SUPPORT OF GUYED TRANSMISSION TOWER -
USING SELF-ADJUSTING SPRUNG GUY WIRES

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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Abstract

Manitoba Hydro transmits high-voltage electric power hundreds of kilometers using conductors suspended from guyed transmission towers. Towers located in central and northern Manitoba can heave or settle due to discontinuous permafrost. The problem is that excessive heave can cause loss of guy wires or buckling of tower shafts and excessive settlement allows lateral leaning of the towers. The tower of interest in this thesis is the latticed tower of Manitoba Hydro designated as A-203. The objective of this thesis project is to design a tower-support method that will safely permit an A-203 tower to heave or settle.

A new method of tower support is proposed which allows the tower to heave four inches or settle six inches from its mean seasonal position. The method involves retrofitting existing towers with a device called the guy-wire tension stabilizer or GTS. The device consists of a large spring and locking mechanism which is installed between the guy wires and tower. As the tower base heaves or settles, the spring displaces to maintain acceptable guy-wire tension. When wind loads act against the tower and conductors, the spring is temporarily restrained by the locking ring, preventing excessive leaning of the tower. A 1:20 scale steel model of the device and tower was built for demonstration.

The objectives, as stated by the client, have been met. A design of a tower - support method for the tower of interest has been prepared.

It is recommended that consideration be given to developing the GTS to a working prototype.

Acknowledgments

I would like to thank those who contributed and helped with the production of this thesis. First of all, I would like to thank my thesis advisors, Dr. A.B. Thornton-Trump for his valued assistance and Dr. J. Shewchuk(co-advisor), for providing the concept of the thesis and for his support in the design and editing of the thesis.

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Finally, I would like to thank my parents for their support and assistance during the course of the project.

Table of Contents

List of Figures Page

1. INTRODUCTION

1.1 Overview of Manitoba Hydro

Manitoba Hydro is a crown corporation which is in the business of power generation and distribution. Most generation occurs at twelve hydro-electric power generating stations located on various rivers in Manitoba. The power is distributed hundreds of kilometers to urban areas via high-voltage transmission lines. The voltage is then reduced and transmitted to local customers. This thesis deals with transmission of high-voltage power.

1.2 Power Transmission in Manitoba

Power is distributed to urban areas by high-voltage transmission lines consisting of overhead conductors suspended from transmission towers. These towers are constructed of latticed steel, tubular steel, or wood and are either free-standing or guyed.

This thesis deals with a specific guyed lattice steel tower, designated as A-203. A typical A-203 tower is shown in Figure 1-1. The tower is supported by a pinned base and guy wires. The pinned base is secured to a pad and the guy wires are anchored rigidly into deep subsoil.

Substantial amounts of hydro-electric power are transmitted across central and northern Manitoba using guyed towers. This area of the province contains discontinuous permafrost, a condition of subsoil containing ice and water. In the winter months, the subsoil water can freeze, heaving the top soil and the base of the tower which it supports. As the tower base heaves, the guy wires stretch and increase their load at the top of the tower, thus, creating an increase in tower compression. At some critical magnitude of heave, the tower may buckle, the guy wires may break, or the guy anchors may fail.

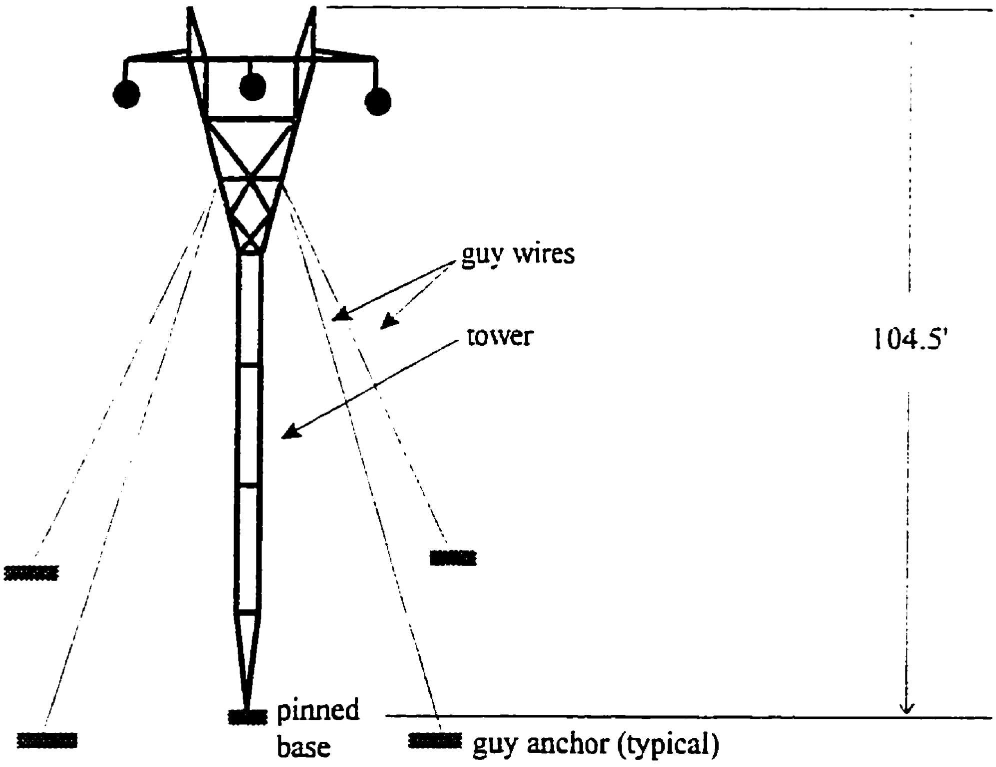


Figure 1-1 Typical A-203 Tower Configuration

On the other hand, in summer months if the water melts, the topsoil will settle. The problem is that ground heave or settlement beneath a tower leaves the tower unstable due to loss of proper guy-wire tension.

Some of the current methods and proposed new techniques to overcome the effects of vertical ground motion are described in Appendix A.

1.3 Thesis Objectives

The objectives of this thesis project is to design a tower-support method that will permit a tower to heave four inches or settle six inches from its mean seasonal position, while maintaining acceptable guy-wire tension. The design must satisfy the following:

- It must install into an A-203 tower.
- The guy-wire tension must be between 500 and 4,000 lb under no wind conditions.
- The guy wires must be able to resist leaning and twisting of the tower.

A detailed list of the design requirements is shown in Appendix B.

2. PROPOSED GUY-WIRE TENSION STABILIZER (GTS)

2.1 Introduction

An overview of the design is given in Section 2.2, while the features of the design are presented in Section 2.3. Section 2.4 shows the predicted performance of the system and Section 2.5 gives the fabrication cost estimate of the device. Note that the discussion is in concept only and that all necessary engineering detail is presented in appendices as referenced.

2.2 Overview of GTS

The proposed GTS is illustrated in Figure 2-1. As is seen in the detail of the figure, the GTS consists of a compensating rod, cross arm and locking ring assembly, compensating spring and two guide slots.

For tower installation in regions of discontinuous permafrost, guy-wire anchors are so designed and installed that their upper elevation remains relatively unaffected by ground settling or heaving. On the other hand, the vertical displacement of the tower base follows the ground motion, and this displacement must be accommodated in series by the guy wires in tension and the tower in compression.

Because the guy wires and the tower are relatively rigid, only a limited range of vertical base motion can be tolerated between that amount of settling that leaves the guy wires too slack or that amount of heaving that leads to a structural failure of the tower installation. In a tower installation with GTS, the rigidity of the guy wires/tower system is significantly decreased by the addition of a compensating spring in series with the tower. Thus, such an installation can operate over a larger range of vertical base motion.

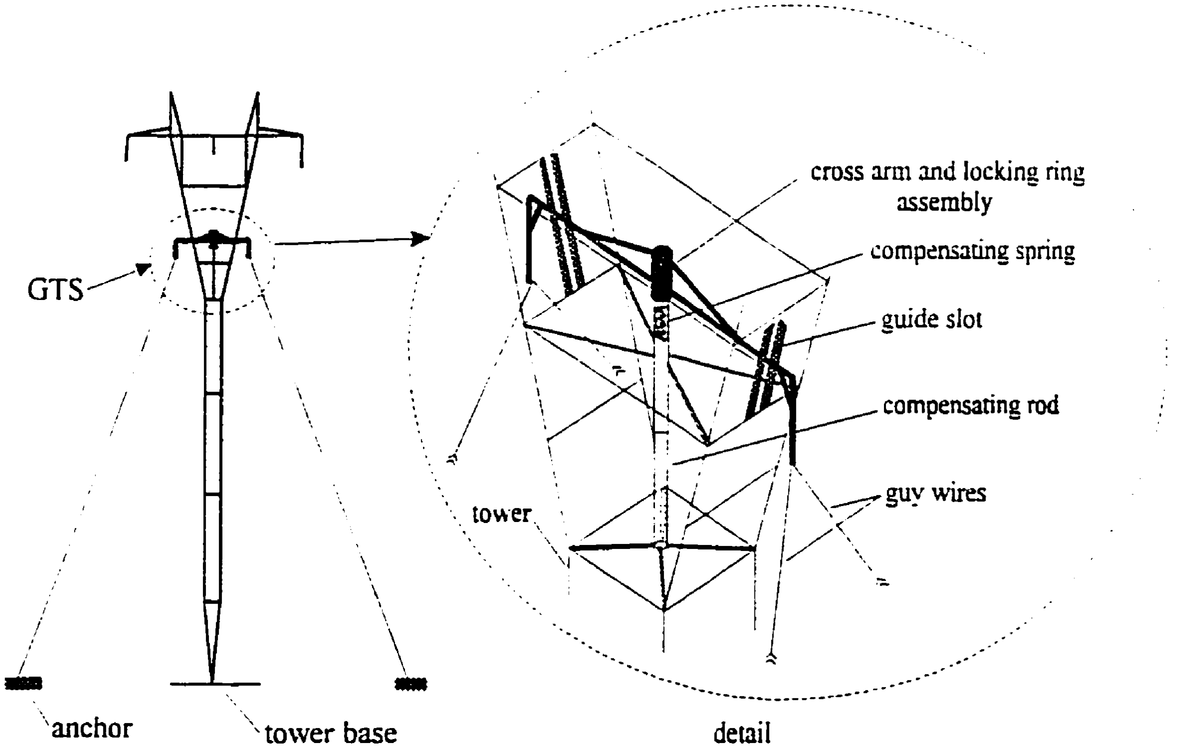


Figure 2-1 Tower with GTS

The GTS is installed with a magnitude of initial pre-tension in the guy wires which will permit acceptable values of tension within the design range of settling and heaving. In normal operation, the four guy wires are in equal tension, and the sum of the guy-wire forces is in equilibrium with the compressive force at the top of the compensating spring. Under certain conditions, however, the four guy wires are not in equal tension.

In the presence of strong transverse winds, tension increases in the windward guy wires causing the cross arm and locking ring assembly to lock against the compensating rod thereby preventing additional compressive deformation in the spring and limiting any subsequent transverse leaning of the tower.

The loss of a conductor at a tower results in an unbalance of longitudinal forces which tends to displace the top of the tower longitudinally. The resultant unbalance force may be either centric or eccentric, depending on the position of the failed conductor. In either case, the resulting uneven guy-wire tensions activate the cross arm and locking ring assembly and prevent any further compressive force on the compensating spring.

In a GTS installation, the upper guy-wire attachments are at approximately the same radial distance as in a conventional tower. Hence, the GTS provides the same resistance to tower twisting about its vertical axis as does the conventional installation.

The guy wires are attached to the cross arm and locking ring assembly which compresses the compensating spring. In normal operation, as the tower heaves, the compensating spring compresses further, preventing over-tensioning of the guy wires. As the tower settles, the compensating spring extends to hold the guy wires from becoming slack.

2.3 Features

2.3.1 Components

Compensating Spring

The compensating spring holds up the cross arm and locking ring assembly as shown in Figure 2-2. The lower end of the spring is set inside the compensating rod. In normal operation, when the guy wires are in equal tension, the spring load is in series with the guy-wires tension and the tower shaft compression. The installation of a tower system requires the guy wires to be pre-tensioned, which will cause the spring to compress by some initial amount.

Cross Arm and Locking Ring Assembly

The cross arm and locking ring assembly is set over the compensating rod as shown in Figure 2-2. The assembly is supported by the compensating spring inside the compensating rod. The cross arm protrudes through the sides of the tower through the two guide slots, and the guy wires are attached at the lower ends of the cross arm. Again, in normal operation, when the guy wires are in equal tension, the compensating rod is able to slide through the assembly to compress or allow elongation of the compensating spring.

Guide Slots

The two guide slots are located on either side of the tower as shown in Figure 2-2; each of the ends of the cross arm and locking ring assembly are set through a vertical guide slot. The role of the guide slots is to allow vertical displacement and rotation of the cross arm in each slot and to restrain the cross arm from horizontal displacement or twisting about the tower shaft.

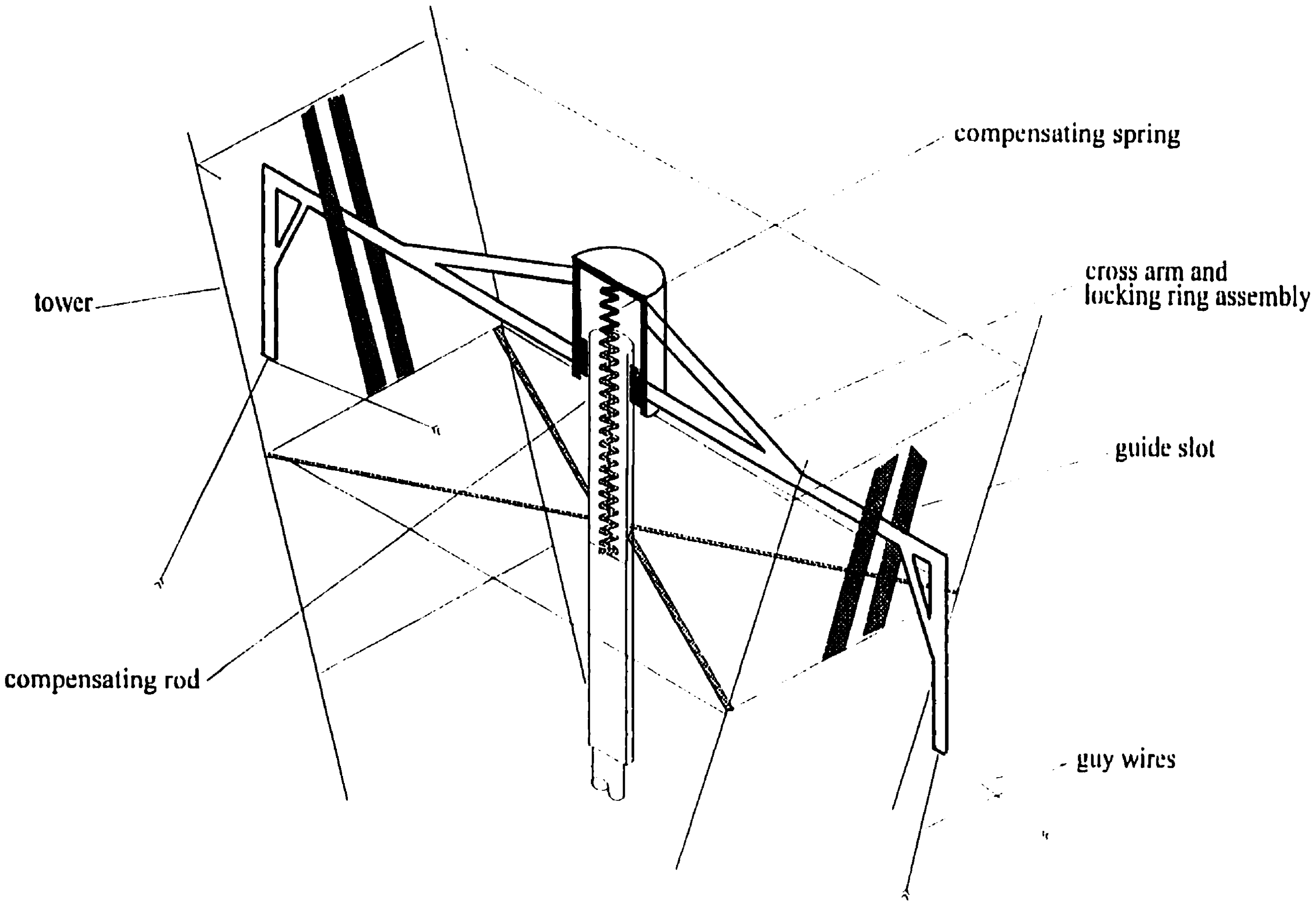


Figure 2-2 GTS Components

2.3.2 Resistance to Tower Leaning

A key function of the GTS is its ability to prevent the tower from leaning. As illustrated in Figure 2-3, strong transverse winds against the tower and conductors produce an increase in windward guy-wire tension, creating a resultant downward force F_V as indicated. This force creates a moment in the cross arm, causing the locking ring to lock by friction against the compensating rod, and thereby preventing additional spring deformation and, hence, additional leaning of the tower.

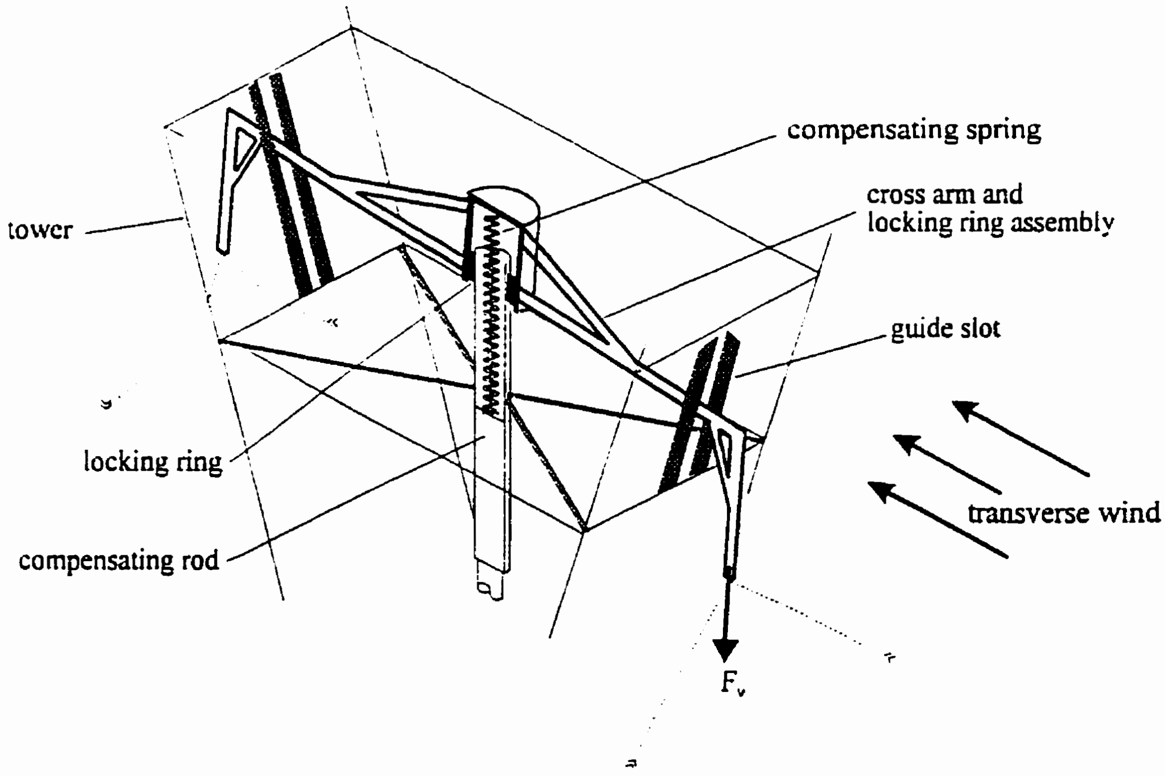
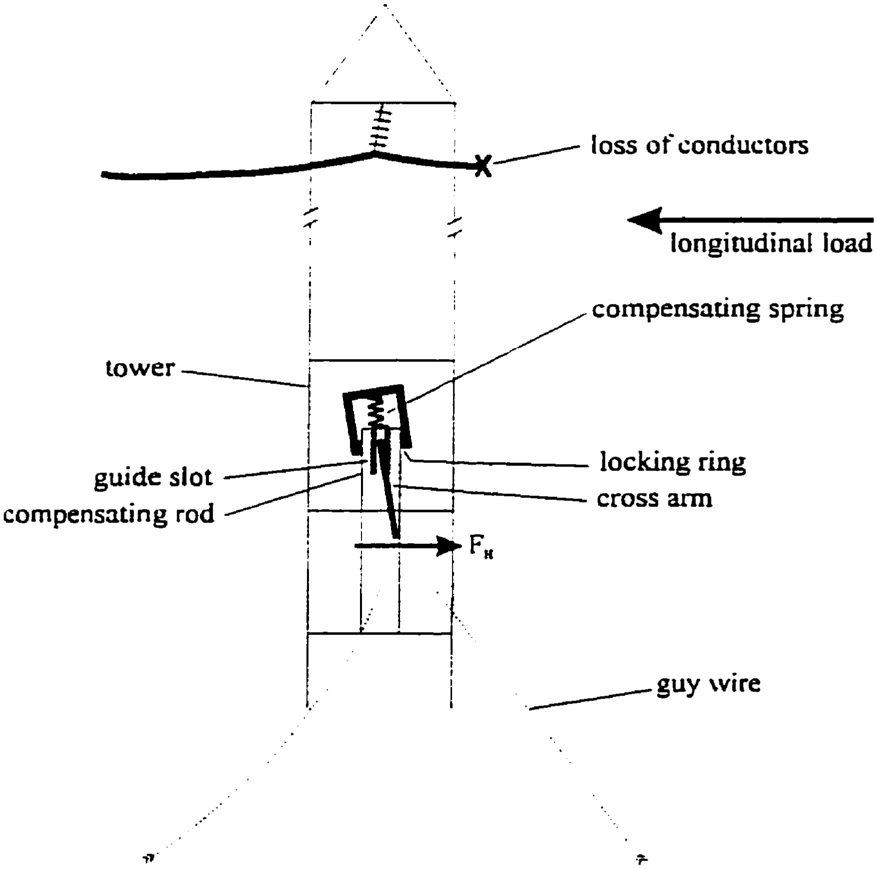


Figure 2-3 Locking Ring Locked by Transverse Load

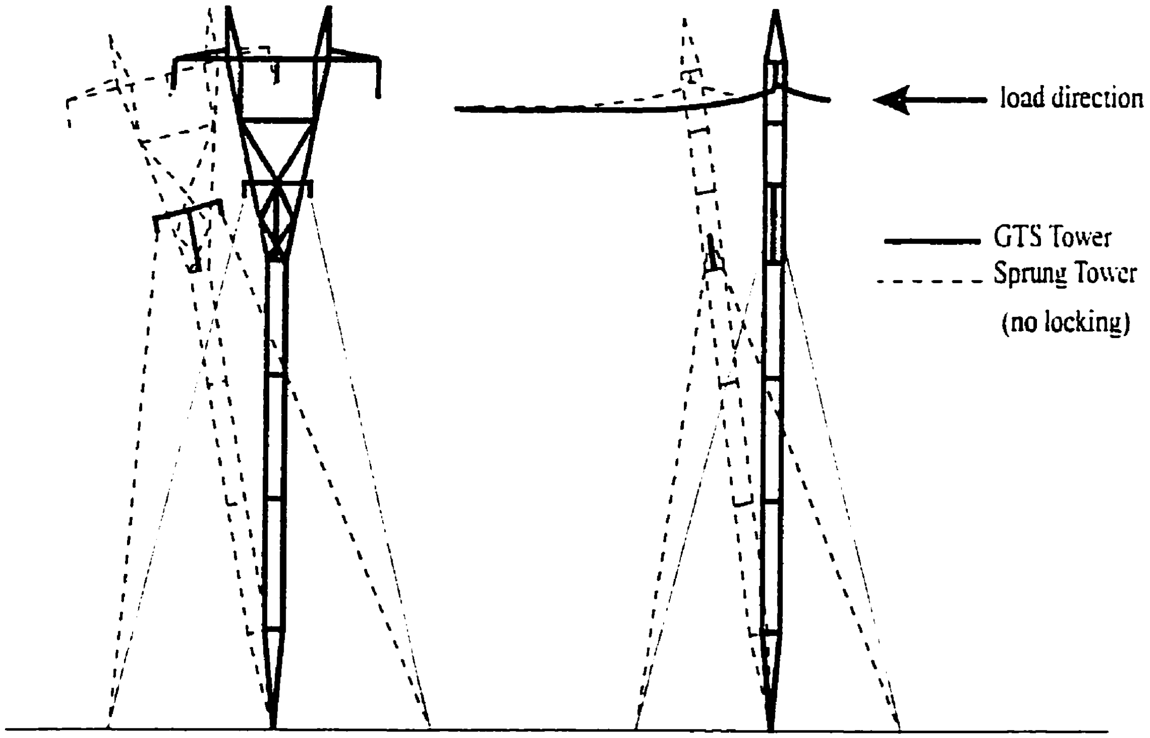
Strong longitudinal winds or loss of conductors can produce a longitudinal load on the tower as shown in Figure 2-4. In the case of a single or group of conductors lost, a centric or eccentric load is produced on the tower, depending on the position of the failed conductor(s). In either case, the resulting longitudinal load produces an uneven guy-wire tension, creating a resultant horizontal force F_H on each side of the tower as indicated. This force also creates a moment in the cross arm causing the locking ring to lock against the compensating rod, again preventing additional spring deformation and additional leaning of the tower.



Side View

Figure 2-4 Locking Ring Locked by Longitudinal Load

A frictional locking force large enough to restrain the compensating spring is always produced, regardless of the load or its direction, as discussed in Appendix C. To demonstrate the importance of the friction locking, Figure 2-5 illustrates the leaning of the GTS tower, compared to a sprung tower without locking.



Transverse loading

Longitudinal loading

Figure 2-5 Resistance to Leaning

2.3.3 Resistance to Tower Twisting

Another requirement of the guy wires is to restrain the tower from twisting. In a conventional tower, the guy wires are attached rigidly on either side of the tower to resist twisting. The GTS allows the guy wires to be attached at approximately the same position as a conventional tower. As illustrated in Figure 2-6, as the tower begins to twist, each of the guide slots produce a force F_t against the cross arm. The twisting load in the cross arm is restrained by the guy wires, by reaction force R, as shown in the figure.

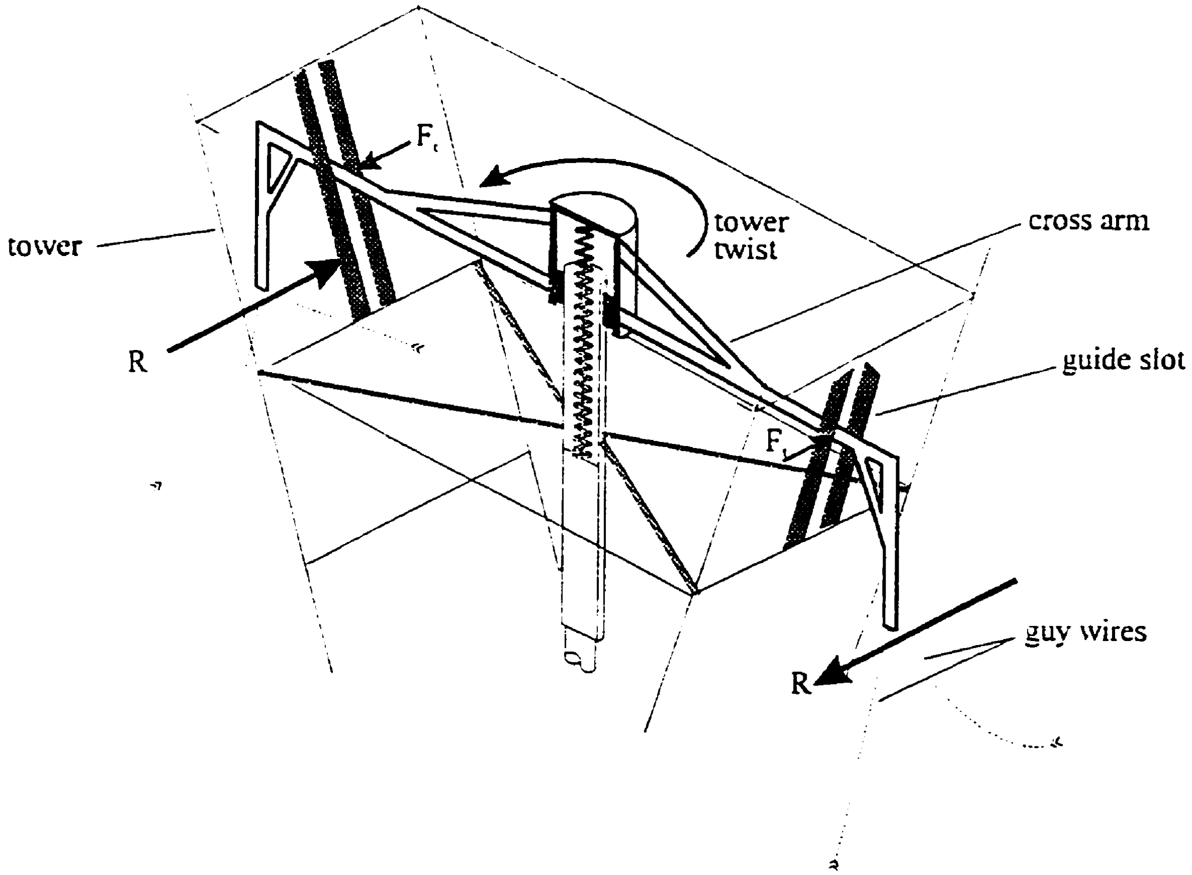


Figure 2-6 Resistance to Twisting

2.3.4 Retrofit

The GTS is designed for retrofit into an A-203 lattice tower. One method of fastening the GTS to the tower is by way of braces, one set near the top of the compensating rod, and one set at the base of the rod. Figure 2-7 shows a schematic of the GTS installed with the braces.

A retrofit also requires the two guide slots to be installed and attachment of the guy wires to the ends of the cross arm and then pre-tensioning the guy wires. The details of the braces are given in Appendix D.

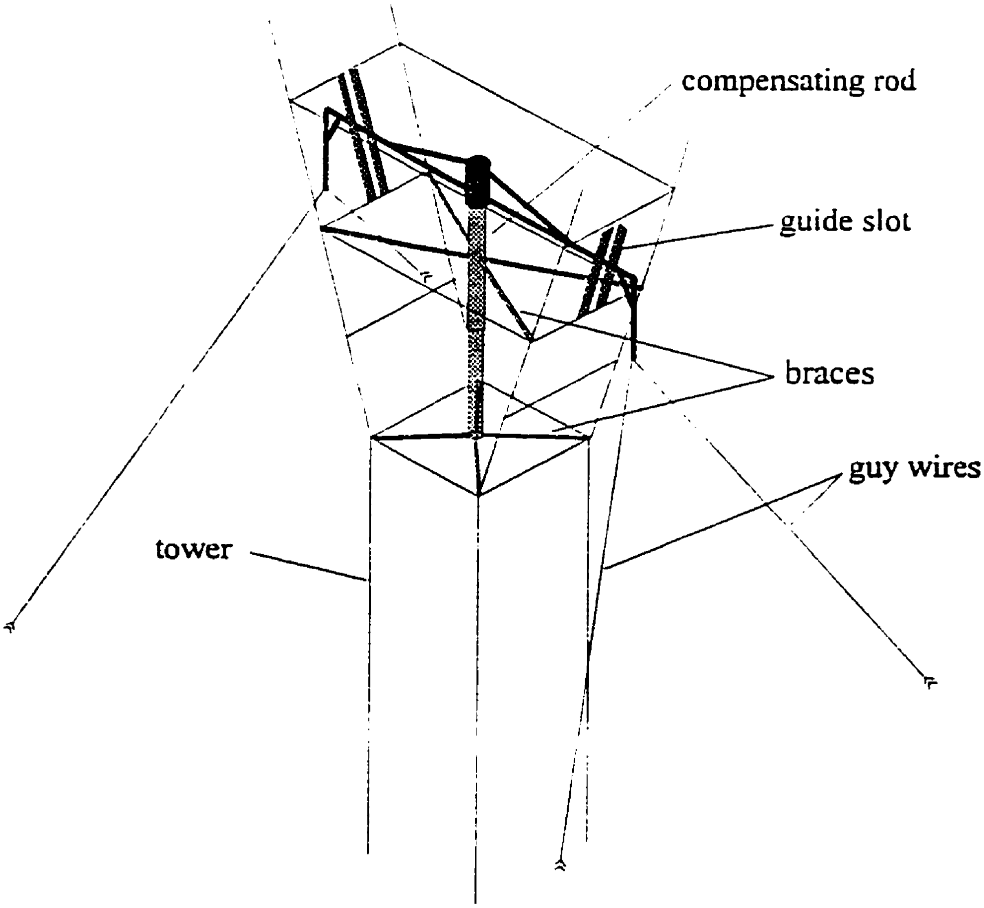


Figure 2-7 GTS Braces

2.4 Predicted Performance

2.4.1 Mathematical Analysis

A mathematical analysis presented in Appendix E was used to develop a relationship between tower base displacement and tower shaft compressive load for both a conventional tower and GTS tower. The analysis predicts the GTS method will allow 2.2 times the base displacement compared to a conventional tower. A plot of tower load versus base displacement compares a conventional tower to the GTS tower method as shown in Figure 2-8.

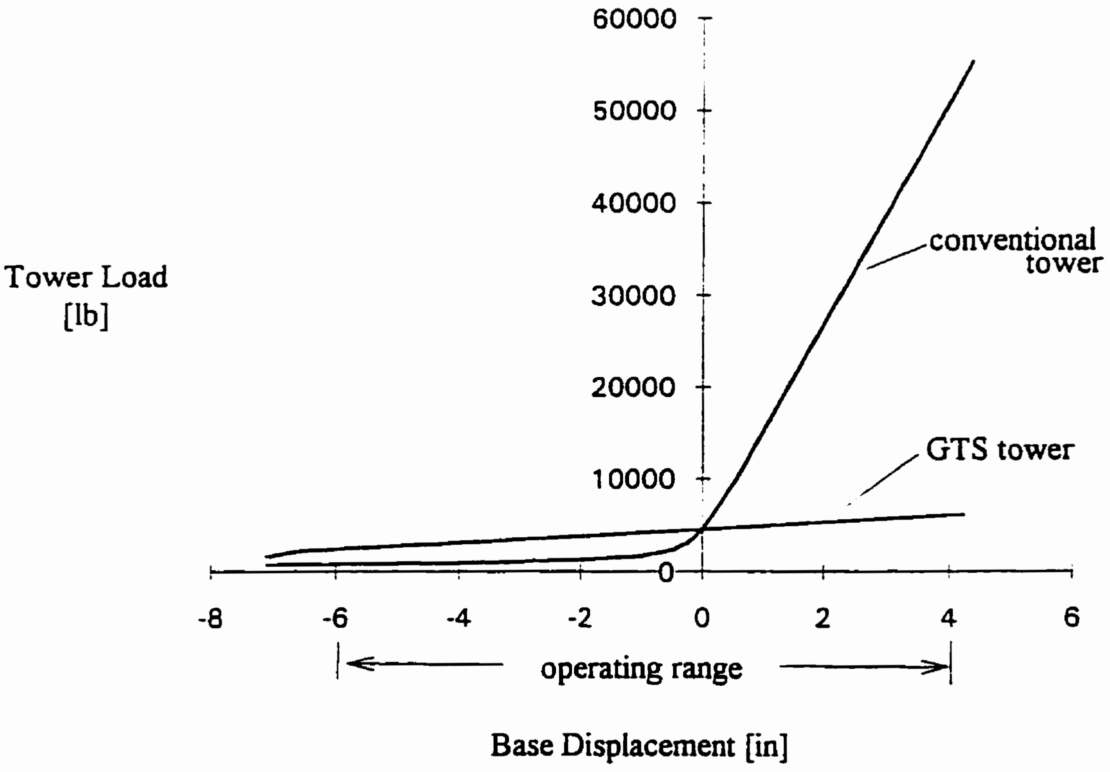


Figure 2-8 Tower Load versus Base Displacement

The plot shows that the predicted load in the GTS tower through its operating range of -6 to +4 inches of base displacement is relatively constant, compared to a conventional tower.

The mathematical analysis is discussed in detail in Appendix E.

2.4.2 Experimental Model

To aid in the design of the GTS, a 1:20 scaled model of the tower and GTS device was built. The model was constructed of spot welded steel angles and has an adjustable base to simulate ground heave or settlement. Figure 2-9 shows the model.

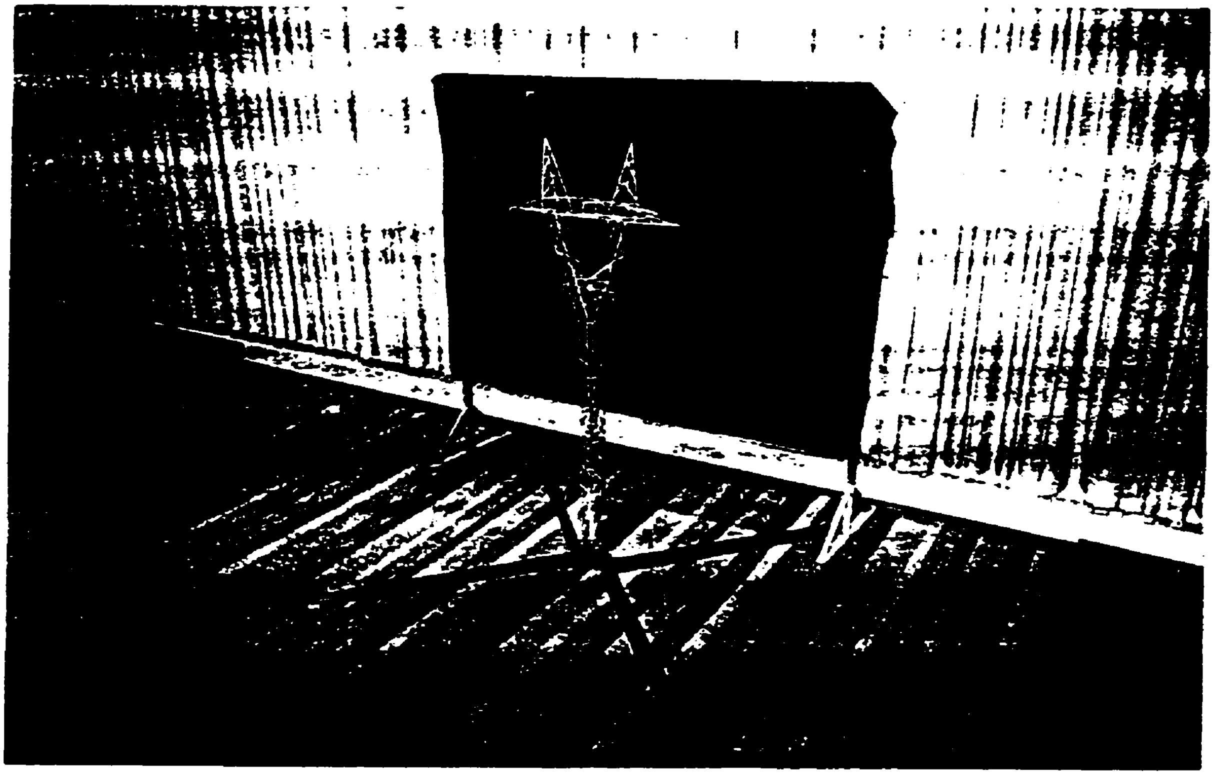


Figure 2-9 Experimental Model

The ability of the model tower to heave or settle can easily be seen. More importantly, the effectiveness of friction locking to resist transverse and longitudinal loading through the locking ring is immediately verified in a model demonstration. A further discussion of the model can be found in Appendix F.

2.5 Cost

A good estimate of cost is based on the weight of the device. The GTS weighs approximately 3,500 lb and the manufacturing cost is estimated at a dollar per pound. This gives a cost of $3,500 per unit.

The additional cost of installing a device is not given and would likely depend on a number of variables, such as location of towers, number of units installed and exact details of the installation.

Appendix D provides the details for costs of the device.

3. CONCLUSIONS

It is concluded that the objectives of this thesis project have been met in full:

- The Guy-wire Tension Stabilizer(GTS) will accommodate a tower ten inches of vertical motion, four inches of tower heave and six inches of settlement, from its mean installed position.

- The GTS will resist tower leaning.

- The GTS will resist twisting loads.

4. RECOMMENDATIONS

It is recommended that consideration be given to implementing the GTS design in a test installation.

Appendices

Appendix A Current and Proposed New Methods of Dealing with Tower Vertical Motion

A.1 Introduction

Current methods of dealing with vertical ground motion beneath a tower are discussed in Section A.2. Section A.3 gives a brief description of two alternate new methods which could be used to support a tower.

A.2 Current Methods

Introduction

There are four methods that can be used to stabilize or reduce tower vertical motion. The first two methods reduce the heaving and settling of soil beneath a tower[1]. This is achieved by either use of piles or by stabilizing the soil temperature under the tower. The third approach is use of a bendable yoke which acts like a mechanical fuse[2]. Finally, the fourth method is a very different approach, where the tower can self-compensate for vertical motion.

Piles

Tower foundations can be stabilized with piles constructed of steel, concrete or wood. They are installed either by being driven in or cast-in-place with concrete. The depth of the pile depends on the soil type found during drilling, and because of adfreeze forces, piles are required to extend several meters below the discontinuous permafrost. The soil can be very hard in northern Manitoba, and typically only the guy wires are secured with piles.

Stabilizing the Soil Temperature

Heat syphons and insulated footings can be used to reduce the discontinuous permafrost motion under a tower.

Heat syphons are used in severely-affected areas. They are installed as a pile, but contain a fluid which allows for the change in temperature between ambient air and deep subsoil, to maintain a relatively-constant year-round soil temperature.

In 1986, a new method of stabilizing the soil was used in the Radisson-Churchill transmission line. The tower base footing is set on top of a large block of rigid foam insulation, buried just beneath the ground. Like the heat-syphon piles, the insulation maintains relatively constant subsoil temperatures, reducing the amount of annual ground motion. This method has the advantage of easier installation, compared to the use of piles and has proven to reduce a large amount of ground motion.

Bendable Yoke

A bendable yoke device has been designed for the large ground displacement experienced between Anchorage and Fairbanks, Alaska. The yoke is a four-foot bar which sits horizontally near the lower end of each guy wire pair. The guy wire pair attaches to each end of the bar like a playground swing. A single guy wire also attaches in the centre of the bar and continues downward to the guy anchor. The yoke is designed to plastically bend under large ground heave, allowing the guy wires to lengthen and protect the tower structure from damaging stresses or buckling.

Compensating Guy Wires

This approach allows the tower to self-compensate for vertical ground motions. A method called the Weight Activated Tension Stabilizer(WATS) was developed in 1990[3]. The method uses a 150 lb hanging weight to maintain proper guy wire tension as the tower heaves or settles. Figure A-1 shows a schematic of the support cable arrangement in its normal and heaved positions.

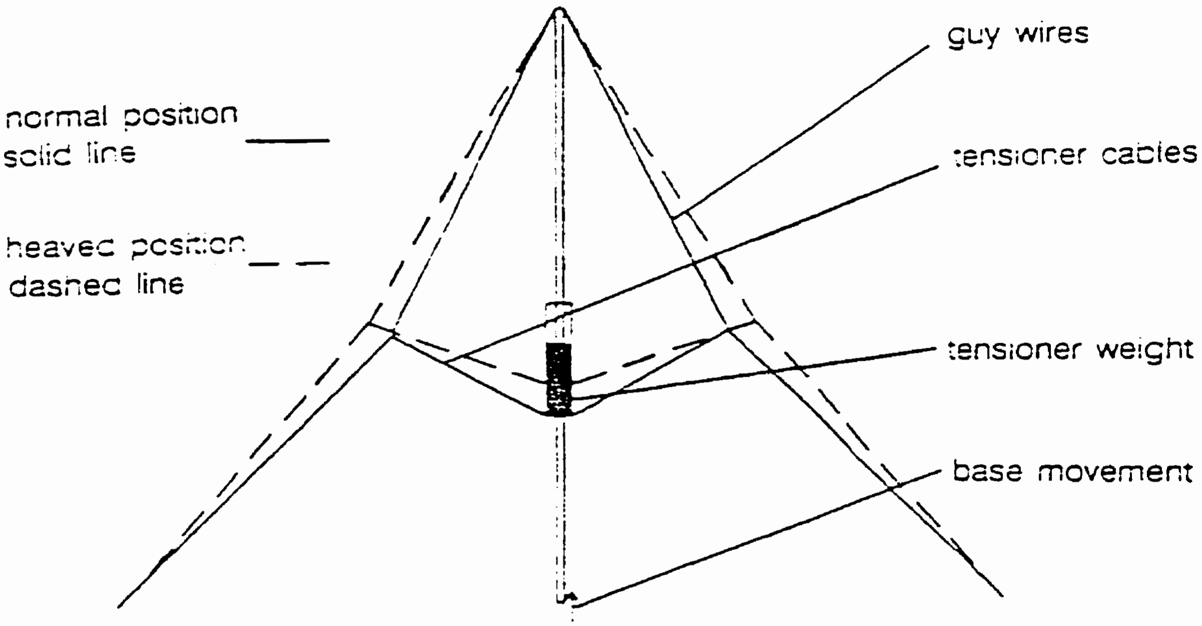


Figure A-1 WATS Tower Support Cable Arrangement

A.3 Proposed New Methods

A.3.1 Introduction

To reduce the size and cost of the GTS, other possible devices were investigated. After evaluating many methods, the use of sprung guy wires and friction locking appears to produce the most reliable combination. The main goal is to reduce the size of the locking mechanism and locate the device as close to the existing guy-wire mounting points as possible. Two of these alternative methods are the Horizontal Sprung Stabilizer and the use of Multiple Sprung Stabilizers.

A.3.2 Horizontal Sprung Stabilizer

This device redirects the guy wires towards the centre of the tower. Figure A-2 shows the Horizontal Sprung Stabilizer, designated as HSS, positioned in a conventional tower.

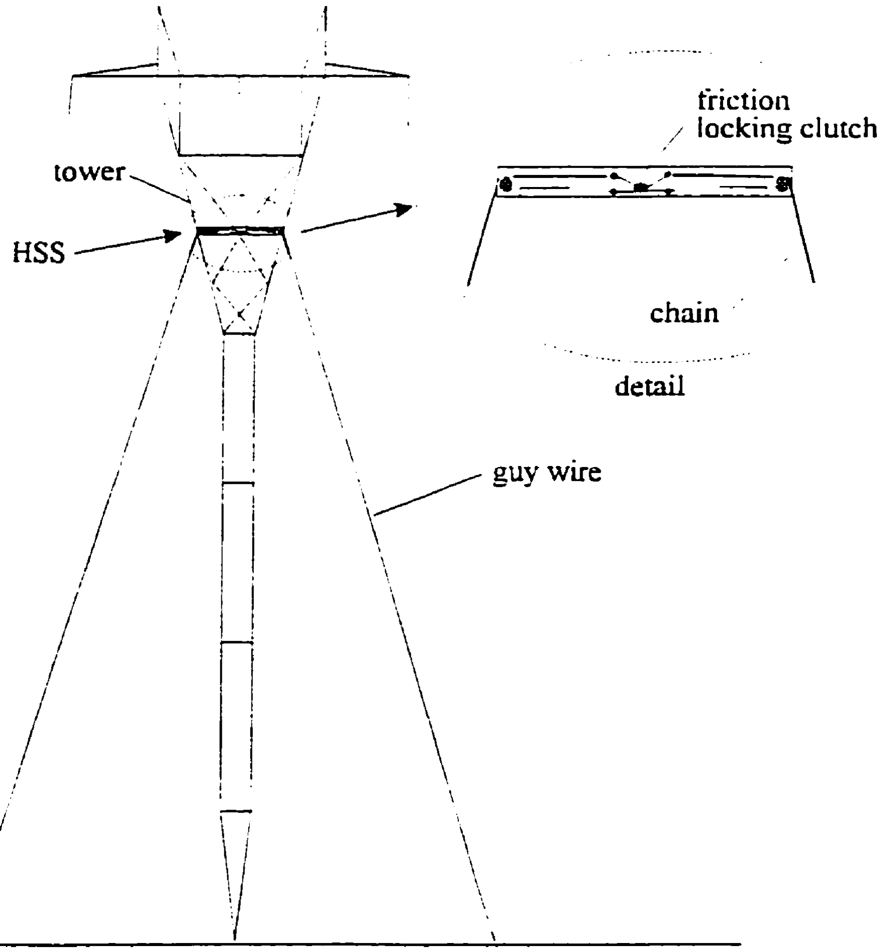


Figure A-2 Horizontal Sprung Stabilizer

As seen in the detail of the figure, the top portion of the guy wires is replaced with chain that runs over a pulley towards the clutch located in the centre of the tower. The friction-locking clutch is shown in Figure A-3.

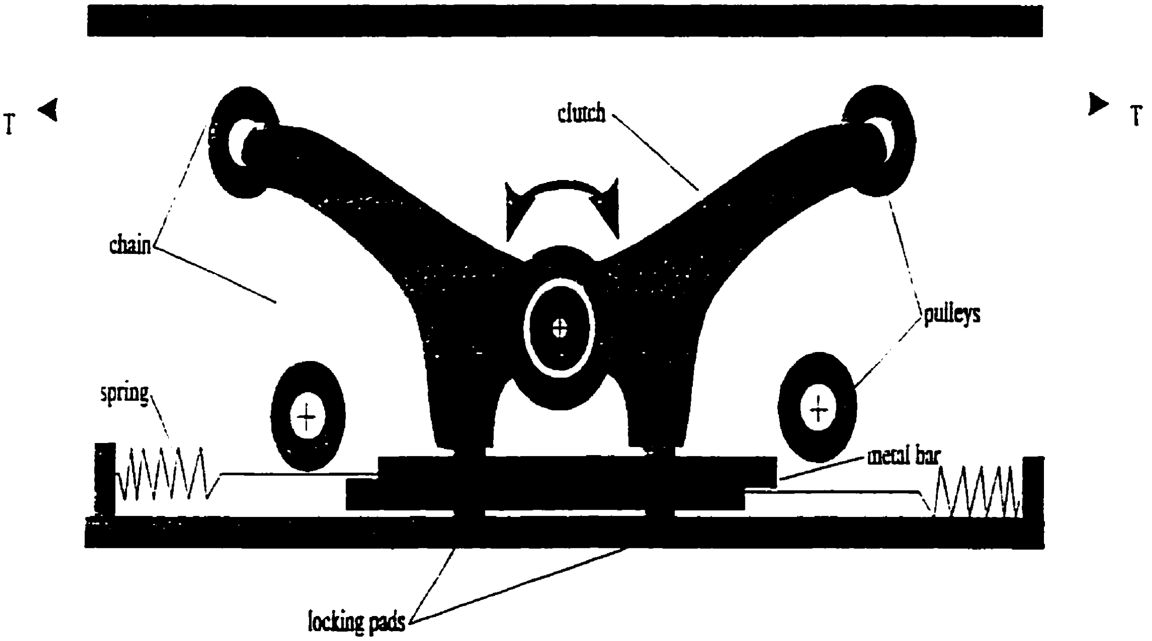


Figure A-3 Friction Locking Clutch

Each of the guy wires(actually chain) passes over two more pulleys and then attaches to a metal bar which is held by a pre-tensioned spring. As illustrated in the figure, the device operates using the difference in guy-wire tension, similar to the GTS. As wind acts against the tower, the tension increases on just the windward side of the clutch, causing it to rotate. The rotating clutch causes the locking pads on the windward side to press together, clamping the metal bars in place, securing the tower from excessive leaning. When there are no wind loads on the tower, the clutch is balanced and the metal bars are free to slide, allowing the tower to heave or settle.

A force diagram for the clutch is shown in Figure A-4.

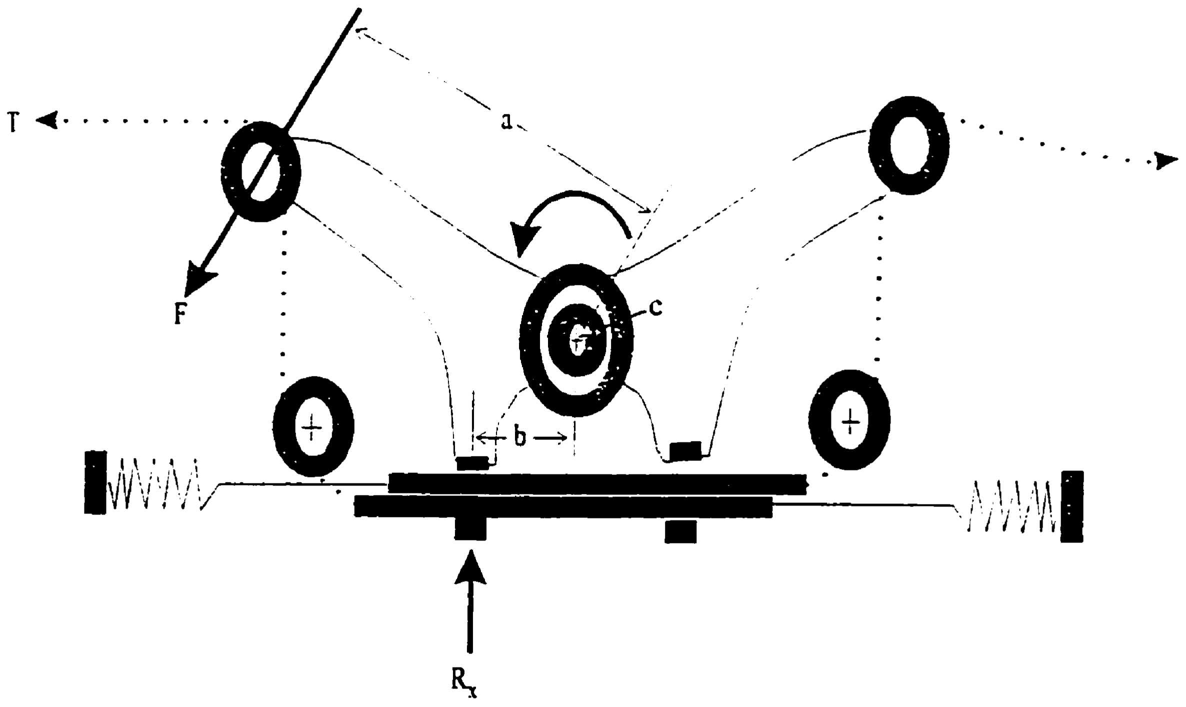


Figure A-4 Force Diagram for Clutch

Summing moments about point c gives

$$F(a) - R_x(b) = 0 \tag{1}$$

or

$$R_x = \frac{a}{b}1.41T$$

where R_x is the friction-locking force.

The predicted performance would be similar to the GTS and the device may allow for greater tower vertical motion, potentially up to two feet. A plot of the predicted performance compared to a conventional and GTS tower is shown in Figure A-5.

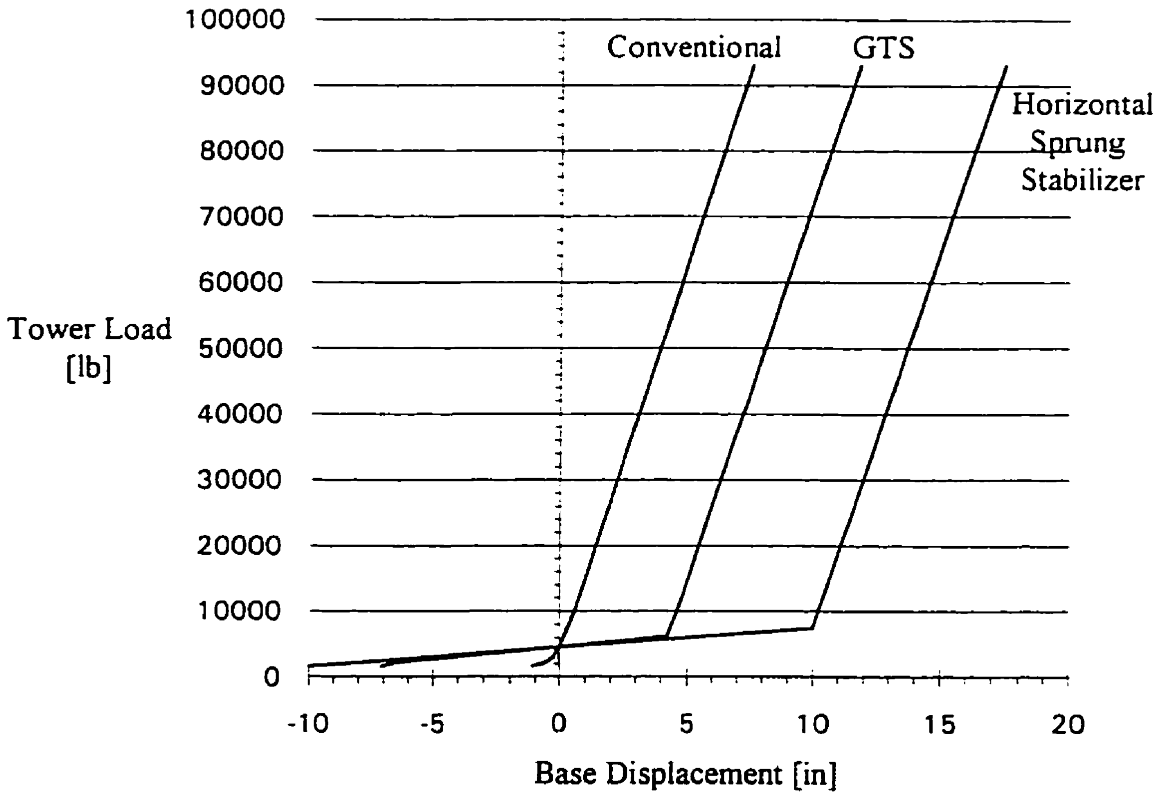


Figure A-5 Comparison of Predicted Performances

The device, compared to the GTS, would be potentially one-third the size and more easily retrofit into towers.

A.3.3 Multiple Sprung Stabilizers

A method using multiple sprung stabilizers, located at existing guy attachment points, may have potential as a retrofit. The stabilizers mount to the tower at the existing guy wire attachment points as shown in Figure A-6.

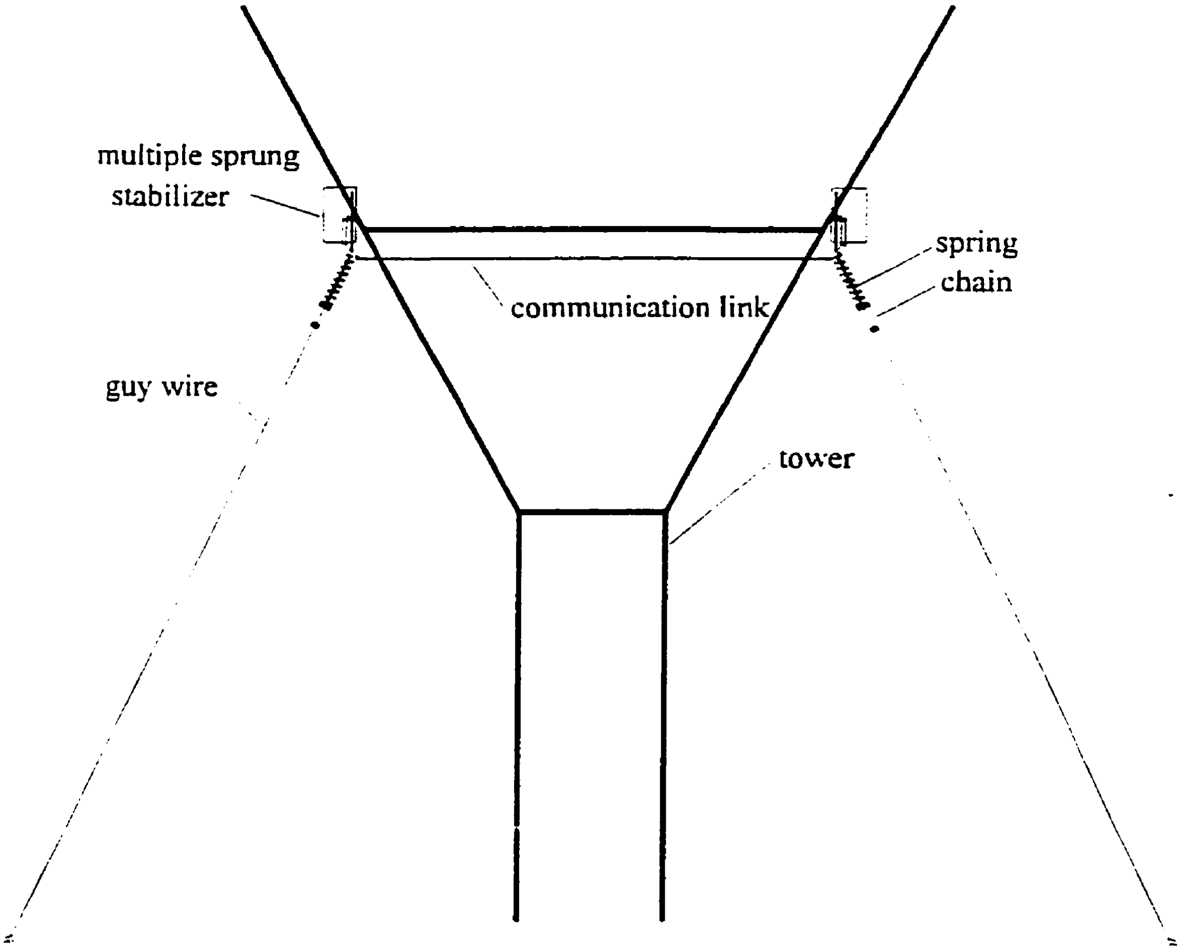


Figure A-6 Multiple Sprung Stabilizer

The upper portions of each guy wire are replaced with chain which runs through a pre-tensioned spring as it enters the stabilizer as shown in the above figure. For the device to work, a communication link or cable must run between the stabilizers as shown. When there are no wind loads, the chain is free to move and the pre-tensioned springs support the tower. The friction-locking method is shown in Figure A-7. As wind loads act against the tower, the chain and spring are locked in place using friction which holds the tower securely.

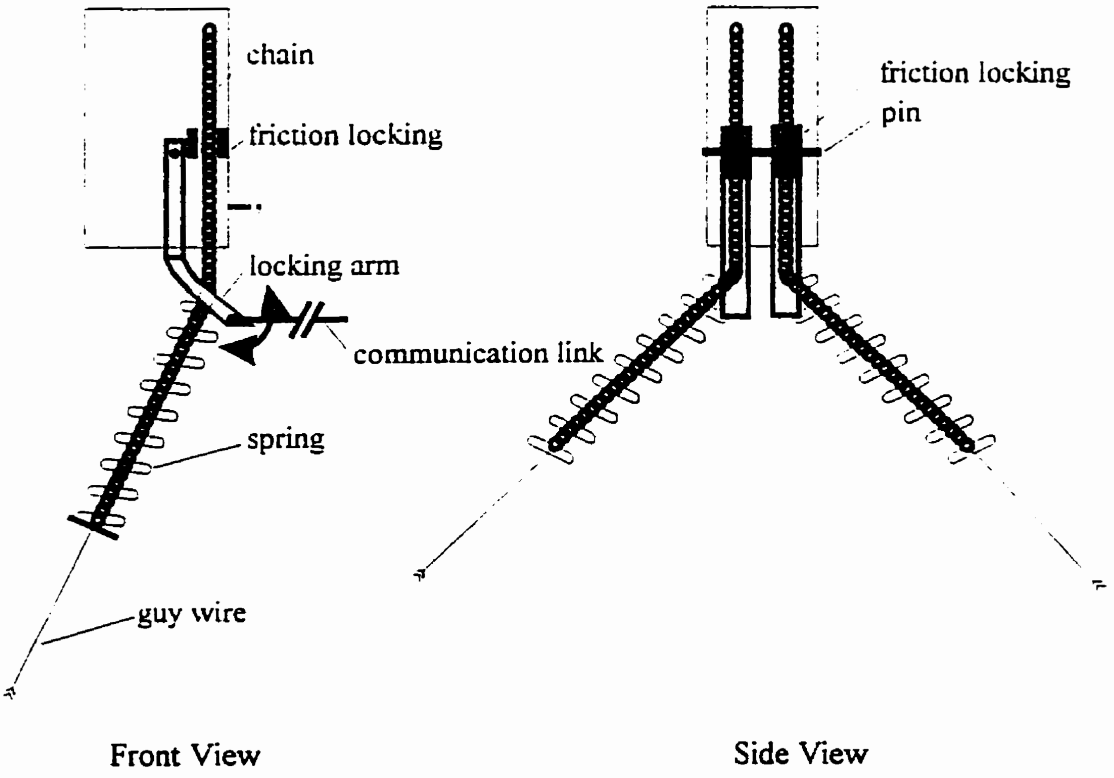


Figure A-7 Friction-Locking of Multiple Sprung Stabilizer

When no loads are acting against the tower, the guy-wire tension and communication link are balanced and the locking arm is held open to allow the chain to slide if the tower base heaves or settles. As loads act against the tower, the guy-wire tension increases on the loaded side, causing the locking arm to rotate about the pin and lock the chain in place. This method could be potentially mounted in the existing guy wire attachment points, producing a device similar in size to the Horizontal Sprung Stabilizer.

Appendix B Design Requirements

Introduction

This appendix lists the six design requirements to be met.

Design Requirements

It is necessary for the device to satisfy the following:

1. The device must be able to retrofit into a typical A-203 lattice tower, where small modifications can be made to the tower on site.

2. The base of the tower must be able to displace vertically a range of ten inches, allowing the tower to heave four inches or settle up to six inches from its mean installed position.

3. The four guy wire pairs are to maintain a no-wind load tension between 500 and 4,000 lb. A modulus of elasticity of $E=20x10^6$ psi can be used for the guy wires.

4. The device must support the tower for a maximum wind load of 26,757 lb of lateral force, based on an ultimate guy-wire anchor load of 30,000 lb.

5. The guy wires must maintain their ability to resist the tower from leaning.

6. The guy wires must also maintain their ability to resist twisting of the tower about its vertical axis.

Appendix C Design

C.1 Introduction

An overview of the Guy-Wire Tension Stabilizer(GTS) operation and design is discussed in this appendix. Section 2 describes the GTS operation and the new guy-wire geometry as well as the loads which act on the tower. Section 3 gives a description of the GTS components, including the acting loads and resulting stresses in each component.

C.2 Design

C.2.1 Overview of GTS

The GTS system allows the guyed tower to vertically displace ten inches. From its mean installed position, the tower can heave four inches and/or settle six inches, maintaining acceptable tension in the guy wires. Figure C-1 shows the components of the GTS, namely the locking ring, cross arm, compensating spring, compensating rod, and guide slots.

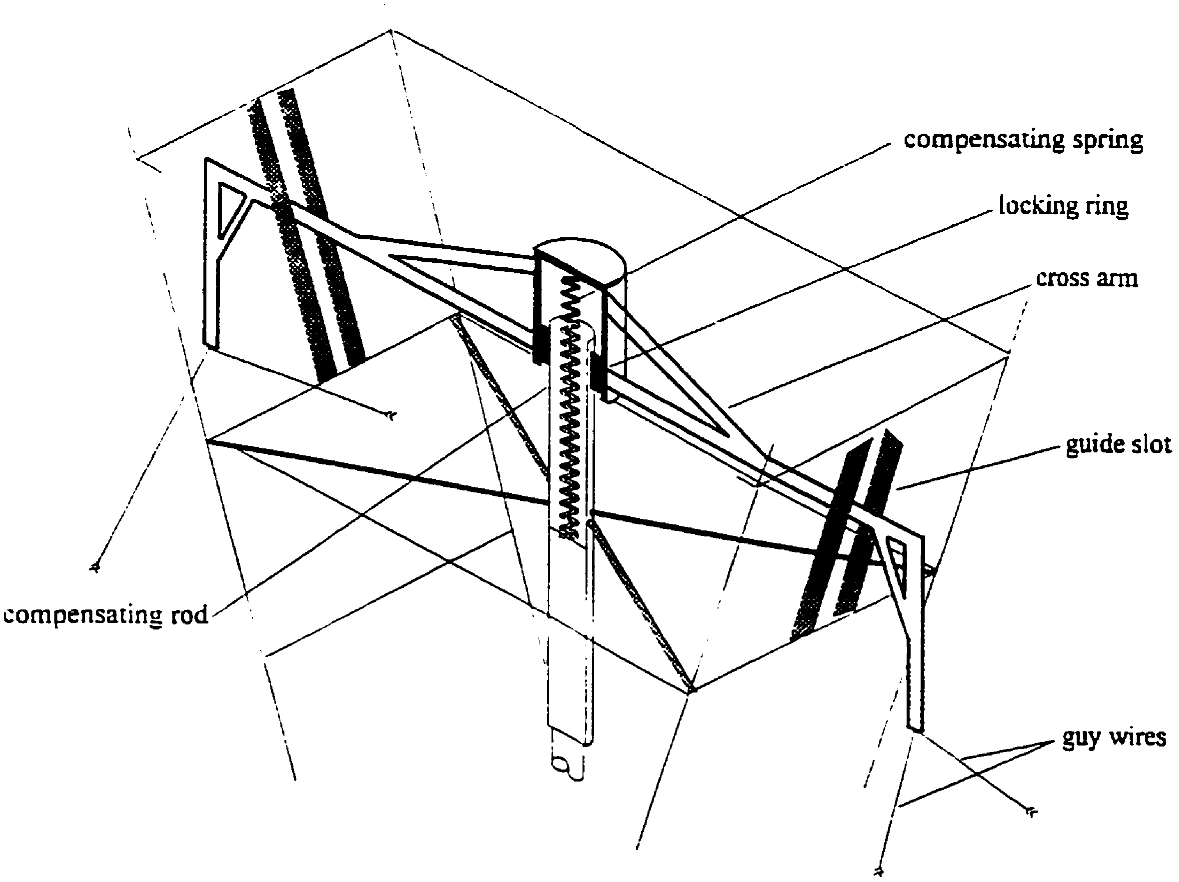


Figure C-1 GTS Components

In normal operation, the four guy wires are in equal tension, and the resultant of the guy-wire forces is in equilibrium with the compressive force at the top of the compensating spring. As the tower base heaves, the compensating rod slides up through the locking ring, compressing the compensating spring, thereby lifting the guy wires only a small amount compared to the tower. Similarly, as the tower settles, the compensating rod slides down through the locking ring, and the compensating spring extends to hold the guy wires at approximately the same position. Outside of this ten-inch range, the tower acts like a conventional tower.

Under certain conditions, the four guy wires are not in equal tension. As strong winds act against the tower and conductors, there is an increase in tension in the two windward guy wires and a decrease in tension in the leeward guy wires. Loss of a conductor will also result in a difference in tension in the guy wires. In each case, the difference in tension causes the locking ring to tilt and lock against the compensating rod. If the locking did not occur, the increased guy-wire tension would compress the compensating spring and allow additional leaning of the tower.

As shown in Figure C-2, transverse winds against the tower and conductors cause the cross arm to tilt with a downward force F_V, forcing the locking ring to tilt against the compensating rod into a locked position, using friction.

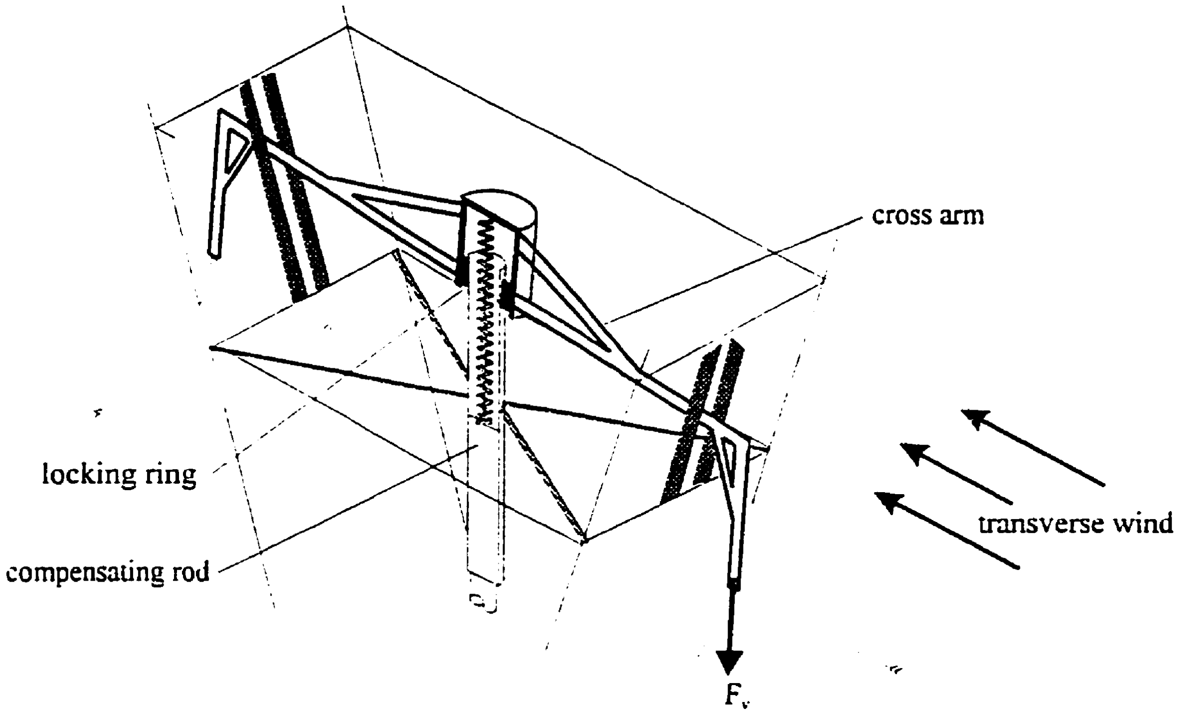
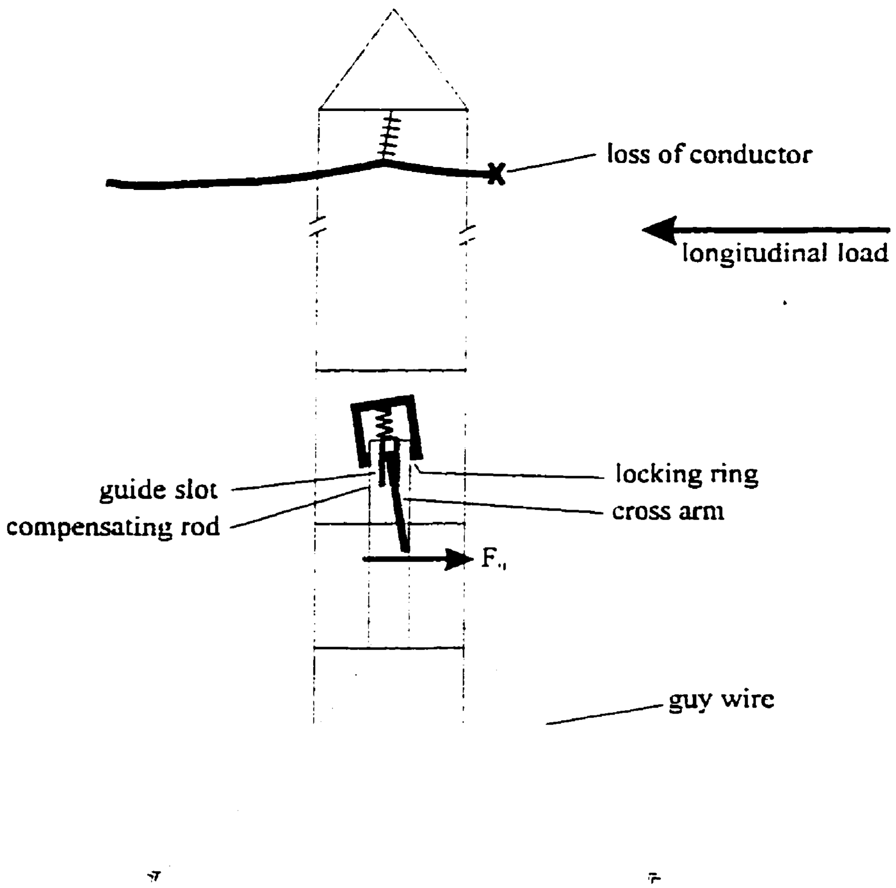


Figure C-2 GTS Locked by Transverse Winds

Figure C-3 illustrates a longitudinal load acting on the tower caused by a broken conductor (or by strong longitudinal winds acting along the conductors). The longitudinal load produces a resultant horizontal force F_H from the guy wires which creates a moment in the cross arm, causing the arm to rotate inside the guide slots, and force the locking ring to lock against the compensating rod.



Side View

Figure C-3 GTS Locked by Longitudinal Load

Regardless of the value of the load or its direction, the frictional locking force between the locking ring and compensating rod will always be able to restrain the compensating spring from displacing.

The cross arm also provides resistance to tower twisting as shown in Figure C-4. As the guide slots twist with the tower, a force F_t is applied to the cross arm as shown, and the twisting force is restrained by the two guy wire reaction forces R.

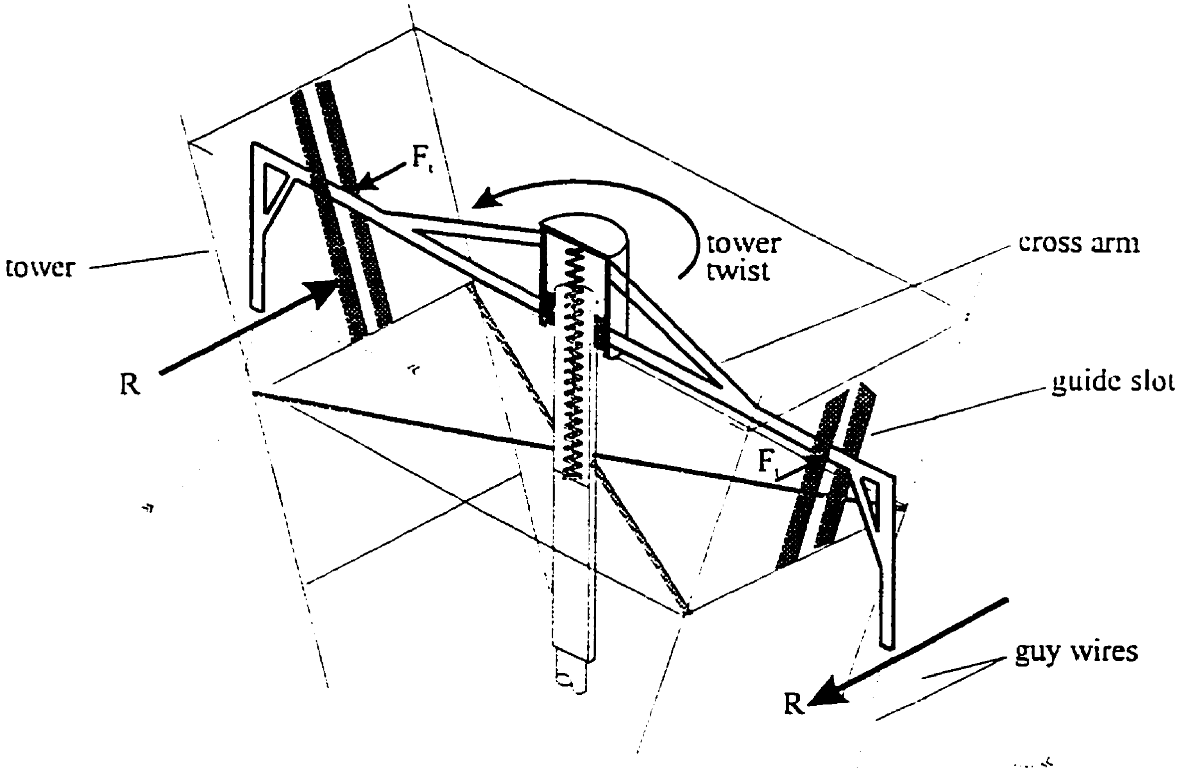


Figure C-4 Guide Slots Restraining Tower from Twisting

C.2.2 Guy Wires

The guy wires are no longer attached directly to the tower but to the ends of the cross arm. The GTS geometry is shown in Figure C-5, where the guy-wire height h= 67.167 ft, guy-wire anchor spread w= 58.279 ft and guy-wire angle θ= 49.027°.

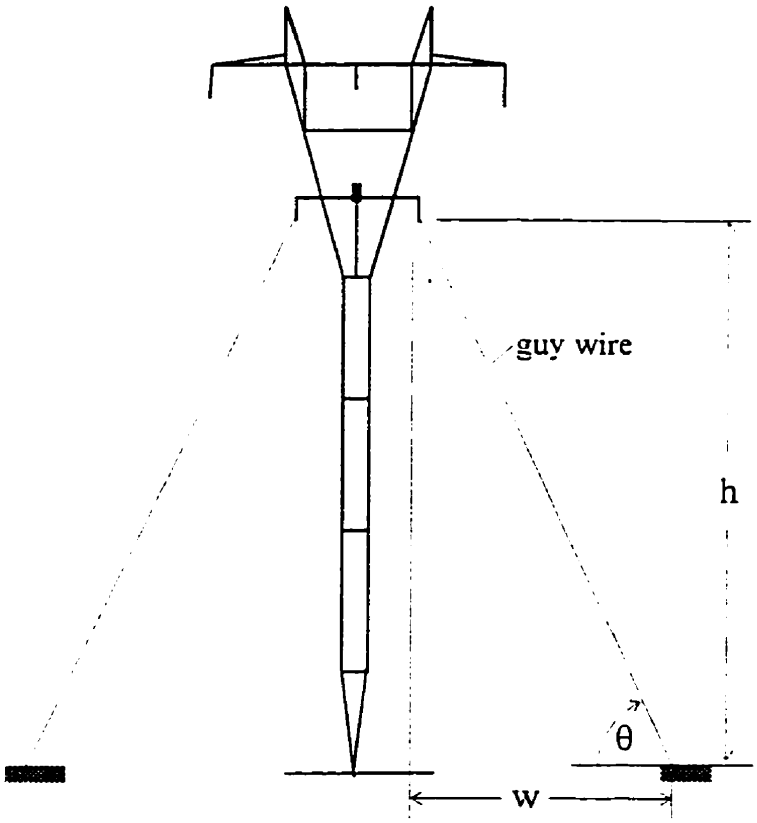


Figure C-5 GTS Guy Geometry

The guy-wire angle is 1.76° lower than that which occurs with a conventional tower. For designing the GTS, the maximum tower loads were based on the guy-wire anchor strength for a conventional tower. The ultimate guy-wire anchor tension is

$$T_{ult} = (23\ 000 \text{ lb})\ (1.3 \text{ F.S.})$$

$$T_{ult} = 30\ 000 \text{ lb.} \qquad (1)$$

A force diagram for one guy wire at T_{ult} is shown in Figure C-6, where the weight of the guy wire is neglected.

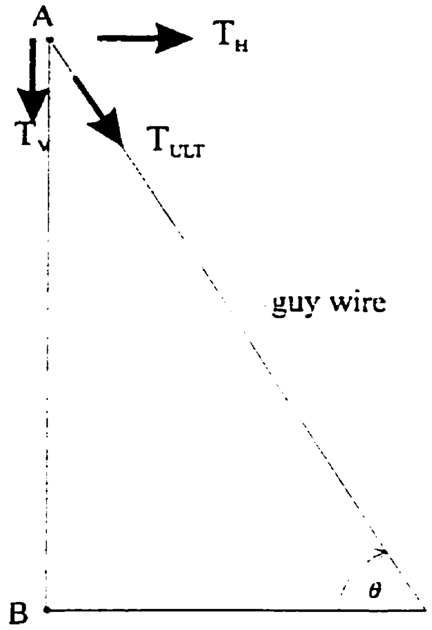


Figure C-6 Force Diagram for Guy Wire

where

T_H= 13 402.5 lb

T_V= 23 253.9 lb.

Since there are two guys on each side of a tower, the maximum lateral load at A is twice T_H or

$$T_H \text{ max} = (13\ 402.5)(2) = 26\ 747.0 \text{ lb} \qquad (2)$$

and the maximum tower shaft load at B is the sum of the vertical components for all four guys

$$\text{Tower Shaft Load max} = (23\ 253.9)(4) = 93\ 015.4 \text{ lb.} \qquad (3)$$

C.3 GTS Components

C.3.1 Locking Ring

The locking ring consists of a two-inch-thick tapered ring that is set inside a 16-inch diameter steel cap as shown in Figure C-7. The ends of the locking ring follow a sinusoidal wave, producing a variation in length from a maximum of 12 inches to a minimum of 6 inches. The variation allows just the right amount of locking force against the compensating rod for the given wind or load direction.

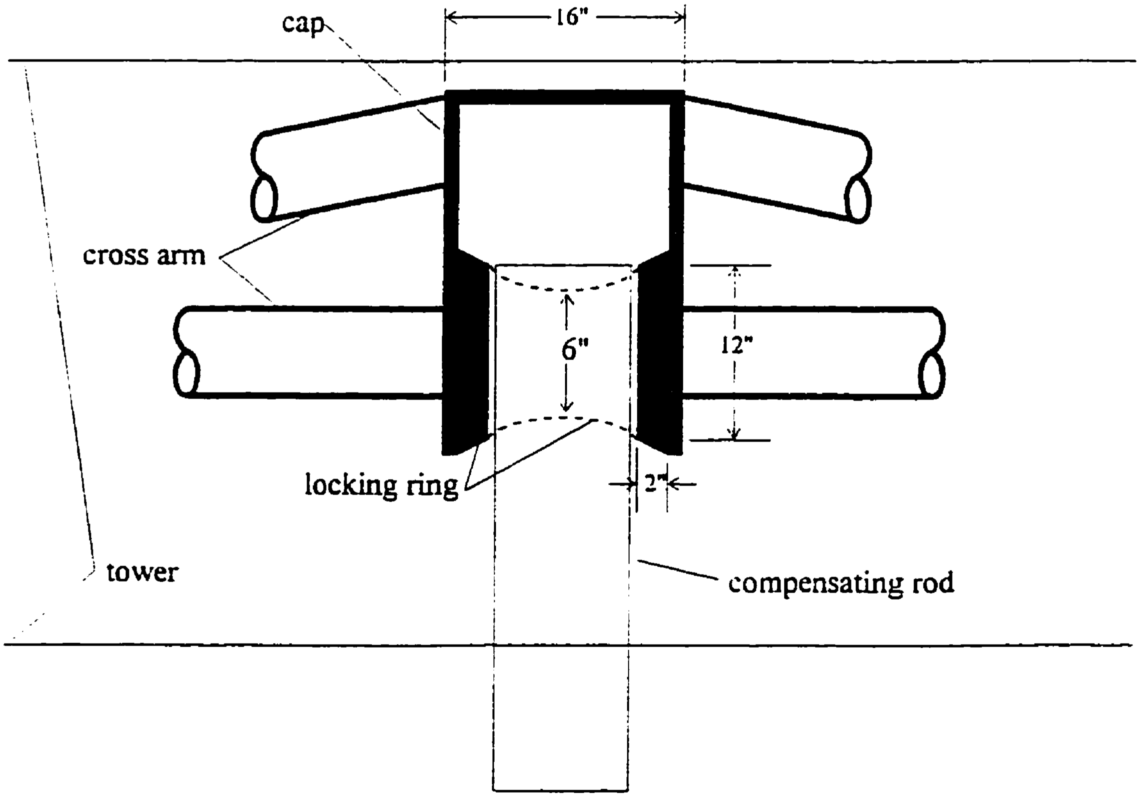


Figure C-7 Locking Ring

As stated earlier, the locking ring will tip and lock in place using friction as loads act against the tower. The greatest tipping will take place under longitudinal loading as shown in Figure C-8, where the tipping angle ϕ shown is defined as

$$\tan\phi = (D-d)/l$$

or

$$\phi = \arctan (D-d)/l. \quad (4)$$

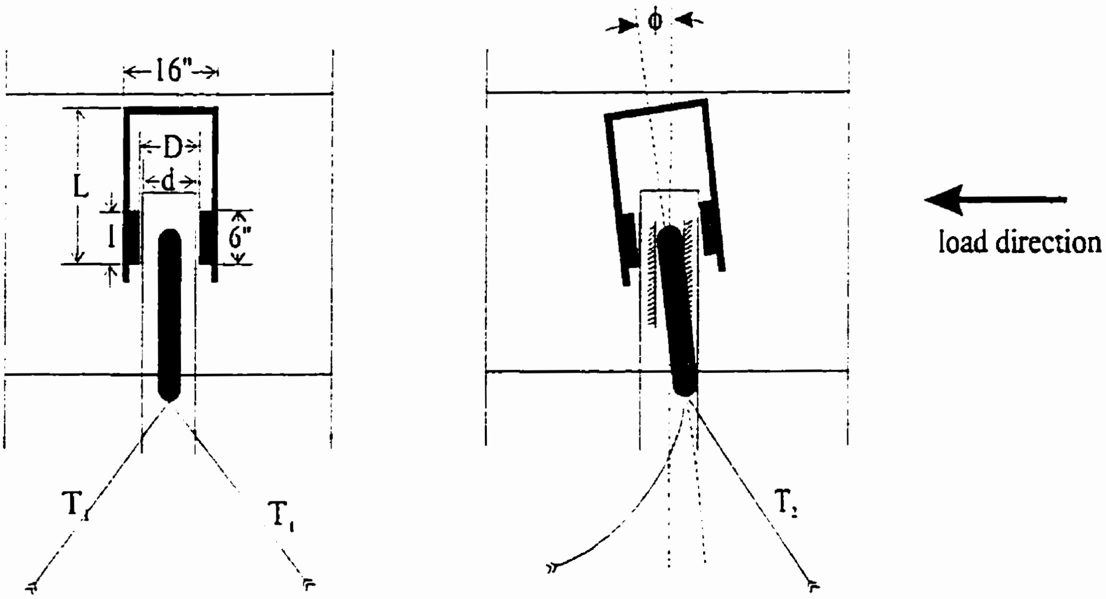


Figure C-8 Locking Ring in Unlocked and Locked Positions

The maximum allowable tipping angle occurs when the inside of the steel cap rubs against the compensating rod, restricting the locking ring from properly locking where

$$\tan\phi_{allow} = t/L$$

With the ring thickness t=1-15/16" and cap length L=19", the allowable tipping angle is $\phi_{allow}=5.82°$. With a 1/16" clearance between the ring and compensating rod and D= 10-1/16", d=10" and l=6", an acceptable tipping angle of $\phi=0.597°$ will occur.

The frictional locking forces between the locking ring and compensating rod are solved and to verify the friction locking for any wind direction, both traverse and longitudinal load cases are analyzed. Figure C-9 shows the force diagram for traverse loading.

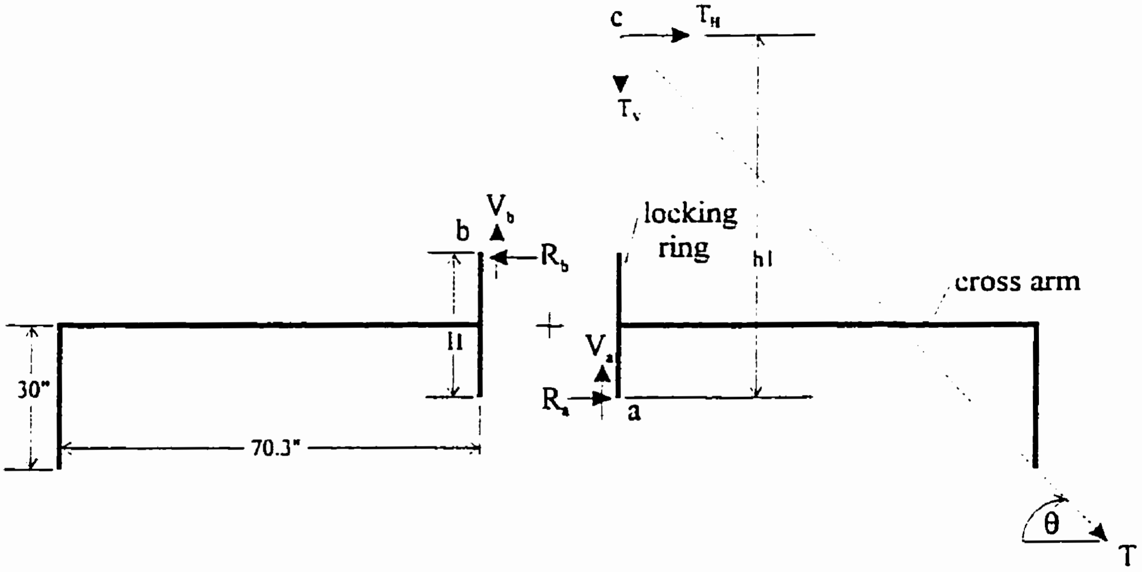


Figure C-9 Force Diagram for Transverse Loads

Guy-wire tension T can be transposed to point c and summing moments about point a gives

$$T_H (h) - R_b (l) = 0$$

or

$$R_b = \frac{T_H h_1}{l_1} \qquad (5)$$

Summing forces in the horizontal direction gives

$$R_a = R_b - T_H \qquad (6)$$

The minimum coefficient of friction, μ_f required for friction locking is

$$\mu_{f_{\min}} = \frac{T_V}{R_a + R_b} \tag{7}$$

The force diagram for longitudinal loading is shown in Figure C-10.

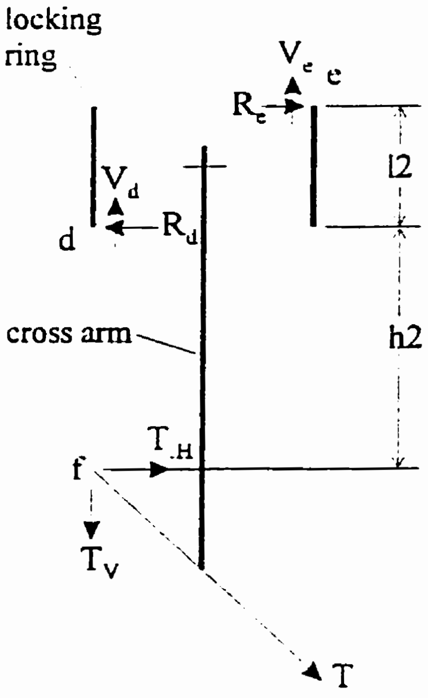


Figure C-10 Force Diagram for Longitudinal Loads

Transposing the guy-wire tension to point f and summing moments about point d gives

$$T_H(h) - R_e(l) = 0$$

or

$$R_e = \frac{T_H h_2}{l_2} \tag{8}$$

Summing forces gives

$$R_d = R_e + T_H \tag{9}$$

and the minimum coefficient of friction required for locking is

$$\mu_{f_2\min} = \frac{T_V}{R_d + R_e} \tag{10}$$

The locking ring values are h_1=56.9",l_1=12",h_2=21.2", and l_2=6". For the maximum tension of 30,000. lb, R_a= 100 172. lb, R_b= 126 919. lb, R_d= 121 284. lb, R_e= 94 537 lb, $\mu_{f1\min}$= 0.205, and $\mu_{f2\min}$= 0.216.

A coefficient of friction greater than 0.22 is required between the ring and compensating rod. Although steel on steel would have large enough coefficient of friction, having similar metals in contact may produce galling from sliding and corrosion of the steel may interfere with a 1/16" clearance fit. A compensating rod made of stainless steel and locking ring of phosphor bronze may produce an excellent combination. The coefficient of friction between the phosphor bronze and steel is approximately 0.34 [4].

The resulting maximum bending stress in the locking ring and cap assembly is given by [5]

$$\sigma_{\max} = \frac{M_{\max}\frac{D_o}{2}}{I} \tag{11}$$

with the maximum bending moment at point b

$$M_{\max} = T_H(h_1 - l_1) \tag{12}$$

and moment of inertia of the cap

$$I = \frac{\pi}{64}(D_o^4 - D_i^4). \tag{13}$$

Using the outer and inner diameters of the cap, D_O=16." and D_i=14." the bending stress is

$$\sigma_{\max} = \frac{(1.202E6in\cdot lb)(8in)}{1331.in^4} = 7,223.7psi$$

C.3.2 Cross Arm

The cross arm is an important part of the GTS because it restrains the tower from twisting. The cross arm is attached to either side of the locking ring as shown in Figure C-11.

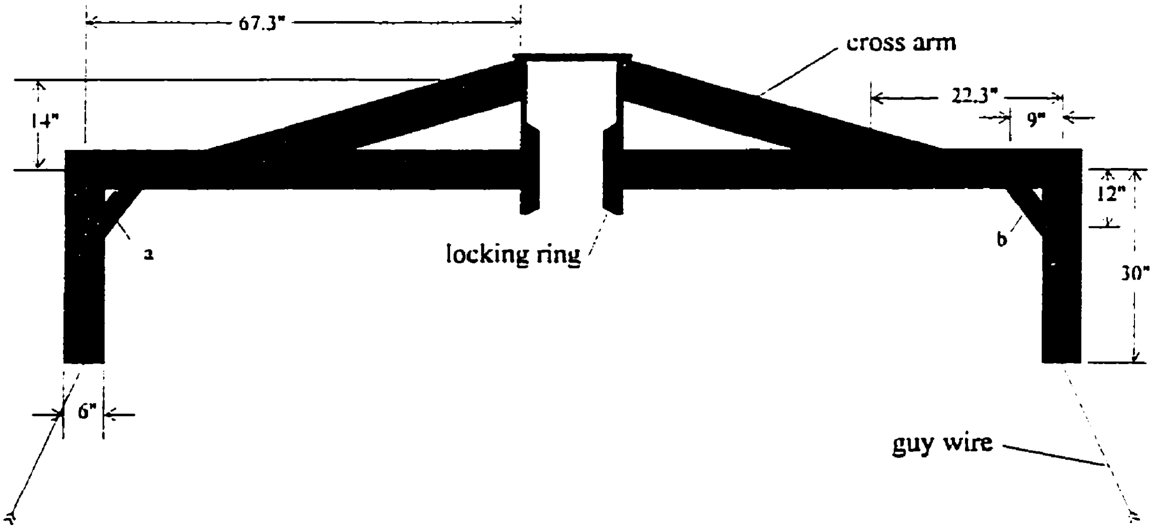
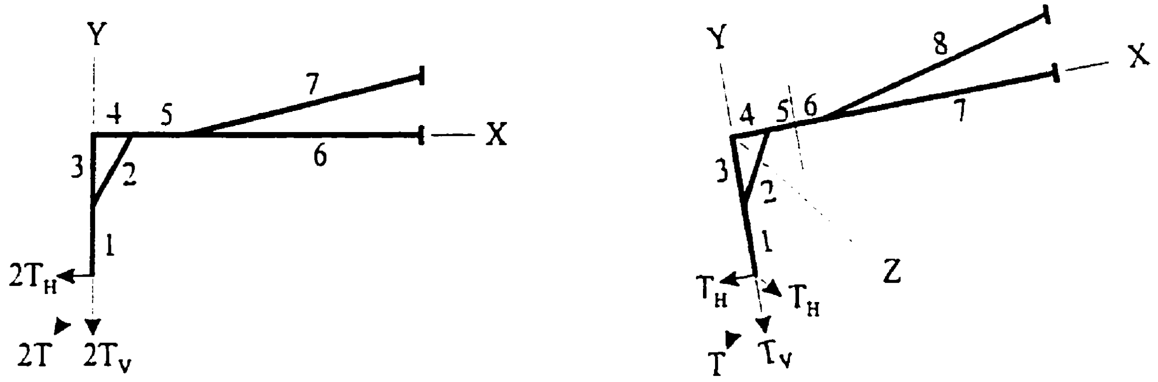


Figure C-11 Cross Arm

The dimensions of the cross arm are shown in the above figure. The arm consists of 6-inch diameter steel tubing a half inch thick, except for members a and b, which are 4-inch diameter of the same thickness.

A force diagram for the maximum guy-wire loads on the cross arm for traverse and longitudinal cases is shown in Figure C-12. The applied load is shown as T, for the guy-wire tension; also shown is the vertical and horizontal components, T_V and T_H, respectively.



traverse loads

longitudinal loads

Figure C-12 Force Diagram for Cross Arm

A simple finite element program was used to solve for the stresses in each of the elements shown(numbered 1-7,1-8). Table I shows the maximum shear stress in each element under maximum loading conditions.

TABLE I Maximum shear stress in cross arm

Element No.	Traverse Loading [ksi]	Longitudinal Loading [ksi]
1	24.5	17.0
2	20.1	15.8
3	18.6	27.6
4	16.5	16.7
5	19.0	27.3
6	14.8	26.8
7	15.5	11.0
8	-	18.8

The largest shear stress of 27.6 ksi occurs in element 3 for longitudinal loading. A grade 60 ASTM A572 structural steel could be used for the cross arm, which has a tensile yield strength σ_y=60 ksi. A corresponding shear strength of half the tensile strength gives τ_y=30 ksi. Using the Maximum-Shearing-Stress Criterion for a ductile material under plane stress,

$$\tau_{\max} < \tau_y$$

or

$$27.6\text{ksi} < 30\text{ksi}$$

therefore the stresses are acceptable.

C.3.3 Compensating Spring

The compensating spring provides the tension in the guy wires. The spring is set inside the compensating rod and supports the cross arm inside the steel cap as shown in Figure C-13.

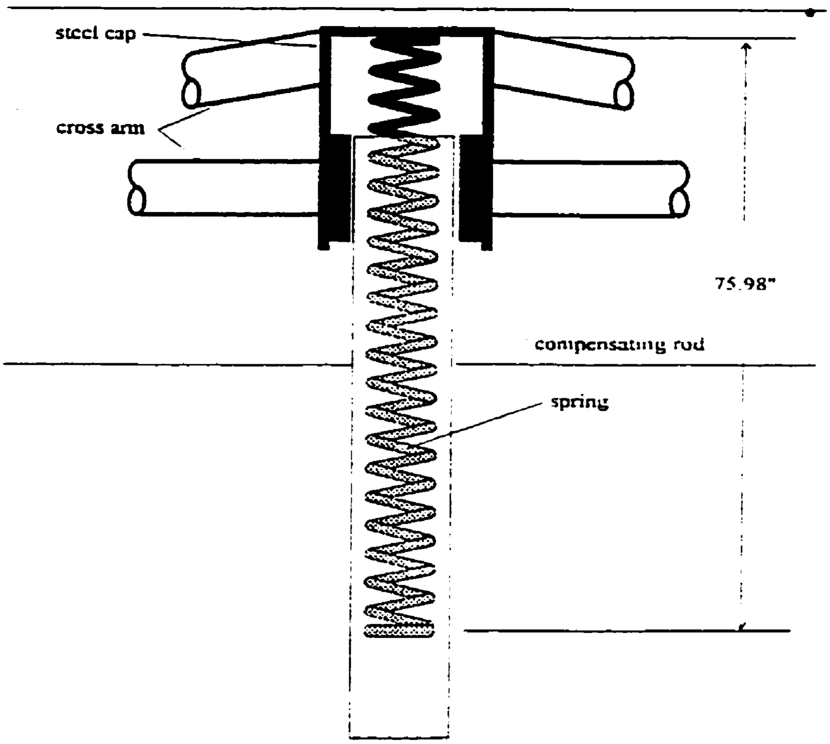


Figure C-13 Compensating Spring

The dimensions of the unloaded spring are shown in Figure C-14.

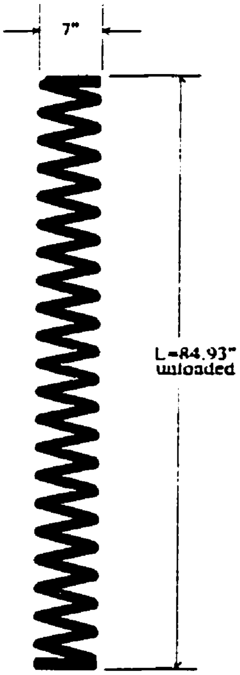


Figure C-14 Unloaded Compensating Spring

The spring constant for the helical compression spring is found by[6]

$$k = \frac{GR}{4c^4 N_c} \tag{14}$$

where G is the modulus of elasticity for shear stress, R is the outer radius of the spring minus half the spring wire thickness, and N_C is the number of coils. The value for c is

$$c = \frac{2R}{d} \tag{15}$$

where d is the diameter of the spring wire.

$$c = \frac{2(2.875)}{1.25} = 4.6$$

$$k = \frac{11.5E6(2.875)}{4(4.6)^4 47} = 392.8 \tfrac{lb}{in}$$

The spring has an unloaded length of 84.93 inches and will be compressed to a working range of 75.98 to 65.98 inches in length. This will give guy-wire no-wind tensions of 700 to 1963 lb respectively. The resulting vertical tower loads are just 3515.0 to 7442.9 lb over the 10-inch vertical range of tower displacement.

The stress in the spring is given by

$$\tau = k_s \frac{16PR}{\pi d^3} \tag{16}$$

where

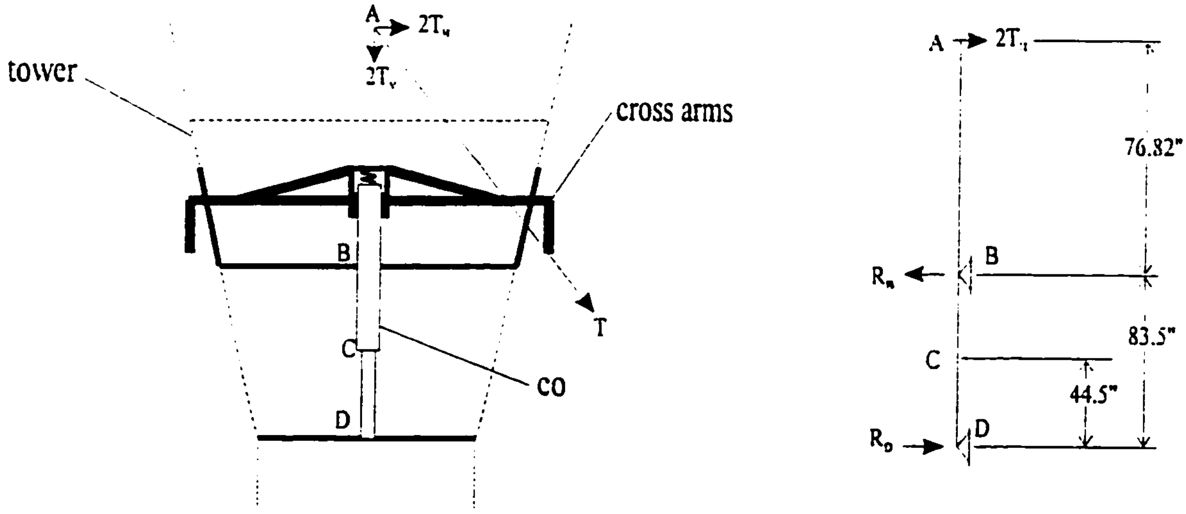
$$k_s = 1 + \frac{0.615}{c} \tag{17}$$

and P is the applied compressive spring force.

The shear stress in the spring through the 10 inch range is 29.86 to 63.23 ksi with τ_{allow} of 80 ksi being common for helical compression springs.

C.3.4 Compensating Rod

The compensating rod is positioned in the centre of the tower, where it allows the locking ring to slide or lock near the top end of the rod. To resist the high locking ring forces, it continues to extend down through the tower for seven feet. The forces acting on the rod are shown in Figure C-15.



(a) (b)

Figure C-15 Force Diagram for Compensating Rod

If the rod is secured to the tower at points B and D and using the larger traverse loading condition, we solve for the two reactions, R_B and R_D.

Taking moments about B gives

$$2T_H(76.82) - R_D(83.5) = 0$$

$$R_D = 24{,}607.lb \tag{17}$$

Summing forces gives

$$-T_H - R_D + R_B = 0 \tag{18}$$

$$R_B = 51{,}354.lb$$

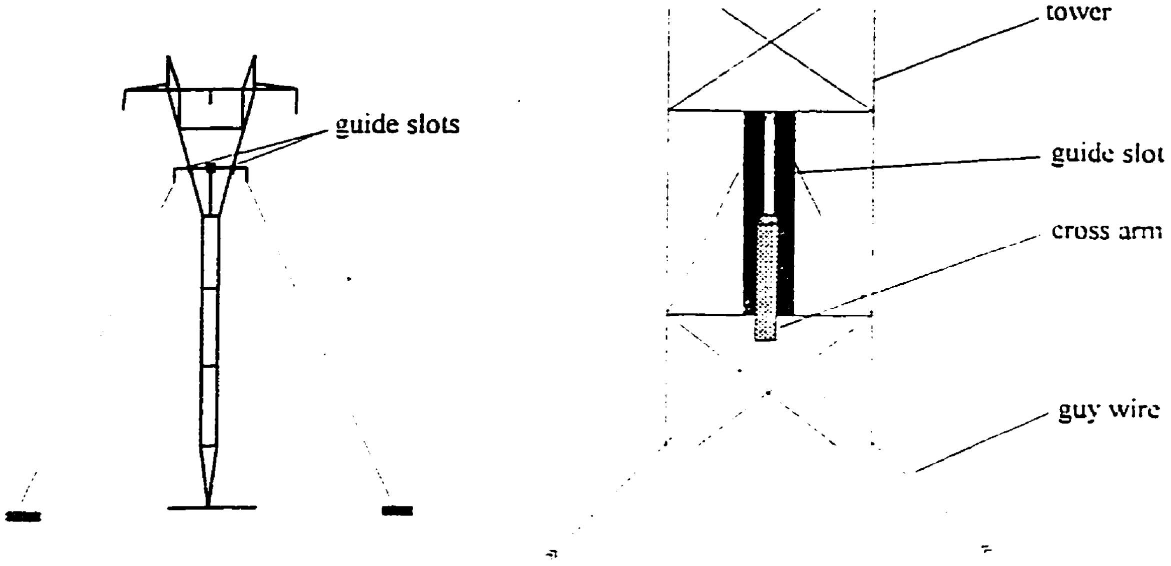
The top section of the rod AC is 10-inch in diameter and 1-inch thick, and the lower section CD is 8-inch in diameter and 1-inch thick. Using similar methods as for the locking ring in Section C.3.2, we find the maximum bending stresses to occur at points B and C where

$$\sigma_B = \frac{26747[\text{lb}](76.82[\text{in}])5[\text{in}]}{289.84[\text{in}^4]} = 35.45\text{ksi}$$

$$\sigma_C = \frac{24607[\text{lb}](44.5[\text{in}])4[\text{in}]}{137.45[\text{in}^4]} = 31.87\text{ksi}$$

C.3.5 Guide Slots

The guide slots support the cross arm on both sides of the tower, as shown in Figure C-16.



Front View

Side View of Slot

Figure C-16 Guide Slots

The slots restrain the tower from horizontal forces caused by tower twist, but allow the cross arm unrestricted vertical motion through the slot. The slots also allow the cross arm to rotate under longitudinal loading and to tilt under traverse loading.

The largest stress in each slot will occur when the cross arm acts at the middle of the slot as shown in Figure C-17.

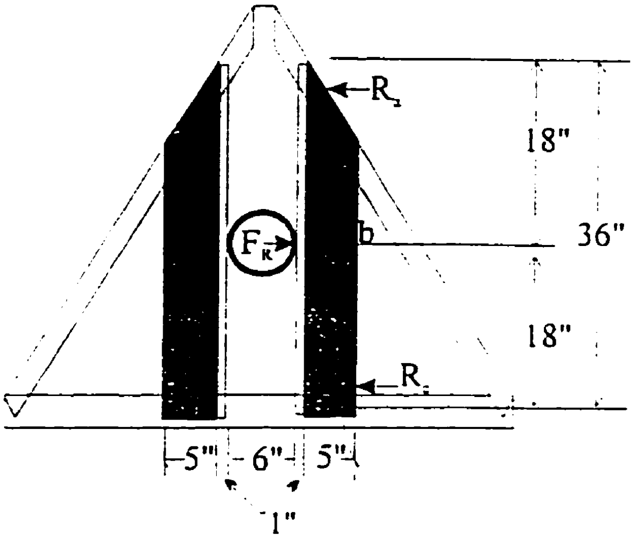


Figure C-17 Guide Slot Forces

The maximum value for F_R=22,056.9 lb was found using the finite element analysis in Section 3.3 for node 5 under longitudinal loading. Each member is made from a 1x12 inch plate attached to 2x5x1/4 inch steel tubing. To reduce wear in the slot, a strip of phosphor bronze could be used between the guide slots and cross arm.

The maximum bending stress in a slot occurs at point b, where

$$M_{max} = (\frac{22056.9}{2})18 = 198,512.1 in \cdot lb$$

$$I = 10.4427 in^4$$

$$\sigma_b = \frac{198,512(2.5)}{10.4427} = 47.5 ksi$$

The maximum contact stress between the cross arm and guide slot is found by[7]

$$\sigma_c = 0.591\sqrt{\frac{pE}{D}}$$

where p is the applied force per inch across the plate and D the diameter of the cross arm.

$$\sigma_c = 0.591\sqrt{\frac{(22{,}056.9/12)30\mathrm{x}10^6}{6}} = 56.6\mathrm{ksi}$$

Appendix D Retrofit of the GTS and Costs

D.1 Introduction

In order for the GTS system to be implemented successfully, it must be able to be secured into an existing tower. Section 2 of this Appendix describes the supporting braces for the GTS. Section 3 gives a brief cost estimate of the GTS device and its supporting members.

D.2 Retrofit of the GTS

The purpose of this section is to discuss one method of retrofitting the GTS into an existing tower. This involves installing braces, guide rails, and the guy wires to the GTS.

One method to attach the device to the tower is by way of braces, as shown in Figure D-1.

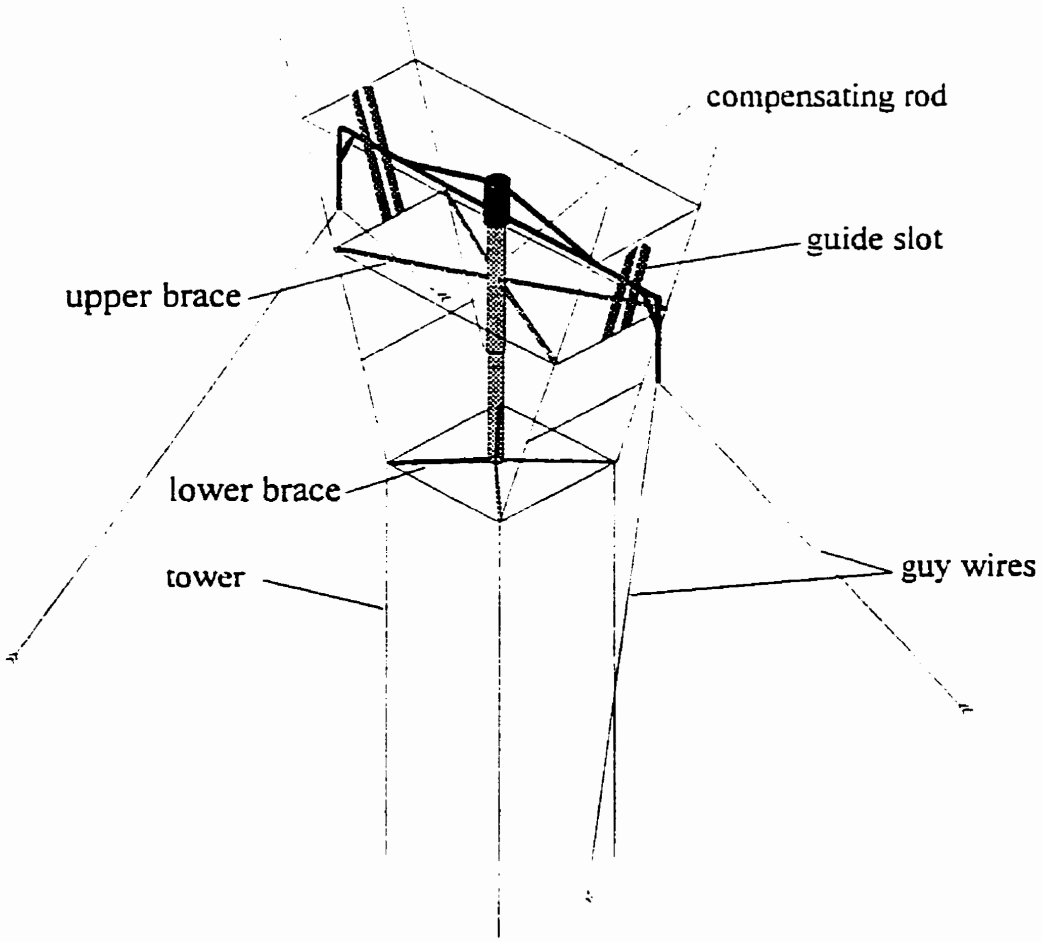
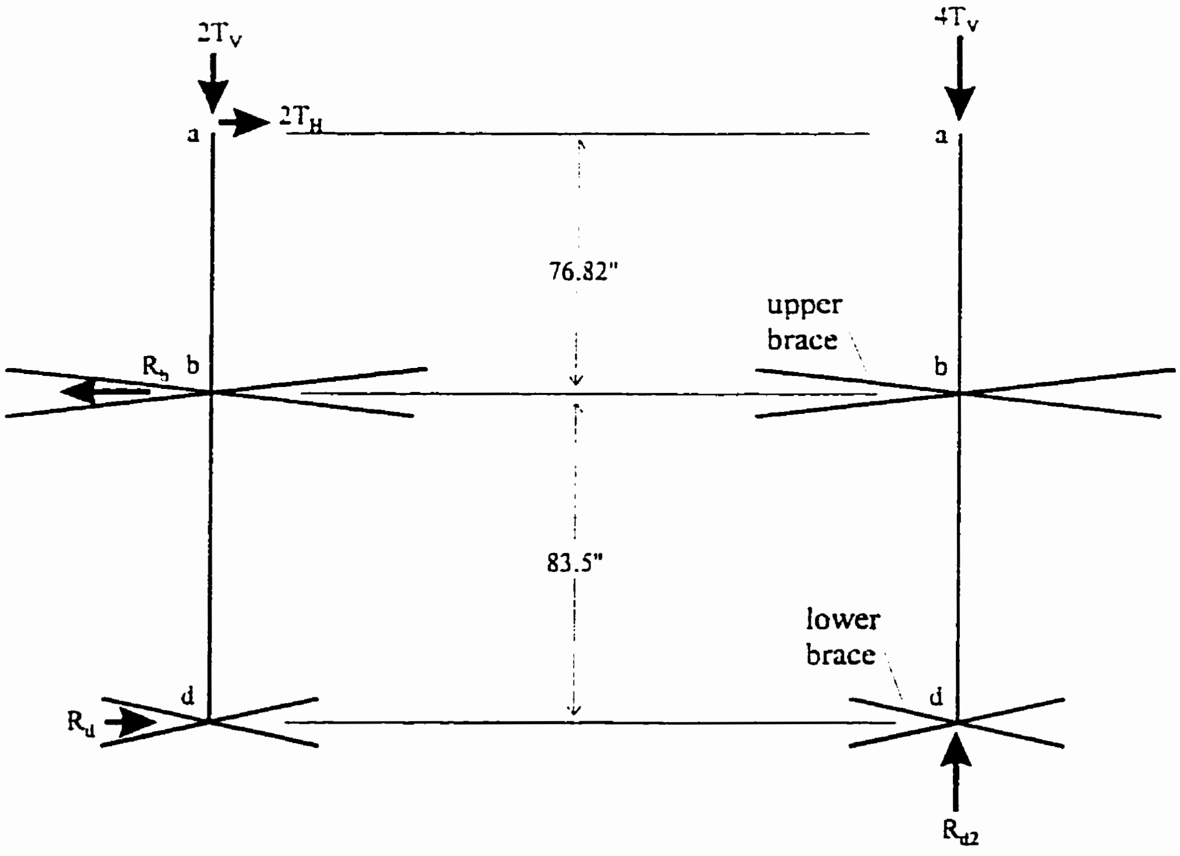


Figure D-1 GTS Braces

As illustrated in the figure, two braces can be used, an upper and lower. The upper brace meets near the bottom of the guide slots and the lower brace is set where the tower shaft cross section reduces to a square.

To design the braces as small as possible, the lower brace will resist the vertical loads. Figure D-2 shows the force diagram for the two highest loading cases.



(a) (b)

Figure D-2 Maximum Brace Loads

Figure D-2(a) shows the case for maximum traverse load conditions, where the reacting forces are

$$R_b = 51{,}354.lb$$

$$R_d = 24{,}607.lb$$

The upper brace is made of 2x4x1/4 inch steel tubing, which crisscrosses in the tower as shown in Figure D-3.

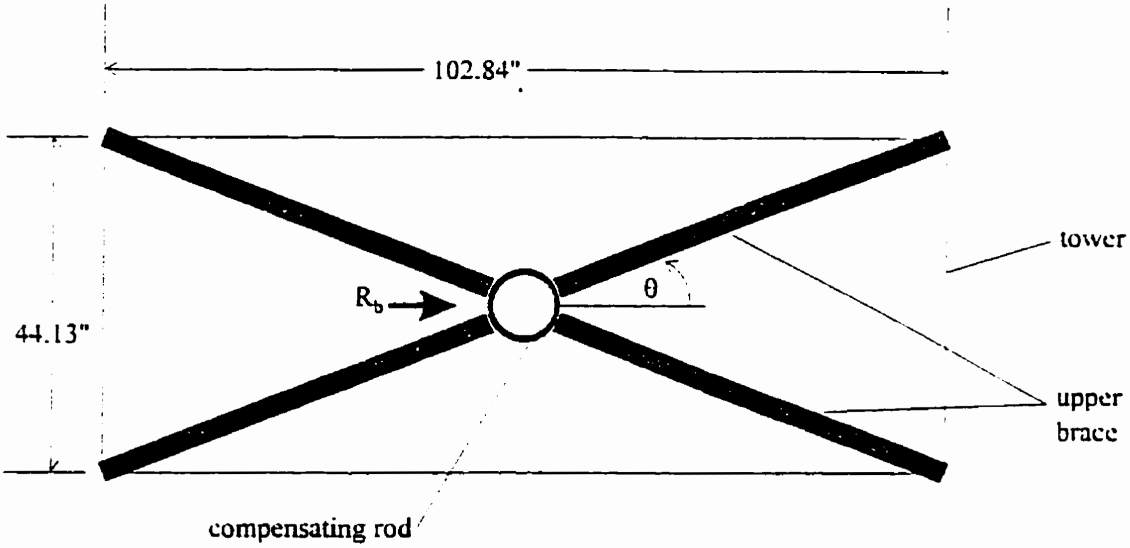


Figure D-3 Top View of Upper Brace

Since each of the four upper brace members will support the rod, the axial load in each will be

$$F_{axial} = \frac{51,354}{4}\sin\theta \tag{1}$$

where $$\theta = \tan^{-1}\left(\frac{44.13}{102.84}\right) = 66.78^{\circ}$$

therefore $$F_{axial} = 13,970.7 lb$$

The cross sectional area of each brace is A=2.75 in^2 and the axial stress is

$$\sigma_{axial} = \frac{13,970.7}{2.75} = 5,080.psi$$

The lower brace is made of 4x6x1/2 inch steel tubing as shown in Figure D-4

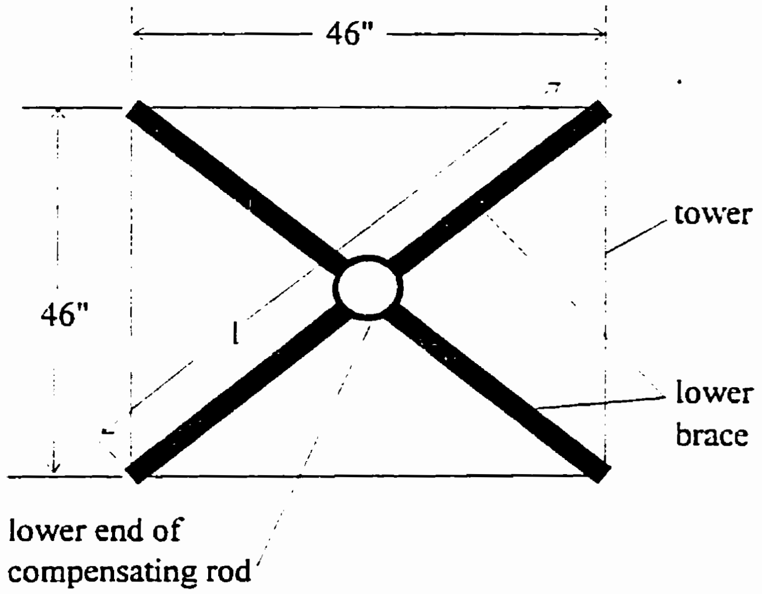


Figure D-4 Top View of Lower Brace

The bending stress in the brace caused by the vertical loading shown in Figure D-2(b) is given by

$$\sigma_b = \frac{Mc}{I} \tag{2}$$

where $$M = \frac{R_{d2}}{4}\left(\frac{l}{2}\right) = 23,281.5\left(\frac{65.05}{2}\right) = 757,275.3\text{in}\cdot\text{lb}$$

$$R_{d2} = T_V$$
$$I = 40.75\text{in}^4$$

giving $$\sigma_b = \frac{757,275.(3)}{40.75} = 55.75\text{ksi}$$

This stress is conservative because it assumes that only the lower brace is supporting the entire vertical load of the GTS.

The two guide slots must also be installed into the tower and are located in the area where the guys are normally attached to the tower as shown in Figure D-1.

Once the GTS is retrofit into a tower, the guy wires are simply unbolted from the tower and attached to the ends of the cross arm. Once attached to the GTS, the guy wires are tensioned until the locking cap lowers to the desired position.

D.3 Costs

Most of the GTS can be built using structural steel. We estimate manufacturing costs to be a dollar per pound of steel. The total weight of each component of the device is given in Table I.

TABLE I Weight of GTS Components

GTS components	weight [lb]	GTS support components	weight [lb]
cap and locking ring	571.02	guide slots	684 9
cross arm	769.63	upper brace	159.2
compensating rod	799.8	lower brace	307.0
compensating spring	296.0		
total 1	2,436.45	total 2	1151.1
Total 1+2	3,587.6		

The estimated manufacturing cost of the GTS components is $2,437 and the cost of the supporting members is $1150, totaling $3,588 per unit. As stated earlier, the additional costs of installation are not given, because they are dependent on a number of variables, such as location of towers, number of units installed and exact details of installation.

Appendix E Mathematical Analysis of Guyed Transmission Towers

E.1 Introduction

This Appendix deals with the mathematical analysis of guyed transmission towers. In Section E.2, the amount an existing tower can heave or settle is determined. In section E.3, the GTS is analyzed to determine its allowable vertical displacement. The results of the two towers are then compared.

E.2 Mathematical Analysis of Conventional Tower Vertical Displacement

It is desirable to first determine the heave and settlement characteristics of the conventional tower. The geometry of a typical conventional tower is shown in Figure E-1.

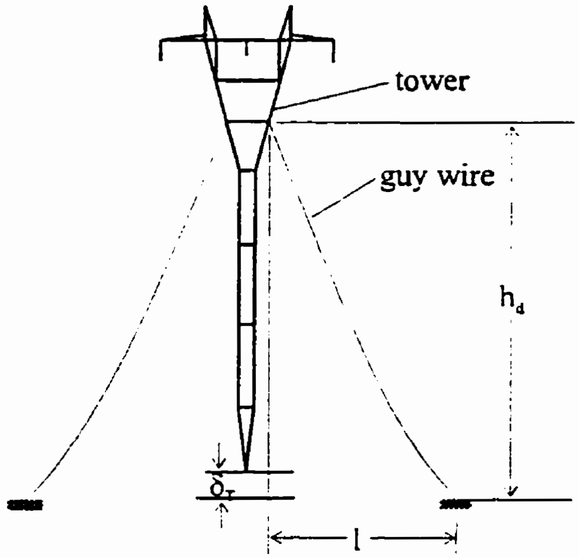


Figure E-1 Geometry of Conventional Tower (typical)

Because of symmetry, only one of the four guy wires is analyzed; the loads and deflections of the four guys will all be equal. The guy wire shown has a height h_d, spread l, and the vertical displacement of the tower base is δ_T.

The vertical displacement of the tower base is divided into three components as shown in Figure E-2. The first component is due to the change in guy-wire sag, δ_1, the second component is due to stretch of the guy wire, δ_2, and the third component, δ_3, is due to the compression of the tower shaft. The sum of these three components gives the total displacement, δ_T, as shown schematically in the figure.

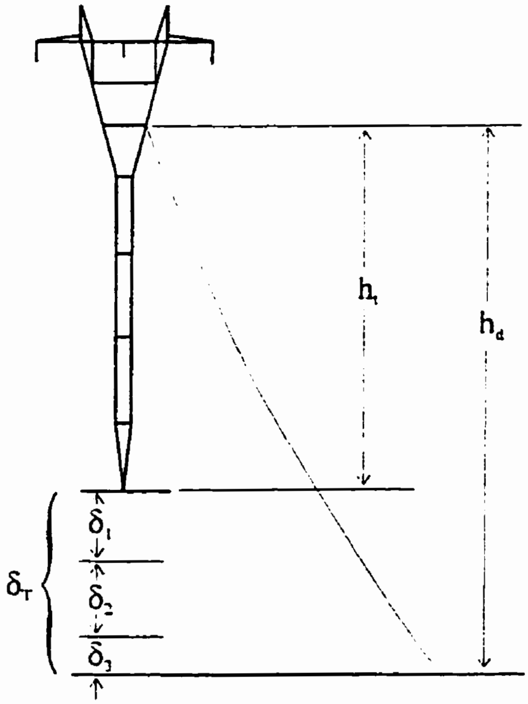


Figure E-2 Displacement Components for Conventional Tower

The first two components, $\delta_{1,2}$ can be solved for by treating the guy wire as a catenary. Knowing the physical properties of the guy and its geometry, we can find a relationship between the height h of the tower and the corresponding vertical tower load V on the tower shaft due to each guy. The guy-wire geometry is shown in Figure E-3; cartesian coordinates are used with the origin located at point A, and the distance along the stretched cable profile is given by p.

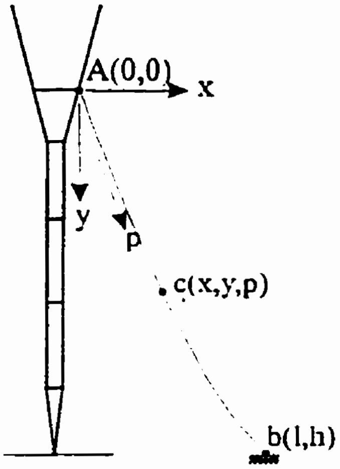


Figure E-3 Guy Wire Profile

A force diagram for a segment of the strained cable is shown in Figure E-4, where V is the vertical reaction at point A, H is the horizontal component of the cable tension T, and mg is the self-weight of the guy wire per unit length.

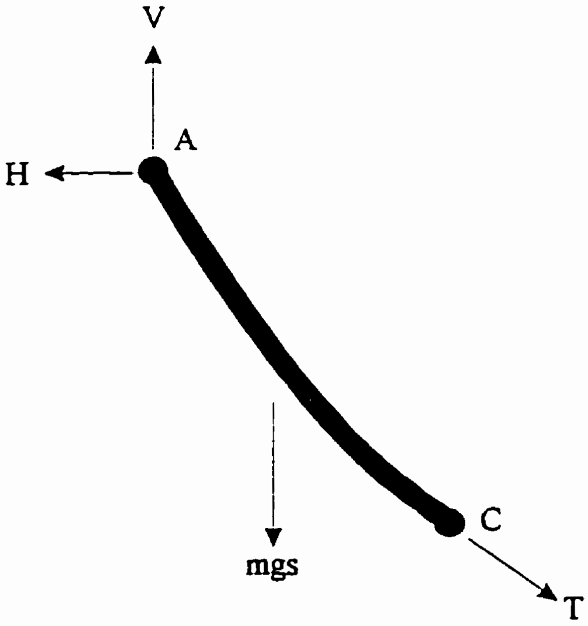


Figure E-4 Force Diagram of Guy Segment

Assuming the cable to be perfectly flexible, Figure E-5 shows the equilibrium of an isolated element[8].

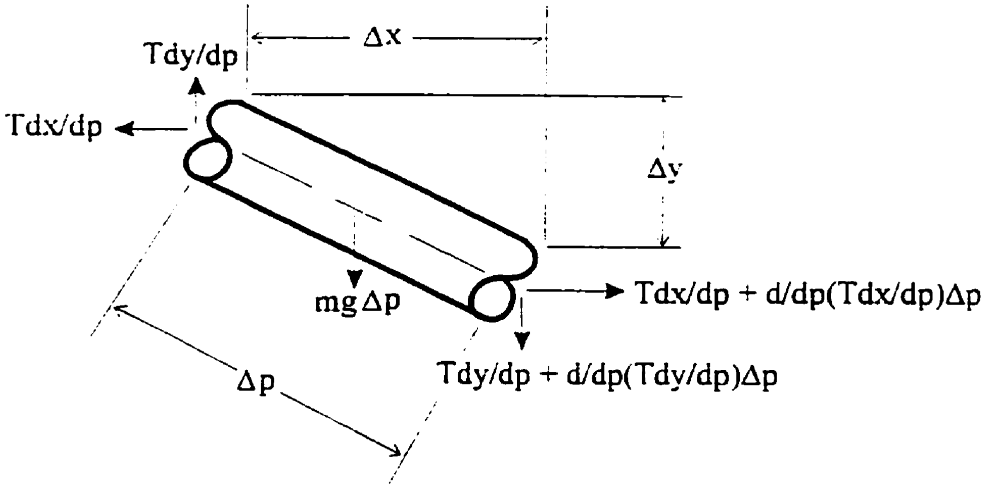


Figure E-5 Element Equilibrium of Guy

Summing the horizontal forces in the element gives

$$-T\frac{dx}{dp}+T\frac{dx}{dp}+\frac{d}{dp}(T\frac{dx}{dp})\Delta p=0$$

or

$$\frac{d}{dp}(T\frac{dx}{dp})=0 \qquad (1)$$

Summing the vertical forces gives

$$-T\frac{dy}{dp}+T\frac{dy}{dp}+\frac{d}{dp}(T\frac{dy}{dp})\Delta p+mg\Delta p=0$$

or

$$\frac{d}{dp}(T\frac{dy}{dp})=-mg. \qquad (2)$$

The geometric constraint for the guy wire is

$$\left(\frac{dx}{dp}\right)^2 + \left(\frac{dy}{dp}\right)^2 = 1 \quad . \tag{3}$$

Integration of equation (1) gives the first term for the geometric constraint,

$$T\frac{dx}{dp} = const. = H \tag{4}$$

Integration of equation (2) produces

$$T\frac{dy}{dp} = -mgs + V \tag{5}$$

where s is the length of the guy wire unstrained.

Substituting equations (4) and (5) into (3), we have

$$\left(\frac{H}{T}\right)^2 + \frac{1}{T}(-mgs + V)^2 = 1$$

or

$$T(s) = [H^2 + (V - mgs)^2]^{\frac{1}{2}} \tag{6}$$

which gives an expression for guy-wire tension as a function of s.

An expression of Hooke's Law is

$$T = E_w A_w\left(\frac{dp}{ds} - 1\right) \tag{7}$$

where E_W is the Young's modulus of the guy wire and A_W is the cross-sectional area of the guy wire unstrained.

The boundary conditions at either end of the guy are:

at A: $x = 0$, $y = 0$, $p = 0$, $s = 0$

at B: $x = l$, $y = h$, $p = L$, $s = L_0$

where L and L_0 are the strained and unstrained lengths of the guy wire respectively.

We can now derive a solution for x(s) and y(s) and substitute in the boundary conditions. For x(s) we use the relation

$$\frac{dx}{ds} = \frac{dx}{dp}\frac{dp}{ds} \tag{8}$$

- obtaining dx/dp from equation (4) and dp/ds from equation (7), we have

$$\frac{dx}{ds} = \frac{H}{E_w A_w} + \frac{H}{T} \tag{9}$$

- substituting in equation (6) for T gives

$$\frac{dx}{ds} = \frac{H}{E_w A_w} + \frac{H}{[H^2 + (V - mgs)^2]^{\frac{1}{2}}} \tag{10}$$

- integrating and using the boundary conditions at point A gives

$$x(s) = \frac{Hs}{E_w A_w} + \frac{HL_o}{W}\left[\sinh^{-1}\left(\frac{V}{H}\right) - \sinh^{-1}\left(\frac{V - mgs}{H}\right)\right] \tag{11}$$

where W is the weight of the guy wire (mgL_0). Finally, using the other boundary condition at point B we obtain

$$l = \frac{HL_o}{E_w A_w} + \frac{HL_o}{W}\left[\sinh^{-1}\left(\frac{V}{H}\right) - \sinh^{-1}\left(\frac{V - W}{H}\right)\right] \tag{12}$$

For y(s) we use the relation

$$\frac{dy}{ds} = \frac{dy}{dp}\frac{dp}{ds} \tag{13}$$

where dy/dp can be given by equation (5) and dp/ds by equation (7), again giving

$$\frac{dy}{ds} = \frac{1}{T}(V' - mgs)(\frac{T}{E_w A_w} + 1) \tag{14}$$

- substituting in equation (6) for T gives

$$\frac{dy}{ds} = \frac{1}{[H^2 + (V - mgs)^2]^{\frac{1}{2}}}(V - mgs)\left[\frac{[H^2 + (V' - mgs)^2]^{\frac{1}{2}}}{E_w A_w} + 1\right] \tag{15}$$

- now integrating and using the boundary conditions at point A gives the function

$$y(s) = \frac{Ws}{E_w A_w}\left(\frac{V}{W} - \frac{s}{2L_o}\right) + \frac{HL_o}{W}\left[\left\{1 + \left(\frac{V}{H}\right)^2\right\}^{\frac{1}{2}} - \left\{1 + \left(\frac{V - mgs}{H}\right)^2\right\}^{\frac{1}{2}}\right] \tag{16}$$

- applying the final boundary conditions at point B,

$$h = \frac{WL_o}{E_w A_w}\left(\frac{V}{W} - \frac{1}{2}\right) + \frac{HL_o}{W}\left[\left\{1 + \left(\frac{V}{H}\right)^2\right\}^{\frac{1}{2}} - \left\{1 + \left(\frac{V - W}{H}\right)^2\right\}^{\frac{1}{2}}\right] \tag{17}$$

For a maximum vertical tower load V, the displaced tower height h can be solved for by simultaneously solving equations (12) and (17) numerically.

Using the displaced tower height h, the vertical displacement can be found by

$$\delta_{1,2} = h - h_t \tag{18}$$

where h_t is the actual tower height. The third displacement component, compression of the tower shaft (δ_3), is given by

$$\delta_3 = \frac{Vh_t}{A_t E_t} \tag{19}$$

where A_t is the cross-sectional area to the tower shaft, E_t is the modulus of elasticity of the tower shaft and V is the tower load due to all four guy wires. The total vertical displacement of the tower is therefore

$$\delta_T = \delta_{1,2} + \delta_3 \tag{20}$$

The amount a typical tower can heave or settle before failing can be calculated using an initial tower load of V=4531.06 lb and the following values:

tower height	h_t = 858.00 "
guy-wire anchor spread	l = 699.35 "
cross-sectional area of tower	A_t = 4.184 in^2
modulus of elasticity of tower	E_t = 30. E6 psi

guy wire length	L_o = 1106.737 "
cross-sectional area of guy wire	A_w = 0.2992 in^2
modulus of elasticity of guy wire	E_w = 20. E6 psi
weight of guy wire	W = 94.073 lb

To obtain A_t for the lattice tower, the cross-sectional area of the four vertical 2x2x1/4" angles were used. The initial tension, T_i, in each of the four guy wires is approximately

$$T_i = \frac{V/4}{\cos\phi} = \frac{4531.06/4}{\cos(39.18)} = 1{,}461.4 lb$$

Tower heave is calculated by substituting the ultimate tower load V=93,015.4 lb / 4 guy wires into equations (12) and (17). Solving equations (12) and (17) we obtain h=864.883" or

$$\delta_{1,2(heave)} = 864.883 - 858.00 = 6.883"$$

The third component is

$$\delta_{3(heave)} = \frac{(93015.4 - 4531.06)858.00}{(4.184)30x10^6} = 0.605"$$

Therefore, the total heave for a conventional tower is

$$\delta_{T(heave)} = 6.883 + 0.605 = 7.488".$$

The amount of tower settlement is calculated using the required guy-wire tension of 500 lb or V_{min}=1550.257 / 4 lb.

Again substituting this V_{min} into equation (12) and (17), we get h=856.761" or

$$\delta_{1,2(settle)} = 858.00 - 856.761 = 1.239"$$

and the third component

$$\delta_{3(settle)} = \frac{(4531.06 - 1550.257)858.0}{(4.184)30x10^6} = 0.020"$$

Therefore, the total allowable settlement of a conventional tower is

$$\delta_{T(settle)} = 1.239 + 0.020 = 1.259"$$

E.3 Mathematical Analysis of GTS

E.3.1 Description of GTS Support Arrangement

The mathematical analysis for the GTS follows similar to the analysis of the conventional tower. Using symmetry, only one guy wire is analyzed to solve for the tower base displacement δ_T as shown in Figure E-6

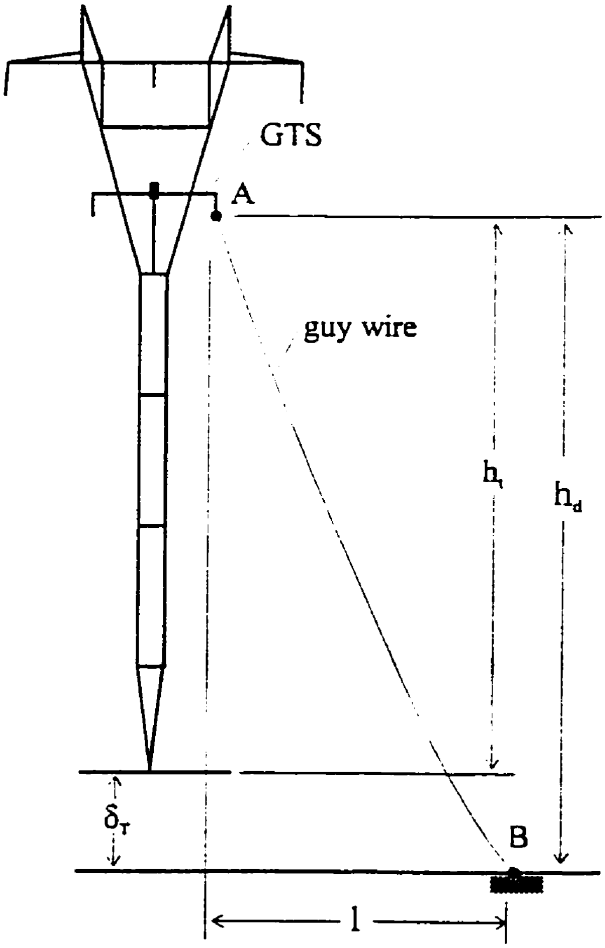


Figure E-6 GTS Support Arrangement

The guy wire shown has a height h_d, spread l, and the initial tower height is h_t. The vertical displacement of the tower base, δ_T, is composed of four components, as shown in Figure E-7. The first three components are the same as in the conventional tower analysis, namely displacement due to change in guy wire sag, δ_1, the stretch or compression of the guy wire, δ_2, and stretch or compression of the tower shaft, δ_3. The fourth component is the displacement of the compensating spring, δ_4.

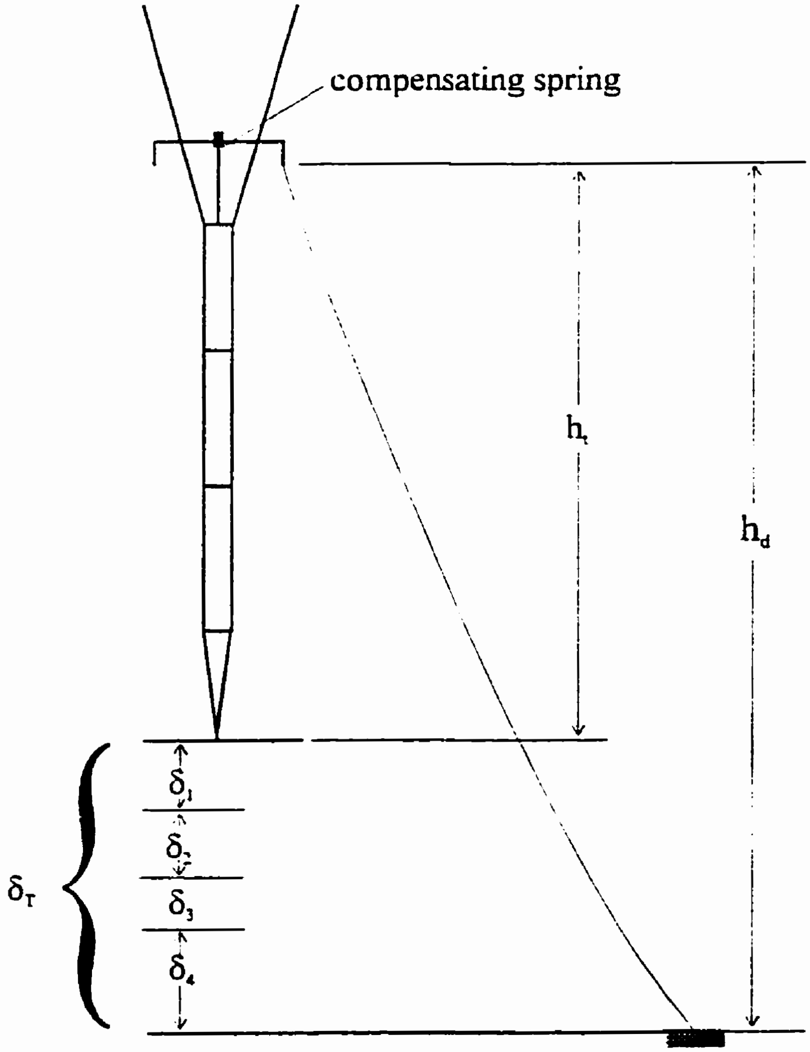


Figure E-7 Displacement Components for GTS Tower

The compensating spring and cross arm can displace a range R as shown schematically in Figure E-8; beyond this range, the tower acts as a conventional tower.

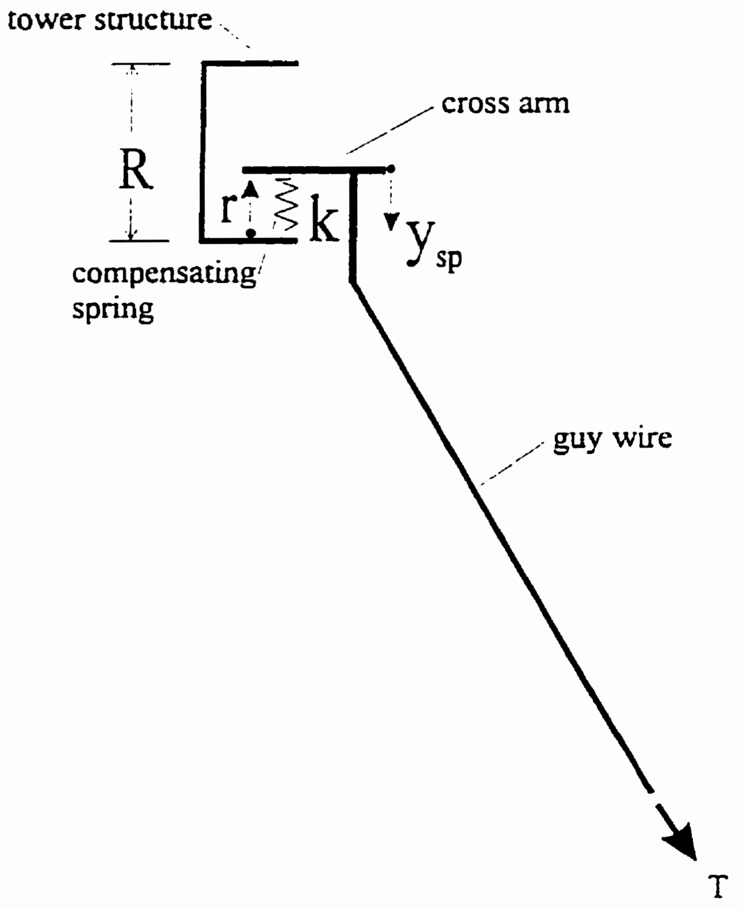


Figure E-8 Schematic of Compensating Spring Displacement

As the tower heaves or settles within the compensating spring range, the tower load V will change as a function of spring displacement y_{spring}, giving

$$V = V_i + ky_{spring} \qquad (21)$$

$$\{(r - R) \le y_{spring} \le r\}$$

where V_i is the initial tower load and k is the spring constant. The fourth component of the tower displacement is

$$\delta_4 = y_{spring} \; .$$

For any spring position (y_{spring}), the total tower base displacement is

$$\delta_T = \delta_{1,2} + \delta_3 + \delta_4 \; . \tag{22}$$

E.3.2 GTS Displacement Limits

The GTS displacement limits for a typical tower will be solved using the same initial tower load V=4531.06 lb and the following values:

tower height	h_t = 806.00"
guy-wire anchor spread	l = 699.35"
cross-sectional area of tower	A_t = 4.184 in^2
modulus of elasticity of tower	E_t = 30 E6 psi
compensating spring constant	k = 392.8
compensating spring initial position	r = 4."
compensating spring range	R = 10. "
guy-wire length	L_o = 1066.932"
cross-sectional area of guy wire	A_w = 0.2992 in^2
modulus of elasticity of guy wire	E_w = 20. E6 psi
weight of guy wire	W = 90.69 lb

Each of the four guy wires will have an initial tension, T_i, approximately

$$T_1 = \frac{V/4}{\cos\phi} = \frac{4531.06/4}{\cos(40.95)} = 1500\text{lb}$$

Using the same ultimate tower load V=93,015.4 lb (same as in the conventional tower analysis) we can now calculate the tower heave. The first two components are found by solving equations (12) and (17), which yield h=812.974" or

$$\delta_{1,2(heave)} = 812.974 - 806.00 = 6.974"$$

The third component due to tower compression is

$$\delta_{3(heave)} = \frac{(930154.4 - 4531.06)806}{(4.184)30x10^6} = 0.568" \ .$$

This value is conservative, however, because it does not include the deflection of the cross arms which could deflect at its ends up to a 1/4 inch, depending on construction.

The fourth component is

$$\delta_{4(heave)} = 4"$$

and the total ultimate heave for the GTS tower is

$$\delta_{T(heave)} = 6.974 + 0.568 + 4 = 11.542".$$

Allowable tower settlement will be calculated using the minimum guy-wire tension of 500 lb or V_{min}= 1510.619 / 4 lb. Solving equations (12) and (17) for the first two components, $\delta_{1,2}$, gives h = 1.2385" or

$$\delta_{1,2(settle)} = 806.00 - 804.761 = \ 1.239"$$

the third component is

$$\delta_{3(settle)} = \frac{(4531.06 - 1510.619)806}{(4.184)30x10^6} = \ 0.019"$$

The spring displacement gives

$$\delta_{4(settle)} = 6" .$$

The allowable total settlement for the GTS tower is

$$\delta_{T(settle)} = 1.239 + 0.019 + 6 = 7.258".$$

E.3.3 Comparison of GTS and Conventional Tower Performance

A comparison between tower load and base displacement for the GTS and conventional tower is shown in Figure E-9.

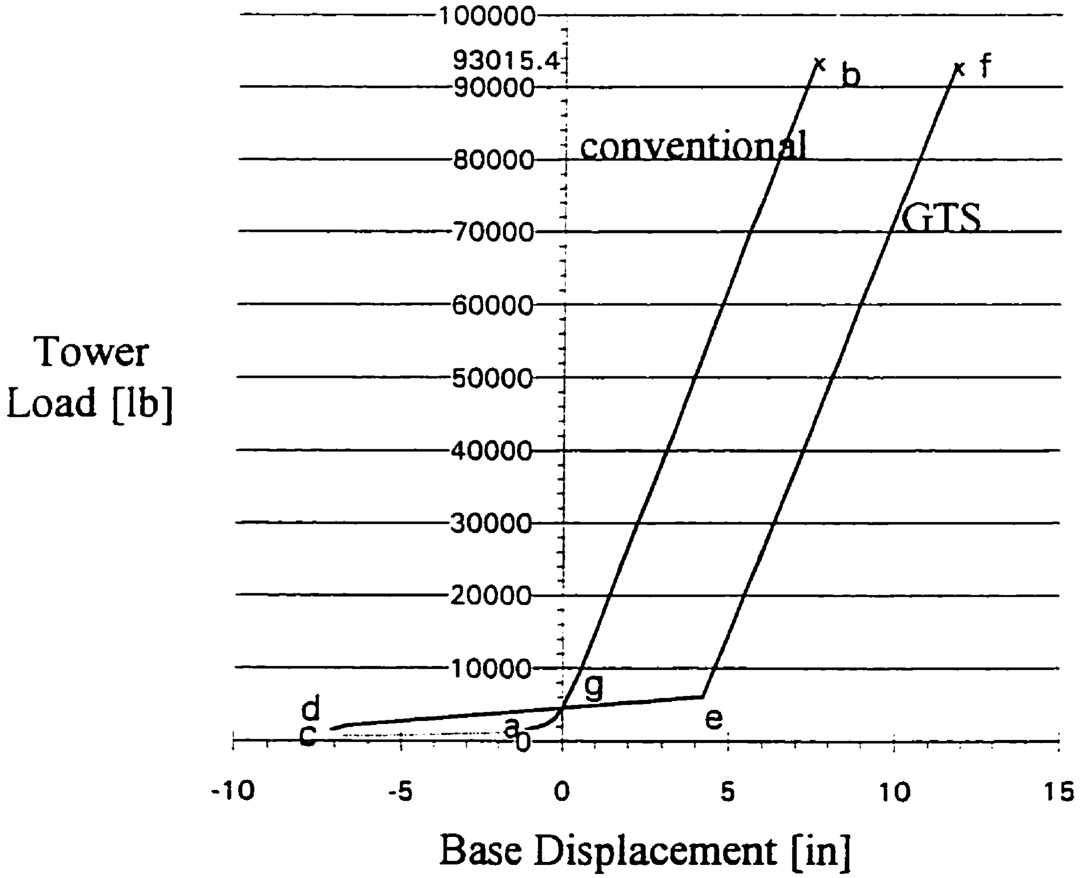


Figure E-9 Comparison of GTS and Conventional Towers

The figure shows that at the installed position of zero base displacement, both tower plots have the same tower load of 4531.06 lb(point g) or approximately 1500 lb of guy-wire tension. As the tower bases heaves four inches, the slope of the conventional tower plot increases steeply to 50,000 lb of tower load, whereas the GTS tower load increases only slightly. At four inches of base heave, the GTS tower, at point e, behaves like a conventional tower until failure at f, where the tower has heaved 11.542 inches. The conventional tower heaves until failure at point b, where the tower has heaved 7.488 inches.

Tower base settlement is also compared in the figure. Point d shows that the GTS tower can settle 7.258 inches and still maintain taut guy wires with 500 lb of tension. Point a indicates that the conventional tower can settle 1.259 inches before the guy wires become slack.

The dotted plot from point a to c shows the performance of the conventional tower if it were to settle the same amount as the GTS(7.258"). This line is deceiving, however, because regardless of the amount of settlement, the guy wires will always induce about a 400 lb tower load due to the weight of the guy wires. The conventional tower between points a and c therefore would experience excess leaning.

The conventional tower displacement range is 8.747", and the GTS tower range is 18.80" or 2.2 times that of the conventional tower.

Appendix F Experimental Model of the GTS

F.1 Introduction

This Appendix discusses two models, both of which were used in the design of the GTS and one is used for demonstrating its operation. Section 2 briefly describes the geometric modeling used and Section 3 covers the model tower.

F.2 Geometric Computer Model

A three-dimensional computer model of the tower was created using solid modelling with AutoCAD. The computer model was to aid in the design of the GTS. With the large number of tower members, it became difficult to design the device using the computer model alone. Figure F-1 shows the model of the conventional tower, where just the area of the retrofit is modeled in detail.

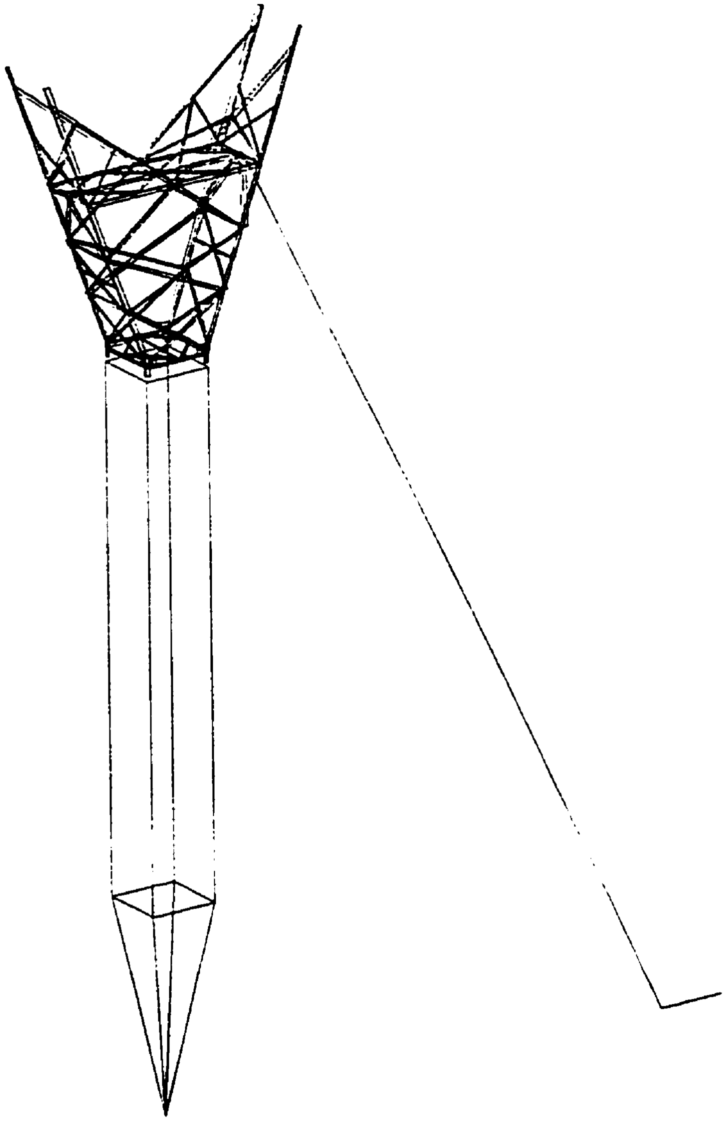
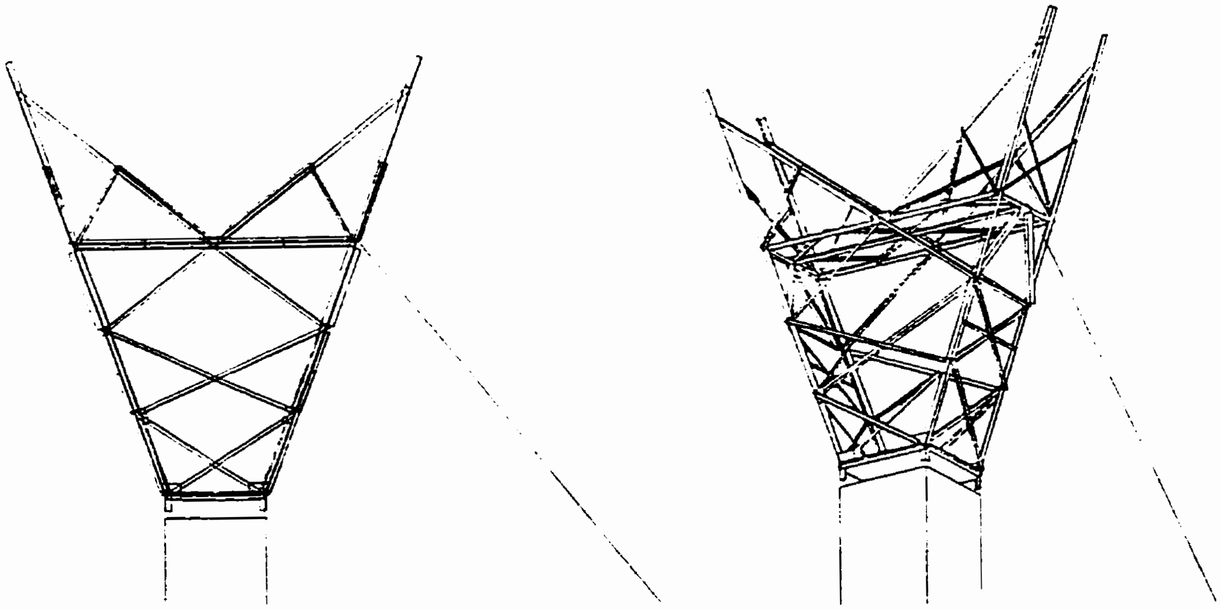


Figure F-1 Geometric Model of Conventional Tower

Figure F-2 shows a closer view of the tower members.



Side View

Perspective View

Figure F-2 Side and Perspective View of Tower

With many different designs being investigated at various locations in the tower, and the time required to create each view; a physical model was also built.

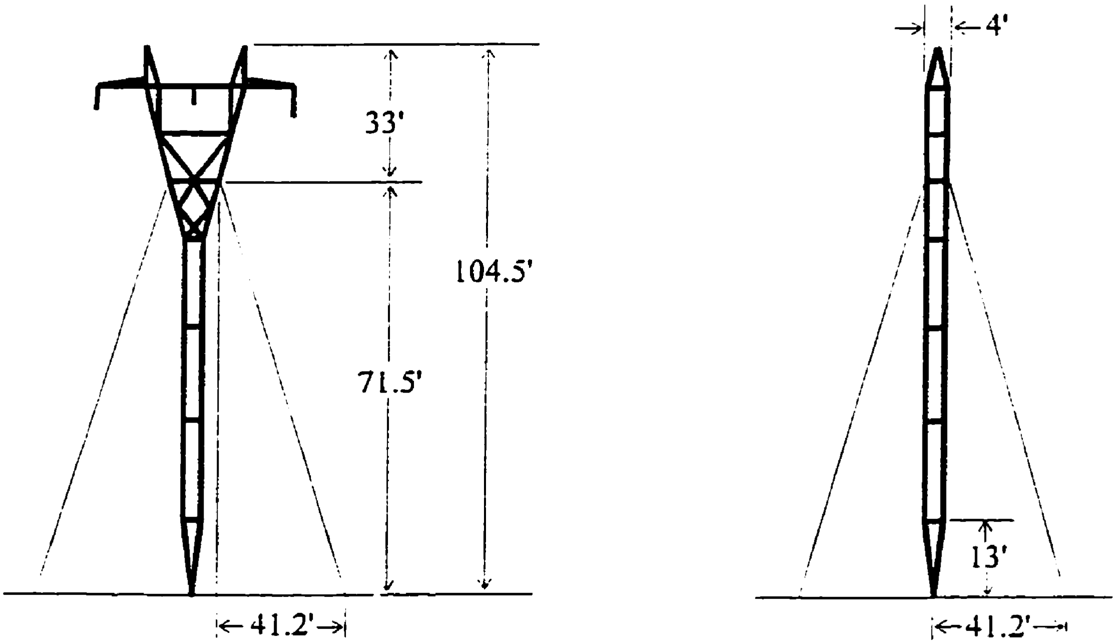
F.3 Model Tower

F.3.1 Introduction

The physical model aided immensely in the design of the GTS and other methods of tower support. The model also has the ability to demonstrate the operation of the GTS.

F.3.2 Model Construction

The model is dimensioned from a typical A-203 lattice tower as shown in Figure F-4.

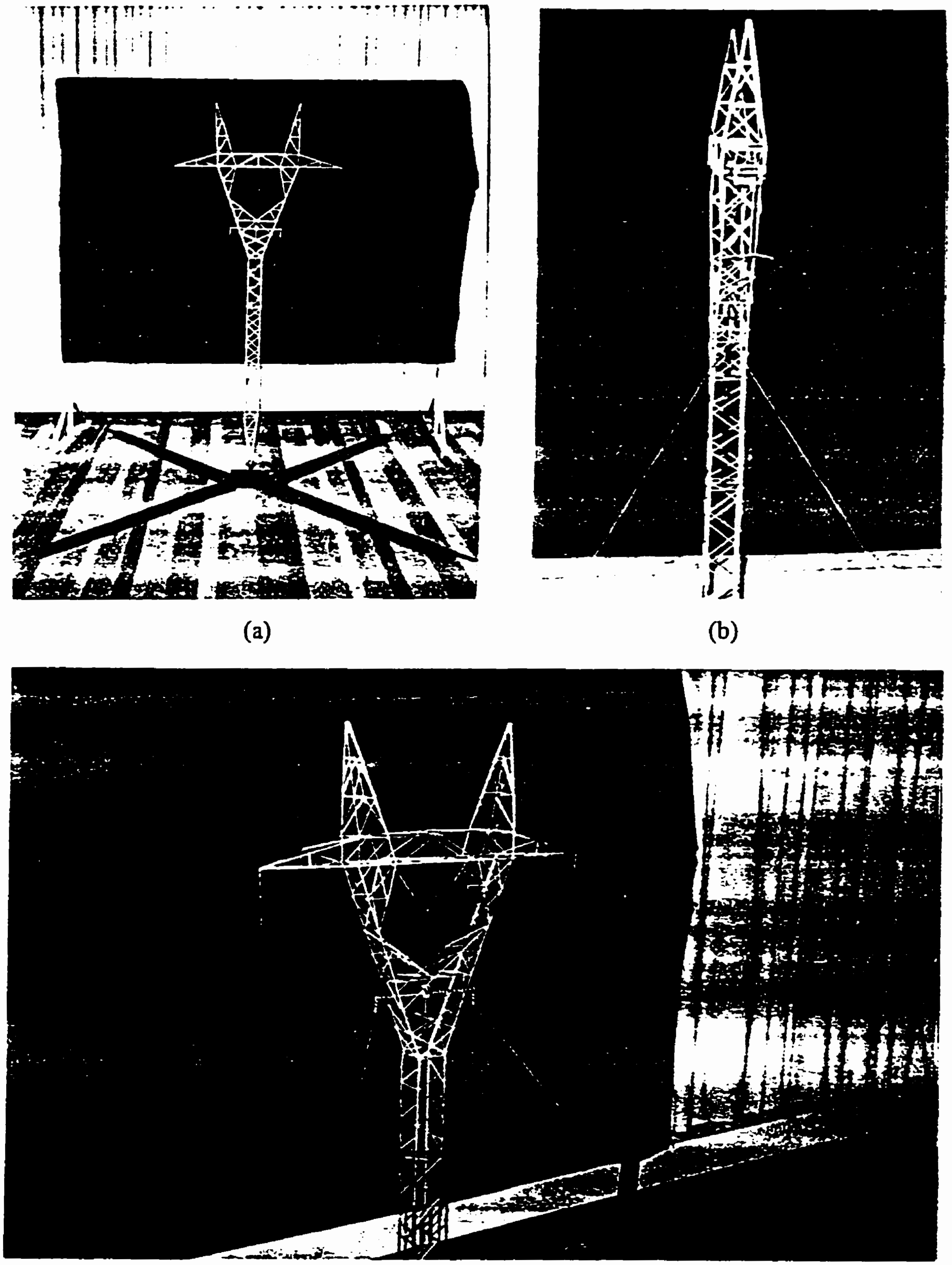


Front View

Side View

Figure F-4 Dimensions of typical A-203 Tower

The model tower has a 1:20 scale and is constructed of steel angles as shown in Figure F-5. It also has an adjustable base to simulate ground heave and settlement.



(a)

(b)

(c)

Figure F-5 Photographs of Model (a)front view (b)side view (c)view of GTS

The model stands 5.2 ft tall and 2.4 inches wide along the tower shaft. The angle members are made from sheet metal bent to the appropriate size and spot welded together. The guy wires are made of 7 strand steel wire. A steel stand supports the tower and holds the guy wires in place.

F.3.3 Model Demonstration

The benefit of the model is that it quickly shows the problem of vertical ground motion and demonstrates the GTS method. Tower heave is simulated by raising the base of the tower shaft. As the tower base lifts, one can observe the compensating rod slide through the locking ring, causing only a slight increase in guy-wire tension. As the tower shaft is lowered, ground settlement is demonstrated. Now the compensating rod slides through the locking ring to keep the guy wires from becoming slack.

Wind loads are simulated by applying a force against the tower near the conductors. As a transverse load is applied to the tower at right angles to the conductors, the cross arm tilts and locks against the compensating rod. Even as the wind load is increased, the compensating spring does not compress, thus preventing the tower from excessive leaning. As a longitudinal load is applied along the direction of the conductors, the cross arm rotates to lock in place, holding the tower again from excessively leaning. Regardless of the wind direction, the locking ring stays locked without slippage.

Resistance to tower twisting is demonstrated by simply applying a torque to the tower shaft. As the tower tries to twist, the guide slots are restrained by the cross arm and guy wires.

If the tower is not perfectly balanced or is leaning slightly, it does not inhibit the ability of the model to simulate the GTS operation.

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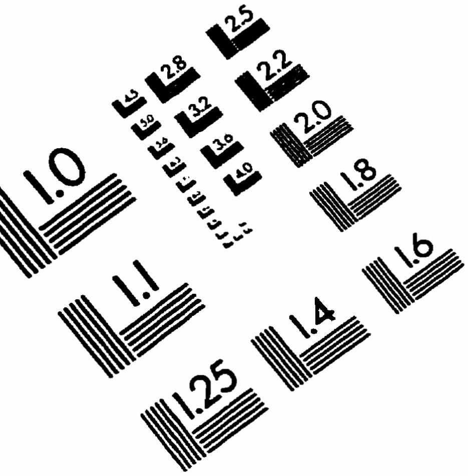
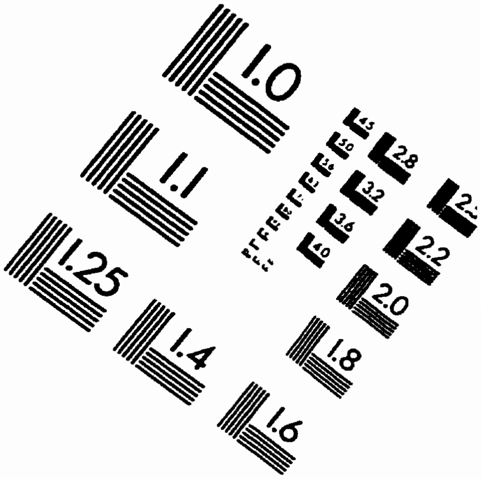
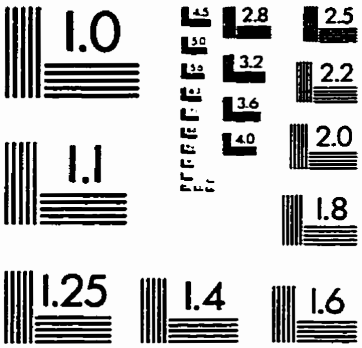
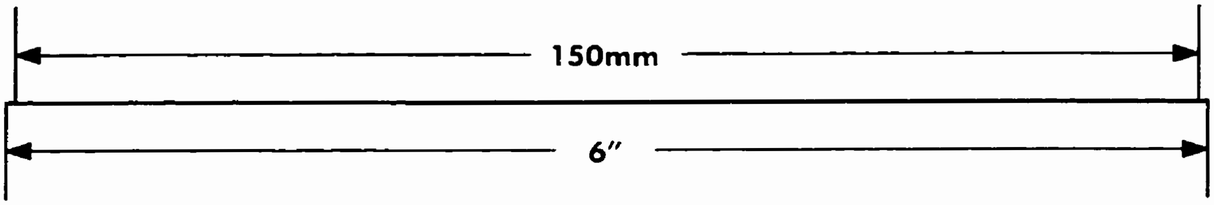
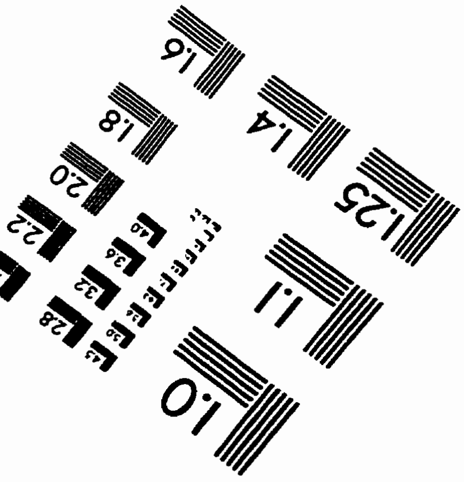
IMAGE EVALUATION TEST TARGET (QA-3)

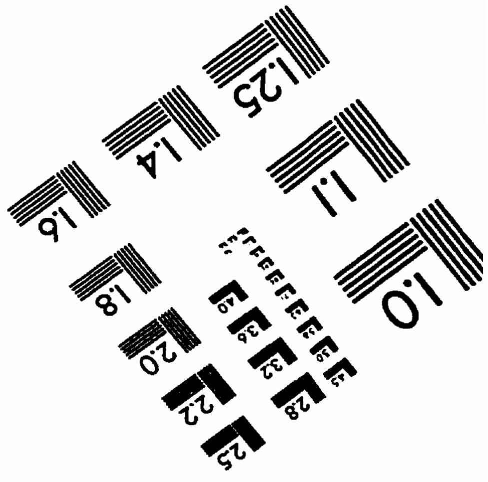












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