCE 7 Section 6.5.3, are as follows:

1. Determine the **basic wind speed, V**, and **wind directionality factor, K_d** in accordance with ASCE 7 Section 6.5.4.

2. Determine the **importance factor, I**, in accordance with ASCE Section 6.5.5.

3. Determine the **exposure category** or **exposure categories** and **velocity pressure exposure coefficient, K_z or K_h**, as applicable, for each wind direction according to ASCE 7 Section 6.5.6.

4. Determine the **topographic factor, K_{zt}**, if applicable, according to ASCE 7 Section 6.5.7.

5. Determine the **gust effect factor G or G_f**, as applicable, in accordance with ASCE 7 Section 6.5.8.

6. Determine the **enclosure classification** in accordance with Section 6.5.9.

7. Determine the **external pressure coefficient, C_p or GC_{pf}**, or **force coefficients, C_f**, as applicable, in accordance with ASCE 7 Section 6.5.11.2 or 6.5.11.3.

8. Determine the **velocity pressure, q_z or q_h**, as applicable, in accordance with ASCE 7 Section 6.5.10. The velocity pressure, q_z evaluated at height z is calculated by the following equation:

$$q_z = 0.613\, K_z\, K_{zt}\, K_d\, V^2\, I \qquad (\text{N/m}^2 \text{ ; V in m/s})$$

9. Determine the **design wind load, F**, in accordance with ASCE 7 Section 6.5.15. The design wind load, F, on open buildings and other structures is determined by the following formula:

$$F = q_z\, G\, C_f\, A_f \qquad (\text{lb})\ (\text{N})$$

where

q_z = velocity pressure evaluated at height z of the centroid area A_f

A_f = projected area normal to the wind (ft^2) (m^2)

$C_f = 4.0\varepsilon^2 + 5.9\varepsilon + 4.0$ for a square cross section

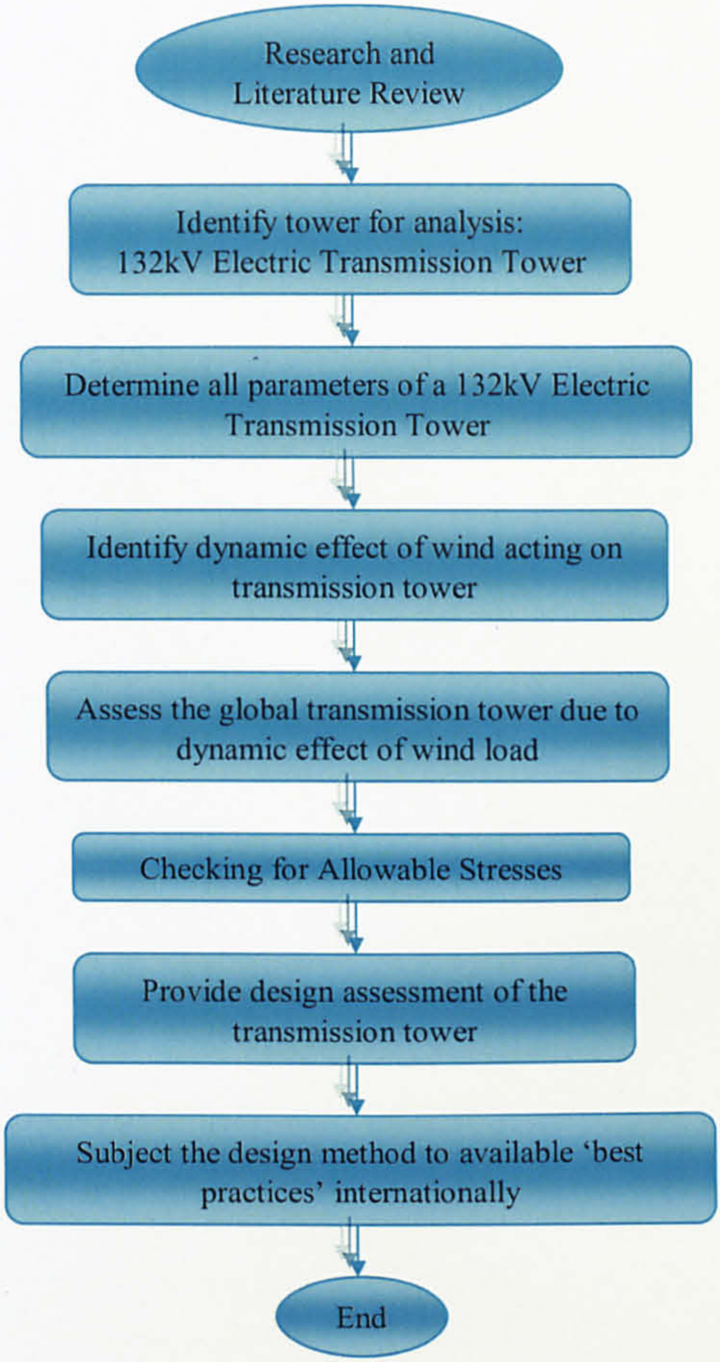
All the design wind load calculations for this study are obtained using the procedure from ASCE 7-05 as above. Wind load is dynamic in nature because wind pressure, direction, and duration are constantly changing with time. Wind loads act on a transmission tower in two ways. First, the wind loads act directly on the transmission tower itself. Second, the wind loads act on the conductor which in turn the loads is transmitted to the transmission tower as well.

The global transmission tower is assessed for overturning moment, due to dynamic effect of wind load. It is assumed that the tower is located at worst site, which is mountainous area with a wind speed of 38 m/s. Allowable stresses on critical members are evaluated for two different condition; normal condition and broken conductor condition. As the outcome of the analysis, a design assessment of the transmission tower is provided.

3.4 Evaluation on Current Practice

Interviews are conducted with focal person at Rohas-Euco Industries to get detail view on their design method. The reliability of their current practice on design and the design adequacy are evaluated. The current design practice adopted in Malaysia is to apply very much conservative loads and then design the transmission tower as lattice structure. Based on the result obtained, the author compared the estimated factor of safety with Rohas-Euco design factor of safety. At the end of the study, the design method is subjected to available best practice internationally.

3.5 Project Activities



CHAPTER 4
RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the analysis on a four-legged 132kV lattice transmission tower. The tower is analyzed as a global structure and assumed to be located at a mountainous outskirt area with a dominant wind speed of 38 m/s. Each member of the tower is assumed pin-connected at its joints carrying only axial load and no moment. The tower dimension, conductor parameter, and wind load calculation required in the analysis are attached in Appendix I. Calculation of wind loads are based on ASCE 7-05.

4.2 Allowable Stresses

The primary members of a tower are the legs and the bracing members. Tower members are designed to carry axial compressive and tensile forces. Allowable stress in compression is usually governed by buckling. As the unbraced length of the member increases, the allowable stress in buckling is reduced. In contrast, allowable stress in a tension member does not depend on the member length. Commonly, in order to reduce their unbraced length and increase their load carrying capacity, secondary or redundant bracing members are used to act as intermediate support to the primary members.

Allowable stresses for both tensile and compressive stress on the critical member of the four-legged 132kV lattice transmission tower are determined. For the purpose of analysis, the allowable stresses are being calculated on main leg angle since the main leg angle is the critical member which is significant towards the buckling of global structure.

The calculations for allowable stresses are given in Appendix II and the results are summarized in Table 1 and Table 2.

Table 1: Under combined dead load and wind load

Critical Member	Max Tensile Stress	Allowable Tensile Stress	Estimated Factor of Safety	Rohas-Euco Design FoS
Main Leg Angle	53.23 MPa	156.0 MPa	2.93	2.8
Critical Member	Max Compressive Stress	Allowable Compressive Stress	Estimated Factor of Safety	Rohas-Euco Design FoS
Main Leg Angle	53.23 MPa	253.54 MPa	4.76	4.5

Table 2: Under breakage of conductor load

Critical Member	Max Tensile Stress	Allowable Tensile Stress	Estimated Factor of Safety	Rohas-Euco Design FoS
Main Leg Angle	49.11 MPa	156.0 MPa	3.18	3.0
Critical Member	Max Compressive Stress	Allowable Compressive Stress	Estimated Factor of Safety	Rohas-Euco Design FoS
Main Leg Angle	49.11 MPa	253.54 MPa	5.16	4.5

4.3 Design Assessment

A design assessment of the transmission tower is made by comparison between estimated factor of safety and Rohas-Euco design factor of safety. In Malaysia, Rohas-Euco Industries Berhad is the leading contractor and consultant company for designing and fabricating of steel structures for high-tension transmission towers, microwave towers, and substation structures. Their designs are based on several assumptions which could be improved by proper research, thus could reduce divergence of actual parameters with the assumptions. The author made a comparison of the results with Rohas-Euco design in an attempt to verify that the result of this study can be used to represent current methodology of designing high voltage electrical transmission tower in Malaysia.

The assessment is based on two situations. The first situation is under normal condition which is combined dead load and wind load (*refer Table 1*). Table 1 show that both maximum tensile and compressive stress are not exceeding the allowable stresses which lead to an estimated factor of safety of 2.93 and 4.76 respectively.

Considering worst condition, it is assumed for the second situation to be under breakage of conductor load (*refer Table 2*). However, the result proves that under broken conductor circumstances, the maximum tensile and compressive stresses are still below the allowable stresses. The estimated factor of safety for tensile stress and compressive stress are 3.18 and 5.16 correspondingly.

Comparing the estimated and Rohas-Euco design factor of safety for both situations, it can be noticed that the factor of safety values are quite similar with discrepancy of approximately 5% - 15%. Hence it indicates that the results are consistent, thus reliable to be used for the evaluation of current method of design.

4.4 Evaluation of Current Method of Design

The factors of safety adopted in designs have a great effect on the cost of structures which aims to be economical as well as safe and reliable. Based on the results for both conditions, it can be observed that the factors of safety are high indicating lack of proper engineering understanding. Under normal condition, wind load in Malaysia is not critical. The factor of safety can be decrease to around 1.5 to 2.0 by reducing the dimension of the tower members, thus reducing the effective area. Subsequently, the cost of constructing the tower would be decrease as well.

In current situation, commercially, producers of transmission tower cannot compete with producers from India and China due to high factor of safety implemented in design. India and China has proper engineering understanding on the design of transmission tower and they practice certain rules of designing that aspire for optimum design. In India, Rule 76 (1) (a) of the Indian Electrical Rules, 1956, specifies the following factors of safety, to be adopted in the design of steel transmission line towers [8]:

1. under normal conditions: 2.0
2. under broken-wire conditions: 1.5

As stated above, it clearly shows that the rules that have been practicing in India and China illustrated proper design practices compared to current practices used in Malaysia.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

After completing this study, the author concluded that existing method which had been practicing in Malaysia is conservative for the following reasons:

1. Static load of conductor is considered as quasi-static, not actual analytical approach to ascertain the dynamic load.
2. Transmission tower is design as an entity regardless of location and cable span. It is not a proper approach since transmission tower must be design to accommodate design parameters instead of one transmission tower to fit all condition.
3. The factor of safety currently used is too high. It has been indicated by Rohas-Euco that most of their international procurement has been defeated by suppliers and designers from China and India. Thus, China and India are supplying a lighter transmission tower or with lesser factor of safety.
4. Analytical method gives stresses approximately 40-50% lesser than the quasi-static method (assuming cable is of standard practice).

5.2 Recommendation

The author recommends that the design shall be made site-specific by taking into account the actual weather and operating conditions. It is crucial to analyze a tower in various conditions in order to get the optimum design for structural members, thus reducing the cost while maintaining the reliability. The calculation of wind load shall consider the actual projected area rather than industrial standard practice which is quite large from the actual area of the tower. In addition, it is recommended for the wind profile to be transformed into quasi-static load, the loading where inertial effects are negligible. Therefore, a more efficient and a more reliable design are obtained.

As a continuation of this study, the author recommends to further research on improvement of factor of safety and propose on new design methodology that would enhance the actual design of the transmission towers and consequently would benefit the power supply industry.

In urban area, future consideration of using monopole as opposed to lattice transmission tower may result in cost saving but such study on monopole is not available yet. It would be beneficial to carry out a study on monopole tower and provide an evaluation to compare between monopole tower and lattice transmission tower in terms of cost saving and reliability to cater for effect of wind load in urban, sub-urban and country side.

CHAPTER 6
ECONOMIC BENEFITS

The design of a transmission tower is aim to be economical as well as safe and reliable, thus it is concluded in this study that the factor of safety currently employed in Malaysia has to be reduced to around 1.5 to 2.0. The preferred factor of safety can be obtained by reducing the allowable stresses as a result of reducing the dimension of the tower members particularly the critical member which is the main leg angle.

	Current Design	Preferred Design	Variation
Factor of Safety	4.5	2	55.6 %
Area of Main Leg (m^2)	C	0.44 C	
Weight of Steel per area (kg/m^2)	A	A	
Price of Steel (RM Y/kg)	RM Y x C x A	RM Y x 0.44 C x A	
Total Cost	RM YCA	RM 0.44 YCA	

Table 3: Cost Comparison between current design and preferred design

Table 3 above shows that reducing the factor of safety of a design will result in cost saving while maintaining the reliability of the design in terms of total materials needed to fabricate a transmission tower.

Currently, a transmission tower weighs approximately 8 tons based on quasi-static design. If analytical approach is used, the overall weight of a transmission tower shall be approximately 5 tons assuming all connecting details remain the same. At the current price of RM 4500 per ton, the fabricated cost of a transmission tower based on analytical method would have provided a saving of approximately RM 13500 per tower alone.

REFERENCES

[1] A.G. Davenport, *The Response of Slender Structures to Wind*, The Application of Wind Engineering Principles to the Design of Structures, Lausanne, Switzerland, 1987.

[2] D. Dempsey, H. White, *Winds wreak havoc on Lines, Transmission and Distribution World*, Vol. 48(6), June 1996, pp. 32–37.

[3] KEPCO. *Evaluation of the Retrofitting Methods for Transmission Tower Body*, Korean Electrical Power Corporation; 2004.

[4] Albermani F, Kitipornchai S. *Numerical Simulation of Structural Behavior of Transmission Towers*. Thin-Walled Structures 2003; 41: 167–177.

[5] Battista RC, Rodrigues RS, Pfeil MS. *Dynamic Behavior and Stability of Transmission Line Tower under Wind Forces*. Journal of Wind Engineering and Industrial Aerodynamics 2003; 91:1051–67.

[6] J. –H. Park, B. –W. Moon, K. –W. Min, S. –K. Lee, C. –K. Kim., *Cyclic Loading Test of Friction-Type Reinforcing Members Upgrading Wind-Resistant Performance Of Transmission Towers.* Engineering Structures 2007; 29: 3185–3196.

[7] Guile A. & Paterson W., Electrical Power Systems, volume I, Pergamon, 1978, p. 138.

[8] Pansini, Anthony J., Power Transmission and Distribution, Fairmont Press, 2004, pp. 204-205.

[9] McCombe, John; Haigh, F.R., Overhead Line Practice (3rd ed.), Macdonald, 1966, pp. 216–219

[10] D. R. Scholes, *Transmission Line Towers and Economical Spans*, Convention of the American Institute of Electrical Engineers, Niagara Falls, 1907.

Rajesh Shimpi, B. S. E., 1996, *Dynamic Gust Response Factors for Transmission Line Structures*, Master Thesis, Texas Tech University

Radhakrishna R. Kadaba, B.E., M.E., 1988, *Response of Electrical Transmission Line Conductors to Extreme Wind Using Field Data,* PhD Thesis, Texas Tech University

Narayanan Nair, Purushothaman Nair, 2006, *Alternative design of foundations subjected to uplift for transmission line tower,* Master Thesis, Universiti Teknologi Malaysia

Guo-hui Shen, C.S. Cai, P.E., F.ASCE, Bing-nan Sun and Wen-juan Lou, 2010, *Study of dynamic impacts on transmission line systems due to conductor breakage using the finite element method,* Journal of Performance of Constructed Facilities

P. Harikrishna et al., *Analytical and experimental studies on the gust response of a 52 m tall steel lattice tower under wind loading*, Computers and Structures, 1999; 70:149-160.

AP Ir. Dr. Mohd Shahir Liew, 2009, *Wind loads on structures: Dynamic Considerations*, Lecture Notes

Prof. S. R. Satish Kumar and Prof. A.R. Santha Kumar, notes on *Design of Steel Structure,* Chapter 6 and 7

European Steel Design Education Program (ESDEP), *Lattice Tower*, Lecture Notes

Sarah Chao Sun and Joe Yung, *Vibration Damping for Transmission Line Conductors*, Dulhunty Power

Fang, S. Roy, and J. Kramer, *Transmission Structures*, Structural Engineering Handbook

American Society of Civil Engineers, (ASCE) 7-05, *Minimum Design Loads for Buildings and Other Structure*

Electric Power Research Institute (EPRI), *Design Standard*

APPENDICES

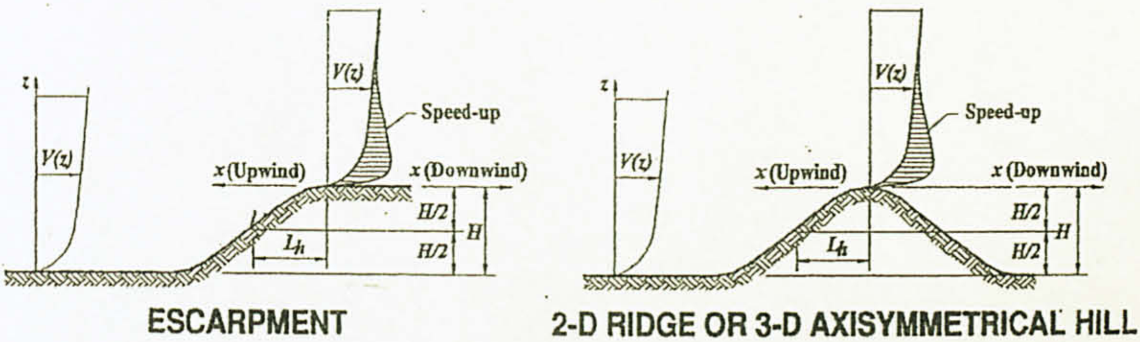
APPENDIX A

ASCE 7-05

Tables extracted from ASCE 7-05:

Topographic Factor, K_{zt} – Method 2

Figure 6-4



Topographic Multipliers for Exposure C										
H/L_h	K_1 Multiplier			x/L_h	K_2 Multiplier		z/L_h	K_3 Multiplier		
	2-D Ridge	2-D Escarp.	3-D Axisym. Hill		2-D Escarp.	All Other Cases		2-D Ridge	2-D Escarp.	3-D Axisym. Hill
0.20	0.29	0.17	0.21	0.00	1.00	1.00	0.00	1.00	1.00	1.00
0.25	0.36	0.21	0.26	0.50	0.88	0.67	0.10	0.74	0.78	0.67
0.30	0.43	0.26	0.32	1.00	0.75	0.33	0.20	0.55	0.61	0.45
0.35	0.51	0.30	0.37	1.50	0.63	0.00	0.30	0.41	0.47	0.30
0.40	0.58	0.34	0.42	2.00	0.50	0.00	0.40	0.30	0.37	0.20
0.45	0.65	0.38	0.47	2.50	0.38	0.00	0.50	0.22	0.29	0.14
0.50	0.72	0.43	0.53	3.00	0.25	0.00	0.60	0.17	0.22	0.09
				3.50	0.13	0.00	0.70	0.12	0.17	0.06
				4.00	0.00	0.00	0.80	0.09	0.14	0.04
							0.90	0.07	0.11	0.03
							1.00	0.05	0.08	0.02
							1.50	0.01	0.02	0.00
							2.00	0.00	0.00	0.00

Notes:

1. For values of H/L_h, x/L_h and z/L_h other than those shown, linear interpolation is permitted.
2. For $H/L_h > 0.5$, assume $H/L_h = 0.5$ for evaluating K_1 and substitute 2H for L_h for evaluating K_2 and K_3.
3. Multipliers are based on the assumption that wind approaches the hill or escarpment along the direction of maximum slope.
4. Notation:

H: Height of hill or escarpment relative to the upwind terrain, in feet (meters).
L_h: Distance upwind of crest to where the difference in ground elevation is half the height of hill or escarpment, in feet (meters).
K_1: Factor to account for shape of topographic feature and maximum speed-up effect.
K_2: Factor to account for reduction in speed-up with distance upwind or downwind of crest.
K_3: Factor to account for reduction in speed-up with height above local terrain.
x: Distance (upwind or downwind) from the crest to the building site, in feet (meters).
z: Height above local ground level, in feet (meters).
μ: Horizontal attenuation factor.
γ: Height attenuation factor.

Topographic Factor, K_{zt} – Method 2

Figure 6-4 (cont'd)

Equations:

$$K_{zt} = (1 + K_1 K_2 K_3)^2$$

K_1 determined from table below

$$K_2 = (1 - \frac{|x|}{\mu L_h})$$

$$K_3 = e^{-\gamma z / L_h}$$

Parameters for Speed-Up Over Hills and Escarpments						
Hill Shape	**$K_1/(H/L_h)$**			**γ**	**μ**	
	Exposure				**Upwind of Crest**	**Downwind of Crest**
	B	**C**	**D**			
2-dimensional ridges (or valleys with negative H in $K_1/(H/L_h)$)	1.30	1.45	1.55	3	1.5	1.5
2-dimensional escarpments	0.75	0.85	0.95	2.5	1.5	4
3-dimensional axisym. hill	0.95	1.05	1.15	4	1.5	1.5

Other Structures – Method 2		All Heights
Figure 6-23	Force Coefficients, C_f	Trussed Towers
Open Structures		

Tower Cross Section	C_f
Square	$4.0\in^2 - 5.9\in + 4.0$
Triangle	$3.4\in^2 - 4.7\in + 3.4$

Notes:

1. For all wind directions considered, the area A_f consistent with the specified force coefficients shall be the solid area of a tower face projected on the plane of that face for the tower segment under consideration.
2. The specified force coefficients are for towers with structural angles or similar flat-sided members.
3. For towers containing rounded members, it is acceptable to multiply the specified force coefficients by the following factor when determining wind forces on such members:

   $0.51\in^2 + 0.57$, but not > 1.0
4. Wind forces shall be applied in the directions resulting in maximum member forces and reactions. For towers with square cross-sections, wind forces shall be multiplied by the following factor when the wind is directed along a tower diagonal:

   $1 + 0.75\in$, but not > 1.2
5. Wind forces on tower appurtenances such as ladders, conduits, lights, elevators, etc., shall be calculated using appropriate force coefficients for these elements.
6. Loads due to ice accretion as described in Section 11 shall be accounted for.
7. Notation:

   $\in$: ratio of solid area to gross area of one tower face for the segment under consideration.

Importance Factor, I (Wind Loads)

Table 6-1

Category	Non-Hurricane Prone Regions and Hurricane Prone Regions with V = 85-100 mph and Alaska	Hurricane Prone Regions with V > 100 mph
I	0.87	0.77
II	1.00	1.00
III	1.15	1.15
IV	1.15	1.15

Note:

1. The building and structure classification categories are listed in Table 1-1.

Terrain Exposure Constants

Table 6-2

Exposure	α	z_g (ft)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	ℓ (ft)	$\bar{\epsilon}$	z_{min} (ft)*
B	7.0	1200	1/7	0.84	1/4.0	0.45	0.30	320	1/3.0	30
C	9.5	900	1/9.5	1.00	1/6.5	0.65	0.20	500	1/5.0	15
D	11.5	700	1/11.5	1.07	1/9.0	0.80	0.15	650	1/8.0	7

*z_{min} = minimum height used to ensure that the equivalent height $\bar{z}$ is greater of $0.6h$ or z_{min}.
For buildings with $h \leq z_{min}$, $\bar{z}$ shall be taken as z_{min}.

In metric

Exposure	α	z_g (m)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	ℓ (m)	$\bar{\epsilon}$	z_{min} (m)*
B	7.0	365.76	1/7	0.84	1/4.0	0.45	0.30	97.54	1/3.0	9.14
C	9.5	274.32	1/9.5	1.00	1/6.5	0.65	0.20	152.4	1/5.0	4.57
D	11.5	213.36	1/11.5	1.07	1/9.0	0.80	0.15	198.12	1/8.0	2.13

*z_{min} = minimum height used to ensure that the equivalent height $\bar{z}$ is greater of $0.6h$ or z_{min}.
For buildings with $h \leq z_{min}$, $\bar{z}$ shall be taken as z_{min}.

Velocity Pressure Exposure Coefficients, K_h and K_z

Table 6-3

Height above ground level, z		Exposure (Note 1)			
		B		C	D
ft	(m)	Case 1	Case 2	Cases 1 & 2	Cases 1 & 2
0-15	(0-4.6)	0.70	0.57	0.85	1.03
20	(6.1)	0.70	0.62	0.90	1.08
25	(7.6)	0.70	0.66	0.94	1.12
30	(9.1)	0.70	0.70	0.98	1.16
40	(12.2)	0.76	0.76	1.04	1.22
50	(15.2)	0.81	0.81	1.09	1.27
60	(18)	0.85	0.85	1.13	1.31
70	(21.3)	0.89	0.89	1.17	1.34
80	(24.4)	0.93	0.93	1.21	1.38
90	(27.4)	0.96	0.96	1.24	1.40
100	(30.5)	0.99	0.99	1.26	1.43
120	(36.6)	1.04	1.04	1.31	1.48
140	(42.7)	1.09	1.09	1.36	1.52
160	(48.8)	1.13	1.13	1.39	1.55
180	(54.9)	1.17	1.17	1.43	1.58
200	(61.0)	1.20	1.20	1.46	1.61
250	(76.2)	1.28	1.28	1.53	1.68
300	(91.4)	1.35	1.35	1.59	1.73
350	(106.7)	1.41	1.41	1.64	1.78
400	(121.9)	1.47	1.47	1.69	1.82
450	(137.2)	1.52	1.52	1.73	1.86
500	(152.4)	1.56	1.56	1.77	1.89

Notes:

1. **Case 1:** a. All components and cladding.
   b. Main wind force resisting system in low-rise buildings designed using Figure 6-10.

   Case 2: a. All main wind force resisting systems in buildings except those in low-rise buildings designed using Figure 6-10.
   b. All main wind force resisting systems in other structures.

2. The velocity pressure exposure coefficient K_z may be determined from the following formula:

   For 15 ft. $\leq z \leq z_g$ — $K_z = 2.01\,(z/z_g)^{2/\alpha}$

   For $z < 15$ ft. — $K_z = 2.01\,(15/z_g)^{2/\alpha}$ → Table 6-2

   Note: z shall not be taken less than 30 feet for Case 1 in exposure B.

   z

3. α and z_g are tabulated in Table 6-2.
4. Linear interpolation for intermediate values of height z is acceptable.
5. Exposure categories are defined in 6.5.6.

Wind Directionality Factor, K_d

Table 6-4

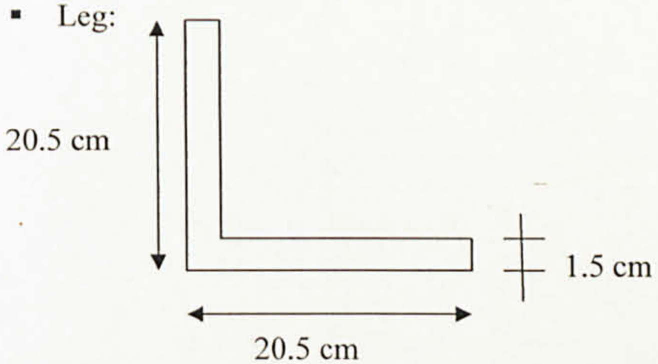
Structure Type	Directionality Factor K_d*
Buildings	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
Arched Roofs	0.85
Chimneys, Tanks, and Similar Structures	
Square	0.90
Hexagonal	0.95
Round	0.95
Solid Signs	0.85
Open Signs and Lattice Framework	0.85
Trussed Towers	
Triangular, square, rectangular	0.85
All other cross sections	0.95

*Directionality Factor K_d has been calibrated with combinations of loads specified in Section 2. This factor shall only be applied when used in conjunction with load combinations specified in 2.3 and 2.4.

APPENDIX B
TOWER DIMENSION

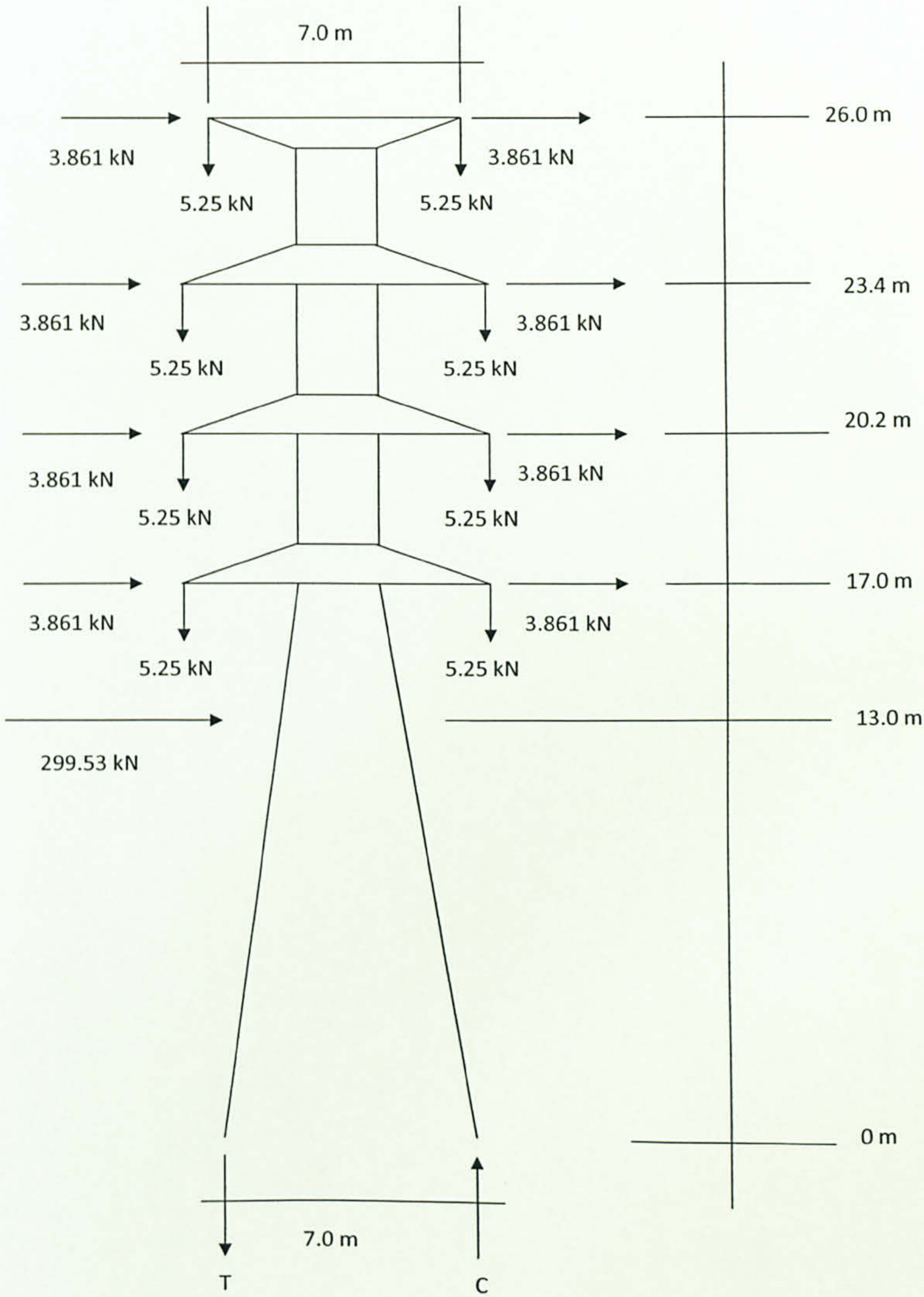
132kV Electrical Transmission Tower Dimension:

- 7 meter square base
- 26 meter in height
- Protrude wing: 8 meter span
- Short wing: 7 meter span (at the top)
- Leg:



- Conductor: 50 mm diameter; 1.5 kg/m weight
- Span: 350 meter (normal)
- Max sag: 7.06 meter
- Location: mountainous outskirt
- Vs = 38 m/s

Tower Diagram:



APPENDIX C

CALCULATION OF WIND LOAD

Wind Load on Structure:

Height	Kz	Kzt	Kd	V^2	I	qz
0.0	0.85	1.0	0.85	1444	1.15	735.4673
8.5	0.967266	1.0	0.85	1444	1.15	836.9322
17.0	1.119233	1.0	0.85	1444	1.15	968.4228
20.2	1.160619	1.0	0.85	1444	1.15	1004.232
23.4	1.197112	1.0	0.85	1444	1.15	1035.808
26.0	1.223962	1.0	0.85	1444	1.15	1059.04

$Cf = 4.0\,\epsilon^2 - 5.9\,\epsilon + 4.0$

$Cf = 4.0\,(0.3) - 5.9\,(0.3) + 4.0 = 2.59$

Af = solid area = 0.3 (7 x 26) = 54.6 m^2 (approximate)

$F = qz\ G\ Cf\ Af$ where

qz = 1059.04 N/m^2

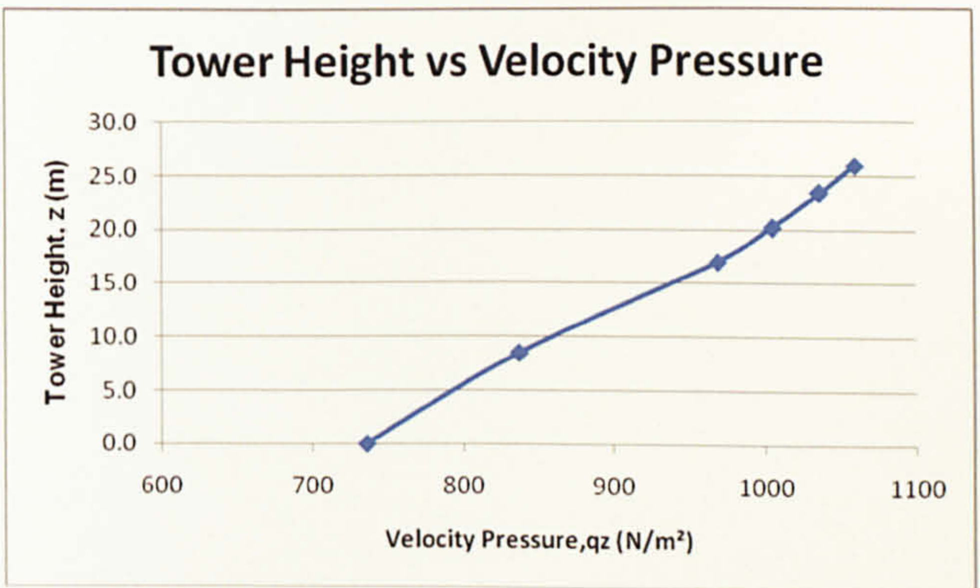
G = 2.0

Cf = 2.59

Af = 54.6 m^2

:: F = 299526.2 N

F = 299.526 kN



Wind Load on Conductor:

$$Fc = p \times d/12 \times H \times OCF$$

where

p = wind pressure = 1059.04 N/m²

d = diameter of conductor = 0.05 m

H = distance between midpoint of adjacent spans = 350 m

OCF = overload capacity factor = 2.5

$$Fc = 1059.04\ (0.05/12)\ (350)\ (2.5)$$

Fc = 3861.08 N = 3.861 kN

APPENDIX D

CALCULATION OF ALLOWABLE STRESSES

Tension Member

- **Under Combined Dead Load + Wind Load:**

$\sum M_B = -3.861\,(26)\,(2) + 5.25\,(7) - 3.861\,(23.4)\,(2) + 5.25\,(7.5)$

$\quad - 3.861(20.2)\,(2) + 5.25\,(7.5) - 3.861\,(17)\,(2) + 5.25\,(7.5)$

$\quad - 5.25(0.5)\,(3) - 299.526(13) + T\,(7) = 0$

$$\mathbf{T = 630.79\ kN}$$

Tension force, $\mathbf{F_T} = T / 2 = 630.79 / 2 = 315.397$ kN

Leg cross sectional area, $\mathbf{A} = (205 \times 15)\ mm^2 + (190 \times 15)\ mm^2 = 5925\ mm^2$

Yield stress, $\mathbf{F_y} = 260\ N/mm^2$; Allowable tensile stress = $0.6\ F_y = 156\ N/mm^2$

Tensile stress, $\boldsymbol{\sigma} = F_T / A$

$= 315\,397\ N / 5925\ mm^2$

$= \mathbf{53.23\ N/mm^2 \leq 0.6\ F_y}$

- **Under Breakage of Conductor Load:**

$\sum M_B = -3.861\,(26) + 5.25\,(7) - 3.861\,(23.4) + 5.25\,(7.5)$

$\quad - 3.861\,(20.2) + 5.25\,(7.5) - 3.861\,(17) + 5.25\,(7.5) - 299.526\,(13)$

$\quad + T\,(7) = 0$

$$\mathbf{T = 581.90\ kN}$$

Tension force, $\mathbf{F_T} = T / 2 = 581.90 / 2 = 290.95$ kN

Leg cross sectional area, $\mathbf{A} = (205 \times 15)\ mm^2 + (190 \times 15)\ mm^2 = 5925\ mm^2$

Yield stress, $\mathbf{F_y} = 260\ N/mm^2$; Allowable tensile stress = $0.6\ F_y = 156\ N/mm^2$

Tensile stress, $\boldsymbol{\sigma} = F_T / A$

$= 290\,952\ N / 5925\ mm^2$

$= \mathbf{49.11\ N/mm^2 \leq 0.6\ F_y}$

Compression Member

Allowable compressive stress, $F_{ac} = [1 - (KL/R)^2 / (2Cc^2)] F_y$

$I_x = I_y = 6456 \text{ cm}^4$

$E = 2.1 \text{ X } 10^5$ MPa

$F_y = 260$ MPa

$K = 1.0$; unbraced length, $L = 190$ cm

$r_x = r_y = (I/A)^{1/2} = 10.4$ cm

$$F_{ac} = [1 - (18.27)^2 / (2 \text{ x } (89.24)^2)] \text{ x } 260$$

$$= 0.979 \text{ x } 260$$

$$= 245.55 \text{ N/mm}^2$$

- **Under Combined Dead Load + Wind Load:**

  Compressive stress = **53.23 N/ mm² ≤ 245.55 N/mm²**

- **Under Breakage of Conductor Load:**

  Compressive stress = **49.11 N/ mm² ≤ 245.55 N/mm²**