University of Southern Queensland
Faculty of Health, Engineering and Sciences

Design Analysis of Guy Wires of Communication Towers: Industry Based Project Proposed by Raytheon Australia

A Dissertation submitted by

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in fulfilment of the requirements of

ENG4111/ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Honours) (Mechanical)

Submitted October 20, 2022

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

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Certification

I certify that the ideas, designs and experimental work, results, analyses, and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

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Acknowledgments

This Project could not have been achieved without the ongoing support of workplace supervisor, Mr Stephen Mitchell. Without his dedication to the project along with his mentorship, guidance, oversight and direction, the project would not have been realised.

Acknowledgements to my academic supervisor Associate Professor Jayantha Epaarachchi at the University of Southern Queensland for his engineering insights and support. Thank you also to the University of Southern Queensland for providing resources and support towards the completion of this thesis.

Above all, acknowledgments to the most remarkable of women, my wife Dr Samantha Rose, who has encouraged and supported me throughout my degree.

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ABSTRACT

Raytheon Australia have contractual oversight of the operation and maintenance requirements for the Harold E. Holt (HEH) communication station in Exmouth, Western Australia. This communication station is an Australian Defence Force (ADF) asset which provides an integral function for the submarine branch of both Australia and its allies. Due to its very low frequency (VLF) transmission, 19.8kHz, and high-power output of approximately 1-1.6MW, it services the Southern Hemisphere, particularly the western Pacific Ocean and eastern Indian Ocean. Specifically, this base provides an integral function for the ADF and its allies to maintain strategic control within its sovereign space.

To maintain this function, the communication station requires maintenance and upkeep. One of the pertinent factors which has, and still is, being considered are the guy wires which support the extremely large tower networks that support the VLF array. When in its ‘as-maintained’ configuration, the structure is stable, reliable, and able to withstand extreme environmental conditions. However, when maintenance on the guy wire support network is required, there is uncertainty as to what stresses are being absorbed by the tower and whether these stresses are reaching critical values.

This project seeks to utilise numerical analysis, via finite element methods, to construct a representative model of a typical tower structure and provide a founded insight into what stressors are being imparted under various guy wire and antenna array configurations.

INTRODUCTION

The Naval Communications Stations (NAVCOMMSTA) and Harold E. Holt (HEH) is a naval base located on a narrow peninsula separating the Exmouth Gulf from the Indian Ocean on the west coast of Australia, 6km north of Exmouth. On this peninsula, the US Naval Communication Station was opened in 1967 to enable submarine communications for vessels in the Indian and western Pacific Oceans. This communication is enabled through Very Low Frequency (VLF) transmissions, which allows the signal to be broadcast great distances over the curvature of the earth as well as being detectable by receivers more than 20m underwater (Tanter 2011). The role of the Communication Station at Harold E. Holt is to provide VLF communications to Australian and United Allies submarines (Wheeler 2011).

In 2002, the Capability Acquisition and Sustainment Group (CASG), on behalf of the ADF, awarded Raytheon Australia the contract for operation and maintenance of the station. There are a multitude of maintenance requirements for any system that is intended for long term use, and HEH is no exception. To perform maintenance on the guy wire support network necessitates that at some period, the cables need to be removed. This process is currently undertaken as required and is detailed further in the ensuing report. However, at the crux of the problem, there is the issue that while guy wires are removed for maintenance, the tower is not supported in its 'as-designed' configuration, and there is uncertainty as to what stressors are impacting the structure.

A Finite Element Analysis (FEA) of a typical tower structure is proposed as a suitable and effective way in which the uncertainty can be quantified and assessed in a deliberate manner. While the use of FEA to conduct structural analysis is not an innovative concept in the current engineering discipline, its application to this specific project is new and is thus deemed a suitable subject for further analysis.

AIMS AND OBJECTIVES

Steel lattice structures braced by guy wires are a common design for transmission towers. This design, in varying configurations, is commonly adopted as a cost effective way in which to put an antenna/receiver at a required altitude, reducing interference losses and making the system as effective as possible (Mouser 2015).

While these configurations are cost effective, they are also subject to relatively large deflections which directly contribute to changes in forces within the supporting structure (Bedford & Fowler 1997). To understand these forces, a numerical approach is often required due to the geometric nonlinearity and complexity that these displacements embed into the problem.

This industry-based project focuses in on this problem as this geometric nonlinearity is further exacerbated by the requirement to remove and install the supporting guy wires as part of an ongoing maintenance regime. When replacing these guy wires and antenna panels, maintaining tower profile is critical in ensuring excessive tower deflections do not lead to failures. This is achieved by following a local lift plan however the method used is not founded on any rigorous engineering analysis, but rather utilising existing practices. As there has not been any analysis, the loads that are imparted during this process are unknown, as are the safety margins.

As these forces would be incredibly difficult to analytically solve, given the large deflections and geometric nonlinearity, a structural model of the tower was built such that a finite element analysis could be conducted.

The aims of this project therefore are to:

- Develop a geometric structural model of the tower within a FEA software package;
- Validate the model by using catenary equation techniques;
- Undertake analysis on the structural model under various loading conditions which are representative of current maintenance practices - eg. Replacing a guy wire cable or removing an array panel, and
- Detail the analysis findings for ongoing work.

BACKGROUND

The Communication Station at Harold E. Holt provides VLF communications to Australian and United Allies submarines (Wheeler 2011). Located on a narrow peninsula separating the Exmouth Gulf from the Indian Ocean on the west coast of Australia, 6km north of Exmouth, the Naval Communications Stations (NAVCOMMSTA) and Harold E. Holt (HEH) naval base was opened in 1967 to enable submarine communications for vessels in the Indian and western Pacific Oceans. Enabled through Very Low Frequency (VLF) transmissions, this communication capability allows the signals to be detectable by receivers more than 20m underwater and more broadly, to be broadcast great distances over the curvature of the earth (Tanter 2011).

Figure 1 provides an aerial overview of the large structure, showing the 13 towers that support the VLF antenna. Tower Zero (T0) is the tallest at 387m and sits at the centre, with six (6) 364m tall towers surrounding T0, and the remaining six (6) 304m tall towers, encompassing them at a radius of 1.3km (Dunstan 2017, Hansen & Chavez 1993). This project focuses on the inner ring of towers, although the methodology could be applied to any of the towers.

Figure 1 - Aerial Image of the HEH VLF Transmitter Array

Each array panel is labelled A to F when viewed clockwise from above. All the towers are supported by grounded guy wires, with the top-hat panels hoisted into position with permanent winches on the tower bases. The transmitter and tuning system are located at a building based at T0, with a feed bus supplying the antenna current. The array can be arranged into different configurations, operating with full six (6) panels, five (5) or four (4). Depending on the configuration, transmission of the VLF signals requires between 1 to 1.6MW of transmitting power (Dunstan 2017, Hansen & Chavez 1993, pp. 1-4).

Figure 2 shows a top view, illustrating the pitch circle diameter (PCD) of the inner towers, and a typical antenna panel. Figure 3 provides an additional image to illustrate the array network layout, again illustrating a typical diamond antenna panel which is supported by the towers (Hansen & Chavez 1993, p. 2).

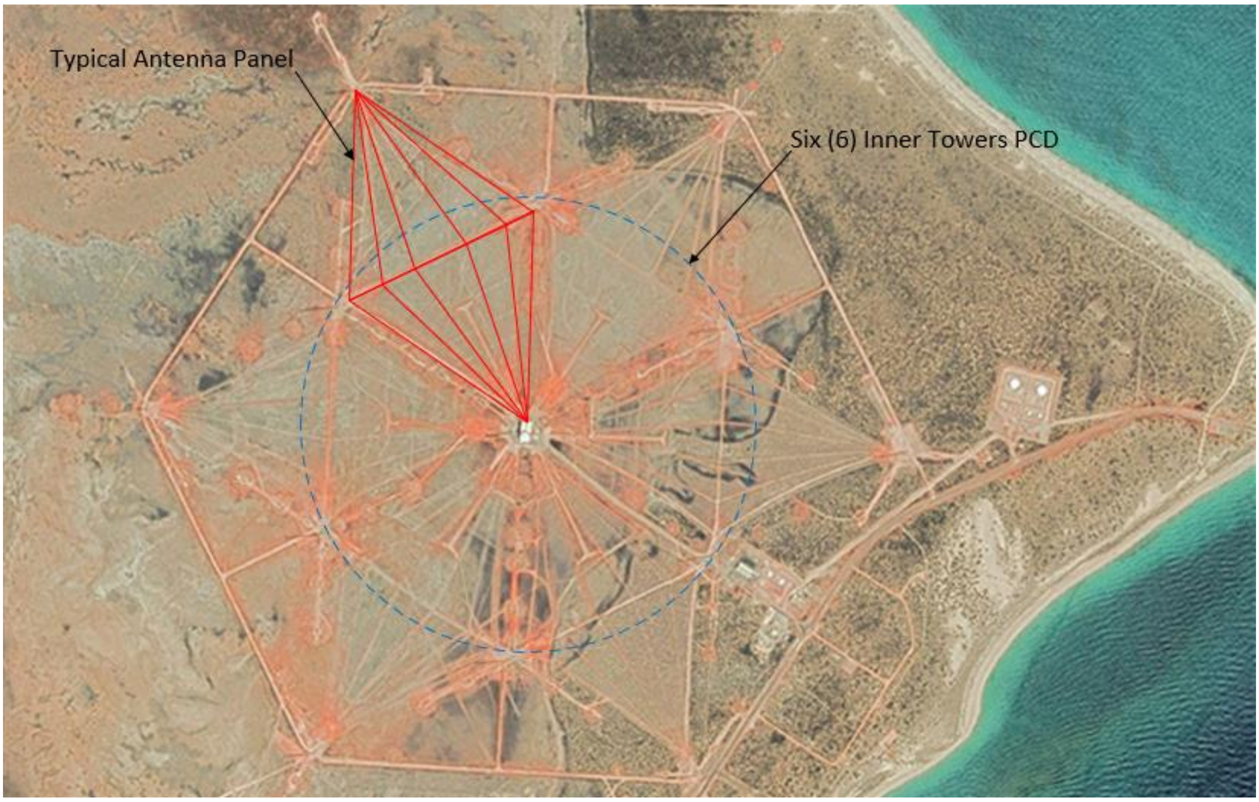


Figure 2 - Top View of HEH VLF Array Network

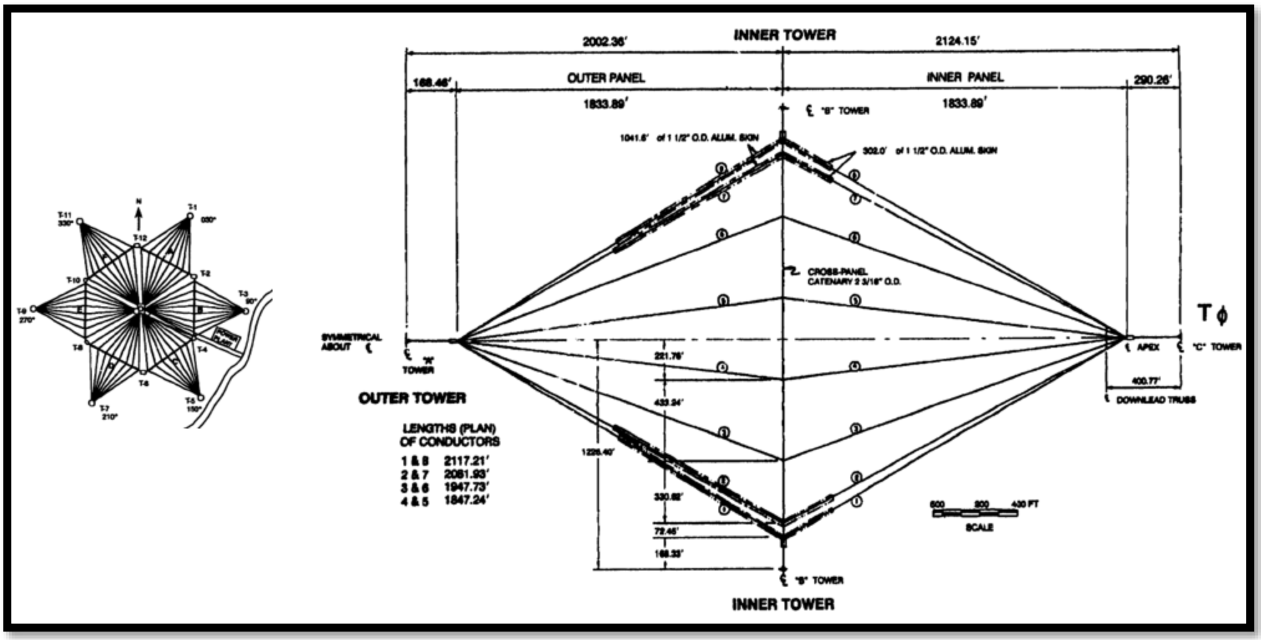


Figure 3 - HEH Tower Array, LH Showing Full Array & RH Showing Single Diamond Panel, Top-View (Hansen & Chavez 1993, p. 2)

LITERATURE REVIEW

In 2002, Raytheon Australia was awarded the contract for operation and maintenance of the station. The maintenance requirements for any system intended for long term use are comprehensive and complex. The HEH is no exception. Removal of the cables is required in order to perform maintenance on the guy wire support network. The key issue during this process is that when guy wires are removed for maintenance, the tower is not supported in its 'as designed' configuration. As a result, there is uncertainty as to what stressors are impacting the structure. This project required the analysis of stress concentrations in both the tower and supporting guy wire transmitter towers to understand what stressors are being affected by the structure in order to more efficiently understand and model the safe maintenance of the tower.

By adopting numerical analysis and computational structural mechanics, this project seeks to address this uncertainty. The application of FEA to conduct structural analysis is not new and is a well-known concept in the current engineering discipline. This literature review will explore existing literature on FEA and how it was applied to this project. The key research question is how to develop a robust model to understand stressors under various loading configurations, specifically when experimental analysis is not able to be conducted to validate the model. The research project is a quantitative analysis, with the aim to make predictions on cable tensions and tower deflections and stresses under various loading configurations.

FINITE ELEMENT ANALYSIS (FEA)

During a design, it is often necessary to determine, or make predictions on, the behaviour of the design under certain conditions. To understand the displacements, stresses, natural frequencies, or temperature distributions, for example, it traditionally necessitated that analytical formulations be derived and solved. As these formulations are generally partial differential equations, it is often necessary to approximate the problems using simplified and idealized parameters, geometries and boundary conditions. These approximations generally oversimplify the problem and lead to conservative estimates (Harish 2020). Numerical analysis, alternatively, utilises algorithms for obtaining solutions to problems that contain continuous variables, which are types of problems encountered during real world engineering analysis (Atkinson 2017). Constructing a predictive model for complex, or even simple designs, often requires partial differential equations be derived. These equations, even for simple geometries, are complex and it is often the case that they cannot be solved analytically. FEA is now commonly used in many engineering fields to provide numerical solutions for complex problems, thus enabling better decision-making foundations. Comparative studies on alternate structures, for example, can be modelled and analysed to determine which option provides higher margins of safety (Mahbob et al. 2013).

The finite element method (FEM) breaks these complex partial differential equations into simpler algebraic expressions for steady state problems, or ordinary differential equations for transient problems. It does this by dividing the geometry into sections in a process called discretization and results in a model of finite elements interconnected at points common to two or more nodes. This meshing transforms a continuous domain into a set of discrete sub-domains.

As stated by Ashcroft & Mubashar, ‘The continuum is now represented by a finite number of degrees of freedom (dof) and determined by the number of elements, the number of nodes per element, and the number of dof per node’ (2018, p. 634). Ashcroft & Mubashar provide detail that on each element, a field quantity (displacement, temperature etc) is generally interpolated in polynomial form from the nodes. When these finite elements are joined in a mesh, the field quantity is interpolated over the entire continuum, resulting in an array of polynomial equations. From this, a set off simultaneous equations are derived, in which the ‘primary unknowns are the values of the field quantity at the nodes’ (2011, p. 635).

FEA MODEL VALIDATION

Experimental analysis is often used to validate the accuracy of an FEA model, replicating the conditions and making a comparison between the model and the product. While this is often possible, there are instances where limitations exist, and this is not feasible. Whether those restrictions be related to access or resources, there are instances when a desk-top analysis is required to either benchmark work or to provide evidence that ongoing work is justified. This project falls into that category, both because access to the site is restricted and the sheer magnitude of the structures would require significant financial input to conduct experimental validation.

As an example of an experimental validation process, cable tension is often estimated through vibration based methods, where tension is proportional to the square of the frequency (Shinke et al. 1980). However, these formulations are limited when applied to non-slender or insufficiently tensioned cables, as is the case with the project tower structures (Zui et al. 1996). These methods are based on the theory of strings, and do not account for dampers which are now often installed to counter dynamic vibrations on cable structures. They are also based on assumptions such as the bending stiffness being negligible, and if deemed significant is incorporated as a correction factor (Furukawa et al. 2022). These factors alone make a vibration analysis unsuitable for the project.

Based on an exploration of the existing literature, the application of FEA to this specific problem was deemed reasonable and feasible. In addition, validating FEA models without experimental data in this type of application was not found in the literature. While this is understandable, the desk-top analysis conducted in this project is intended to form a basis for ongoing analysis. Given the large financial and operational encumbrance that would come with conducting experimental work on the tower structures, this project will provide a foundation for further work at the site. In this way, the industry-based project addresses a significant gap.

CABLE STRUCTURES

Cable structures form a large part of the project, and how accurately they are modelled in any software becomes critically important. Within FEA software packages, a cable structure element is represented directly by assigning it as a cable element, or indirectly by assigning it as a tension only truss element or augmented beam element. If using tension only truss elements as an indirect method, nodal positions for the deformed shape of the cable are estimated, meaning pretensions and sagging cannot be accounted for. Similarly, reducing flexural stiffness (I_z & I_y) in a beam element will result in large defection with any transverse loading, but no increase in axial force (Comino 2022). These reasons alone make using indirect methods inappropriate and direct use of cable elements which follow catenary theory is required.

Strand 7 is a FEA modelling software. As there was a resource constraint, Strand 7 was used as the FEA modelling software. While Strand 7 has a cable element feature which was utilised, there needed to be confidence in the results it was producing, which is often not considered (Hurdsman et. al. 2003). To do this, foundational understanding of cable structures and catenary theory was required. This allowed any results produced by Strand 7 to be validated using traditional theory.

DERIVATION OF THE CATENARY EQUATION

One of the principal outcomes from this dissertation was to accurately model the guy wire tensions that support a typical communication tower. Given the large size, the tower deflections cause large changes in guy wire tension. Due to the large deflections, it was not possible to accurately model the cable stresses in a linear manner due to the geometric non-linearity (Kahla 1993).

While a FEA representation of a typical tower can be modelled and solved using a generic non-linear static solver, the results are only as valuable as they are accurate. In particular, the tensions in the supporting guy wire network are sought to be defined. To determine model accuracy and guy wire tensions, first an understanding of the governing equations which describe cable behaviour needed to be conducted.

Cables geometries are described by the catenary equation; however, they were originally thought to follow a parabolic profile. The catenary equation can be solved by various methods and can be found in many structural analysis handbooks (Meriam & Kraige 2019, Bedford & Fowler 1997). Derivation by differential equations is one such method and is described with reference to Figure 4.

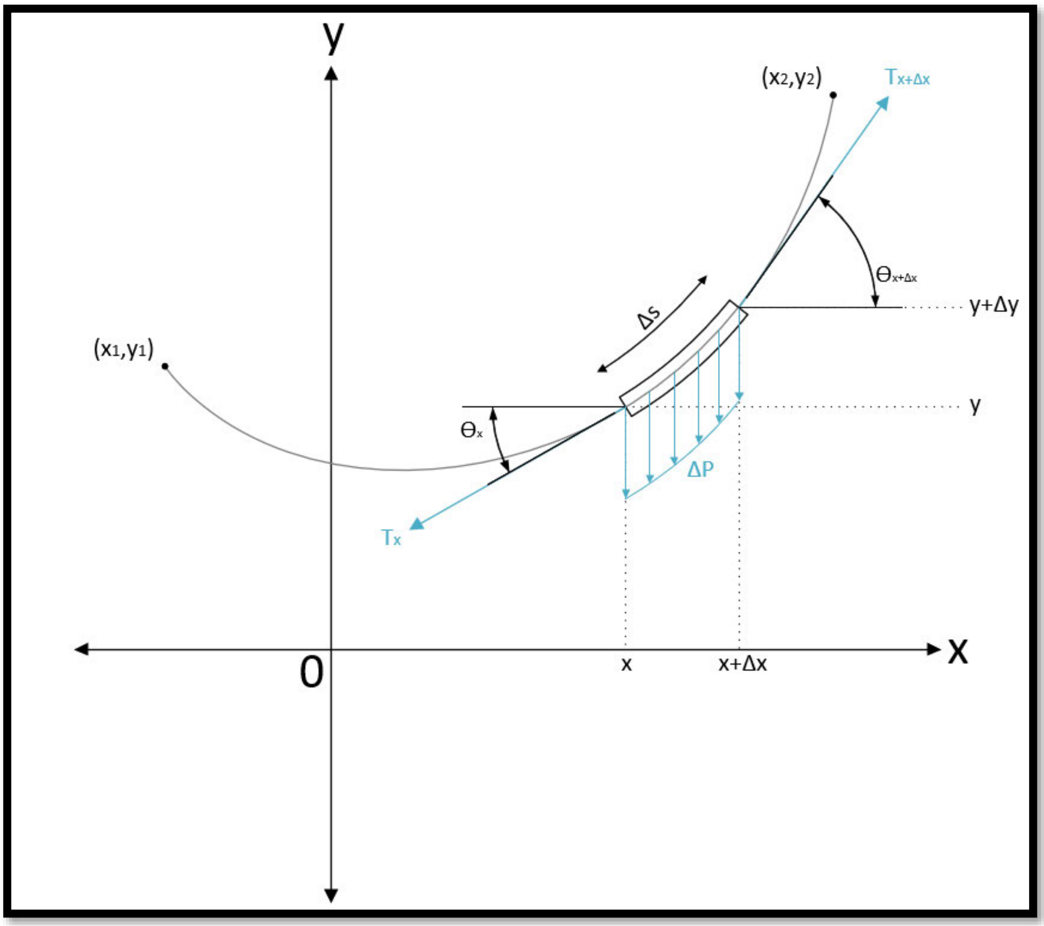


Figure 4 - Equilibrium of a Cable Section

As shown in Figure 4, the distributed gravity force acts on a small section of chain element of length Δs.

$$\Delta P = \rho g A \Delta s$$

where,

ρ is material density,
g is acceleration due to gravity, and
A is cross sectional area

Taking equilibrium equations for element of length Δs.

Summing forces in the x direction,

$$\rightarrow +\sum F_x = 0$$

$$T_{x+\Delta x} cos\theta_{x+\Delta x} - T_x \cos\theta_x = 0$$

$$T_x \cos\theta_x = T_{x+\Delta x} cos\theta_{x+\Delta x}$$

From the above, we see that the horizontal component of tension force, T_x, is constant, and

$$T_x \, cos\,\theta_x = T_0 = constant$$

$$T_x = \frac{T_0}{cos\,\theta_x}$$

Summing forces in the y direction,

$$\uparrow +\sum F_y = 0$$

$$T_{x+\Delta x} sin\theta_{x+\Delta x} - T_x \, sin\,\theta_x - \Delta P = 0$$

In differential form,

$$d(T_x \, sin\,\theta_x) = dP(x)$$

Incorporating $\mathrm{T_x} = \frac{\mathrm{T_0}}{\cos\theta_\mathrm{x}}$ and $\mathrm{P} = \rho \mathrm{gA\Delta s}$

$$d\left(\frac{T_0}{cos\,\theta_x} \times sin\,\theta_x\right) = dP(x) \quad \Longrightarrow \quad T_0\, d(tan\,\theta_x) = dP(x) = \rho g A\, ds$$

$$T_0\, d(tan\,\theta_x) = \rho g A\, ds$$

Using arc length identity

$$ds^2 = dx^2 + dy^2$$

$$\frac{ds^2}{dx^2} = \frac{dx^2}{dx^2} + \frac{dy^2}{dx^2}$$

$$\left(\frac{ds}{dx}\right)^2 = 1 + \left(\frac{dy}{dx}\right)^2$$

$$\frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}$$

$$ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\ dx$$

$$T_0\, d(tan\, \theta_x) = \rho g A \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\ dx$$

$$\text{As} \tan \theta_x = \frac{\text{dy}}{\text{dx}} = y'$$

$$T_0 \frac{y'}{dx} = \rho g A \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \quad or\ equivilently \quad T_0 y" = \rho g A \sqrt{1 + \left(\frac{dy}{dx}\right)^2}$$

Reducing the order of the equation by letting $\text{z} = \frac{\text{dy}}{\text{dx}} = y'$

$$T_0 z' = \rho g A \sqrt{1 + z^2}$$

Seperating variables

$$T_0 \frac{dz}{dx} = \rho g A \sqrt{1 + z^2}$$

$$\frac{dz}{\sqrt{1 + z^2}} = \frac{\rho g A}{T_0}\ dx$$

$$\int \frac{dz}{\sqrt{1 + z^2}} = \frac{\rho g A}{T_0} \int dx$$

$$ln\left(z + \sqrt{1 + z^2}\right) = \frac{\rho g A}{T_0} x + C_1 \qquad \text{and let } \frac{1}{\text{a}} = \frac{\rho\text{gA}}{\text{T}_0}$$

$$ln\left(z + \sqrt{1 + z^2}\right) = \frac{x}{a} + C_1$$

$$z + \sqrt{1 + z^2} = e^{\frac{x}{a}} + C_1$$

Knowing the tangent of the catenary at the lowest point is parallel to the x − axis,

ie. at $\text{x} = 0, \text{z} = \frac{\text{dy}}{\text{dx}} = 0$

$$0 + \sqrt{1 + 0^2} = e^0 + C_1$$

$$1 = 1 + C_1 \quad \Longrightarrow \quad C_1 = 0$$

$$z + \sqrt{1 + z^2} = e^{\frac{x}{a}}$$

Multiplying by the conjugant $\left(z-\sqrt{1+z^2}\right)$

$$\left(z+\sqrt{1+z^2}\right)\left(z-\sqrt{1+z^2}\right)=e^{\frac{x}{a}}\left(z-\sqrt{1+z^2}\right) \quad \Longrightarrow \quad z^2-(1+z^2)=e^{\frac{x}{a}}\left(z-\sqrt{1+z^2}\right)$$

$$-1=e^{\frac{x}{a}}\left(z-\sqrt{1+z^2}\right)$$

$$z-\sqrt{1+z^2}=-e^{\frac{-x}{a}}$$

Adding the two expressions

$$\left(z-\sqrt{1+z^2}\right)+\left(z+\sqrt{1+z^2}\right)=e^{\frac{x}{a}}-e^{\frac{-x}{a}}$$

$$2z=e^{\frac{x}{a}}-e^{\frac{-x}{a}} \qquad \Longrightarrow \qquad z=\frac{e^{\frac{x}{a}}-e^{\frac{-x}{a}}}{2}$$

Using hyperbolic identity, $\sinh(x)=\frac{e^{x}-e^{-x}}{2}$

$$z=\sinh\left(\frac{x}{a}\right)=\frac{dy}{dx}$$

Integrating to find final form of catenary shape

$$\int\frac{dy}{dx}=\int\sinh\left(\frac{x}{a}\right)dx$$

$$y=a\,cosh\left(\frac{x}{a}\right)$$

As $\frac{1}{a}=\frac{\rho gA}{T_0}$, the unique shape which describes a given catenary is given by parameter $a=\frac{T_0}{\rho gA}$

These catenary formulations are further manipulated to form a tool which iterates cable length between two known points, to converge on a desired tension. This is discussed in more detail in the Methodology.

CONSEQUENCES AND ETHICS

HERITAGE IMPLICATIONS

The Harold E. Holt communication's VLF tower array forms part of the Naval Communications Station, located in Western Australia's North West Cape in Exmouth, 1270 kilometres from Perth, as discussed in the Background. The Western Australian Government has listed the HEH VLF towers as municipal inventories (Heritage Council 2016). This listing is a requirement of the *Heritage Act 2018*, which requires the local government authorities document places/infrastructure that are, or may become, of heritage significance.

While there is no immediate impact, any design changes that may arise as part of the project outputs will need to be conducted in consultation with the Exmouth Shire Council to ensure no impact to the listing requirements are affected.

METHODOLOGY

The project work detailed within this dissertation seeks to provide insight into tower and guy wire behaviour under various loading configurations. The current maintenance processes being enacted follow a somewhat ‘grandfather policy’, in that previous procedures are adapted from historic precedence. As the tower installations are over 50 years old, there is growing concern surrounding the uncertainty the stresses that these maintenance practices impart onto the towers and supporting guy wire structures.

As described in the Literature Review, experimental analysis is often used in conjunction with FEA methods to validate a model. During the project work, no access to the physical structure was able to be conducted. Even with ready access, conducting any type of experimental analysis would not have been possible given the magnitude of such an undertaking.

Given the expense that would imbed any experimental analysis of all the possible loading configurations, this project seeks to capitalise on FEA technology and build a robust model which can be used ongoingly, providing insight into tower behaviour. Validating a model is integral to its construction, as there needs to be some understanding and confidence in the results that the solver provides. As no experimental data was available, an alternate methodology was required.

Field data had provided tensions for the tower guy cables with the antenna both down and up. To validate the model, the tension data was used in the development of a Cable Length Solver, which iterated on cable lengths using catenary theory to achieve a theoretical cable length for an objective tension. If the model could produce data for the thirty (30) guy cable tensions that were within 5% of the objective tensions, the model was deemed to be producing sufficiently accurate results and provided confidence it could be used for further analysis.

The methodology discussed within this Section can be generalised into the following,

1. Develop Geometric FEA Model
    a. Model specifications are defined, outlining main components, and required terminology.

   b. Model construction is discussed, detailing how the Tower elements were constructed.
   c. Boundary Conditions, including degrees of freedom as well as application of external loads are detailed.
2. Validate the FEA Model
   a. Once constructed, the models are validated by using catenary theory in developing a Cable Length Solver. The Solver is used in conjunction with the FEA Model to calculate the thirty (30) cable lengths required to achieve the objective tensions. When the models converge on these objective tensions, the models will have met the requirement to progress onto assessing Load Cases.
3. Apply Tower Load Cases
   a. Load Cases are presented, which are intended to replicate tower states during the maintenance process of guy cable removal.
   b. The guy cable removal process is separated into three stages, represented by Load Case 1, 2 & 3.

The process of validating the model prior to running the Load Cases can be summarised in Figure 5.

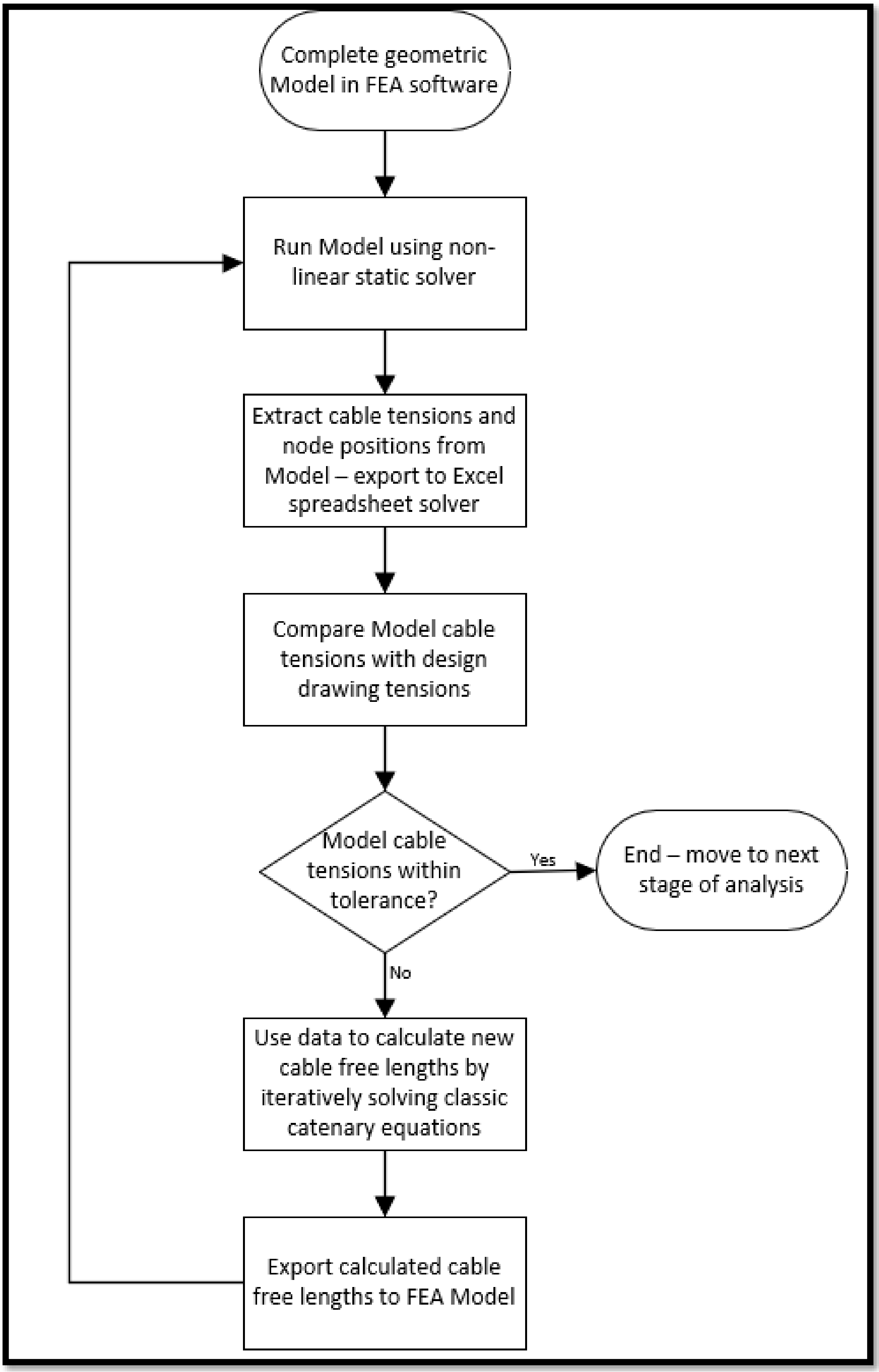


Figure 5 - Basic Flowchart for Initial Cable Tension Convergence

FEA MODEL DEVELOPMENT

NOTE – Due to the sensitive nature of the source drawings, no detailed geometric detail can be disclosed. This does not detract from the findings provided in the Analysis.

The intent of the model was to produce a global understanding of the tower behaviour and get insight into the magnitude of stresses in the major structural components. It was understood that the model needed to be run 100s of times, both while converging on the initial guy cable tensions, then running through all the Load Cases. This global representation therefore needed to balance model complexity with requirements, being adequately complex that it provided the fidelity of measurement while also being cognizant of the processing cost. Figure 6 provides a brief overview of the Tower general construction.

As shown in Figure 6, the Tower has a triangular cross section, with three (3) outer round solid columns running the vertical length and forming the legs of the structure. The triangular prism which forms the body of the Tower is erected with hundreds of bays, a repeating pattern of Horizontal Beams and Diagonal Tie Rods of various sizes and geometry. At five Levels, there are Tower Attachment Bays, where the guy cables attach and secure to the ground anchors. At these levels, the diagonal truss elements are replaced with beam elements of various cross sectional areas.

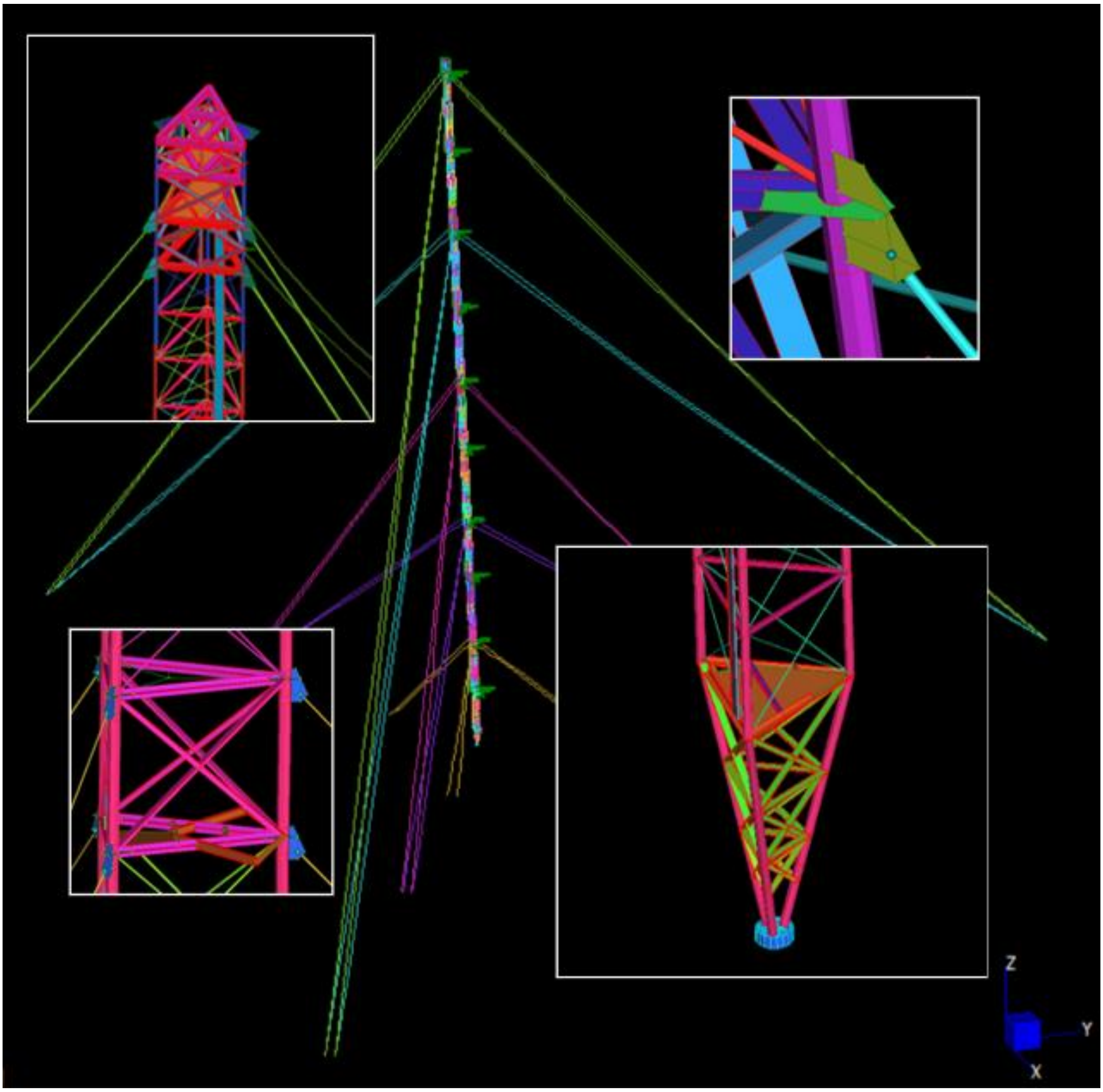


Figure 6 - Tower General Construction Images

MODEL TERMINOLOGY

The Tower Model represents an Inner-Tower in the HEH VLF Array. The model was constructed on the x-y plane, erecting in the positive z-axis (refer Figure 7).

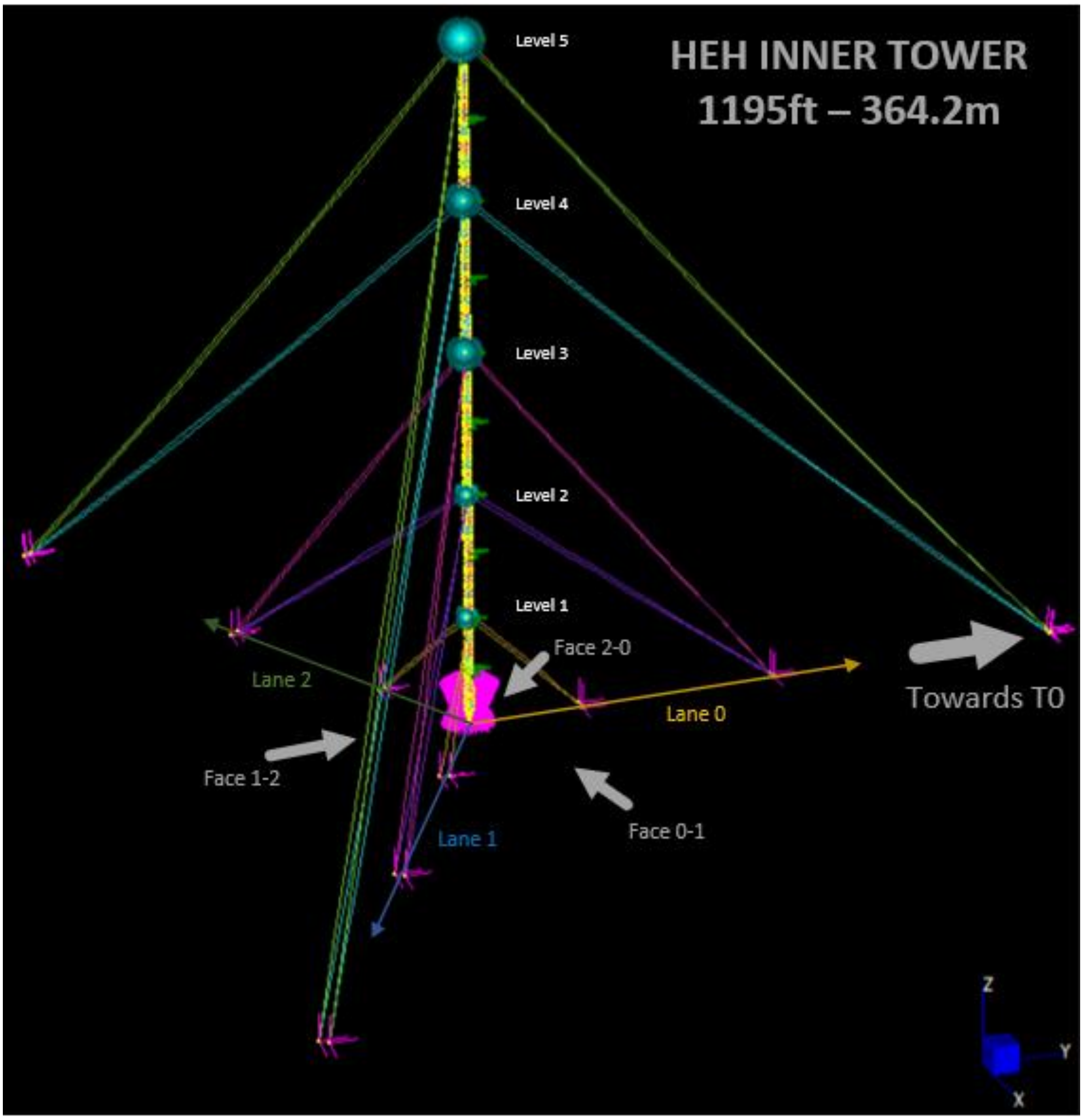


Figure 7 - Tower General Description

The z-axis is aligned with the geometric centre of the Tower, Lane 0 aligned with the positive y-axis, pointing towards Tower 0 of the HEH Array, and Lane 1 & 2 directed 120° around the z-axis (refer Figure 8). Figure 9 illustrates the main components of the tower construction.

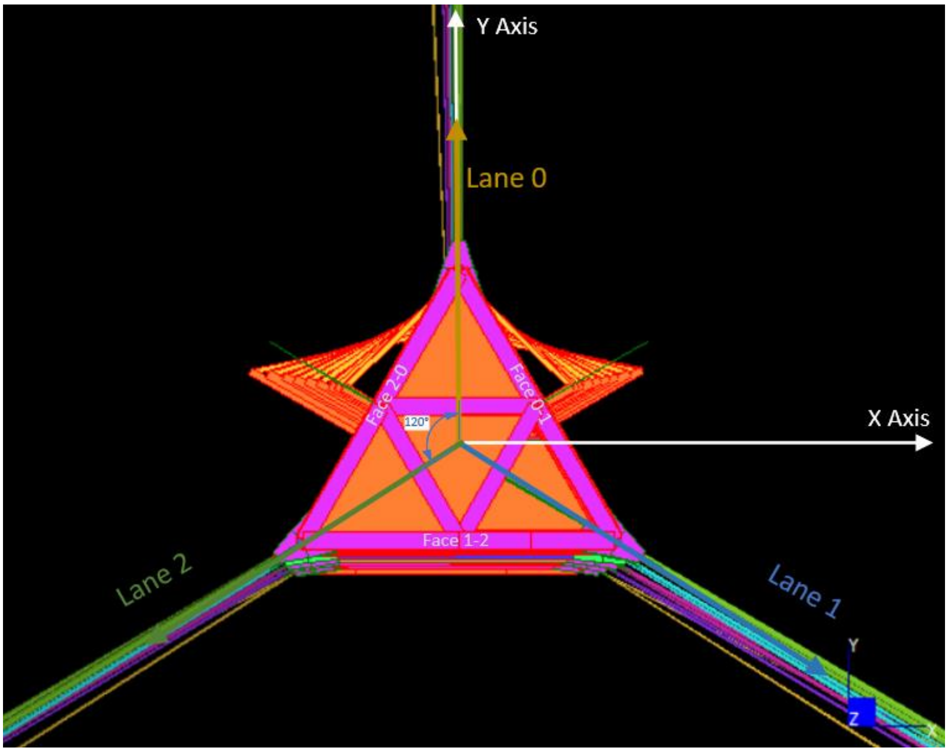


Figure 8 - Tower Top View, Coordinate System and Lanes

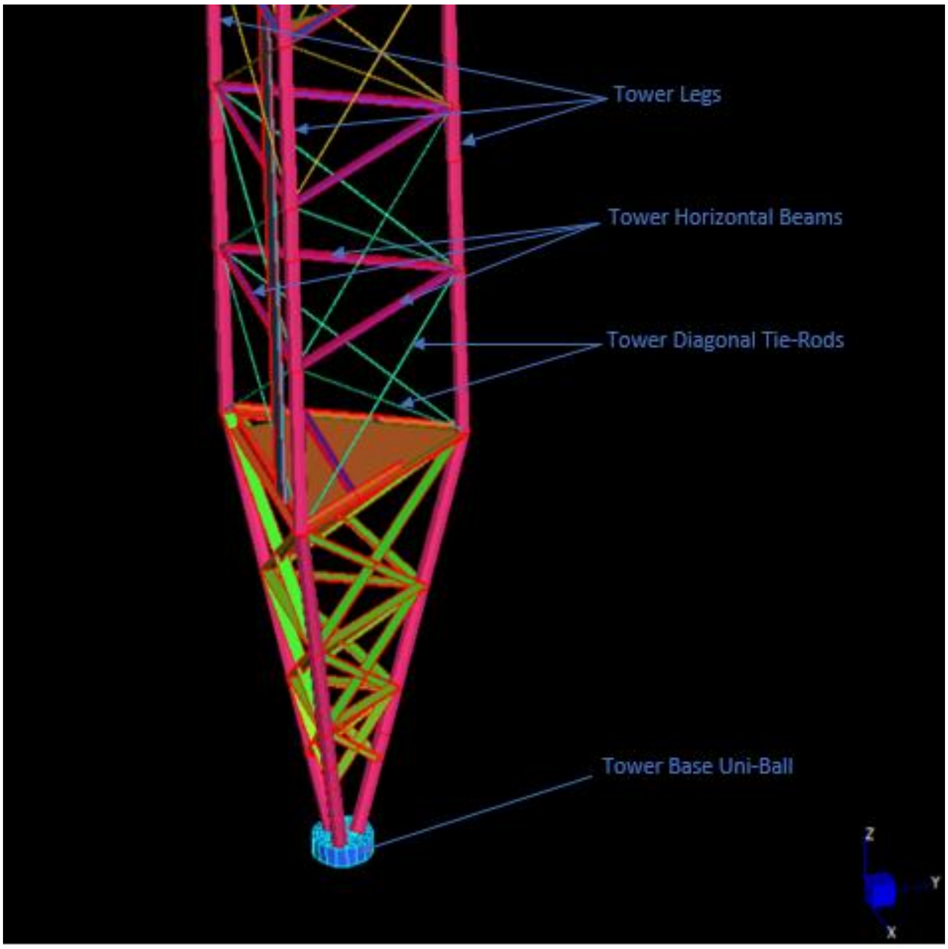


Figure 9 - Tower Construction, Main Components

MODEL CONSTRUCTION

As the primary construction of the tower of a lattice truss framework, it could be modelled with beam element variations with supporting plate and solid elements as required. Each of these elements is discussed below.

NODES

As the tower is largely comprised of beam elements, nodes were placed at all Beam Ends and intersecting points on the structure. Plate structures were modelled by placing nodes at geometrically relevant positions, then meshing with Tri3 and Quad4 plate elements. Solid elements were modelled by first creating a cross section of the geometry using nodes and plate elements. This cross section was then copied around a local axis, then joined with Hexa20 solid elements.

LEGS

The Tower Legs are constructed from solid round columns of various lengths and diameters. Table 1 details the material properties applied in the model for the Tower Legs.

Table 1 - FEA Element Details, Tower Legs

Element Property	Element Type	Youngs Modulus		Yield Point		Poisson's Ratio	Density	
		ksi	GPa	psi	MPa		lb/in^3	kg/m^3
Tower Legs	Beam 2 Bar	29008	200	45000	310.3	0.3	0.284	7870

All of the Tower Legs were of the same material type, with varying lengths and diameters. Figure 10 provides an example of the cross sectional areas of typical Tower Leg.

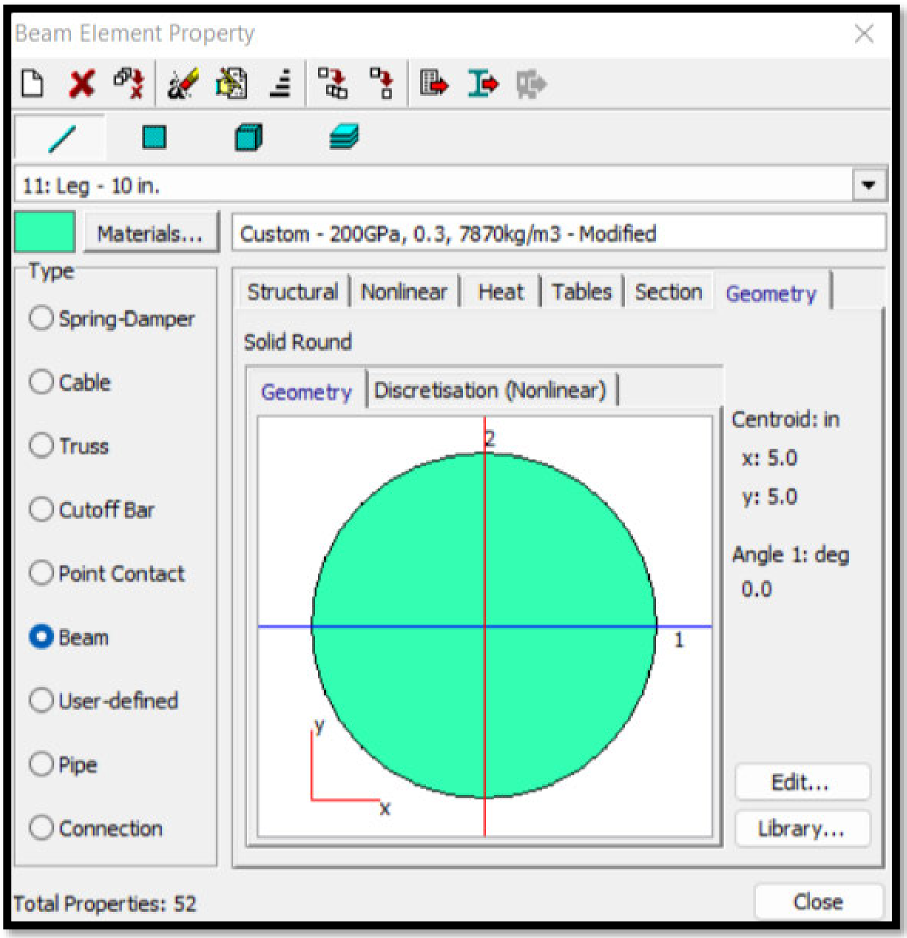


Figure 10 - Example of Typical Tower Leg Cross Section

HORIZONTAL MEMBERS

The Horizontal Members of the tower were modelled using 2 Bar Beam Elements. Table 2 details the material properties applied in the model for the Horizontal Members.

Table 2 - FEA Element Details, Tower Horizontal Members

Element Property	Element Type	Youngs Modulus		Yield Point		Poisson's Ratio	Density	
		ksi	GPa	psi	MPa		lb/in^3	kg/m^3
Horizontal Beam Members	Beam 2 Bar	29008	200	33000	227.5	0.3	0.284	7870

All of the Horizontal Members were of the same material type, with varying lengths and cross sectional areas. Figure 11 provides an example of the cross sectional areas of typical Horizontal Members.

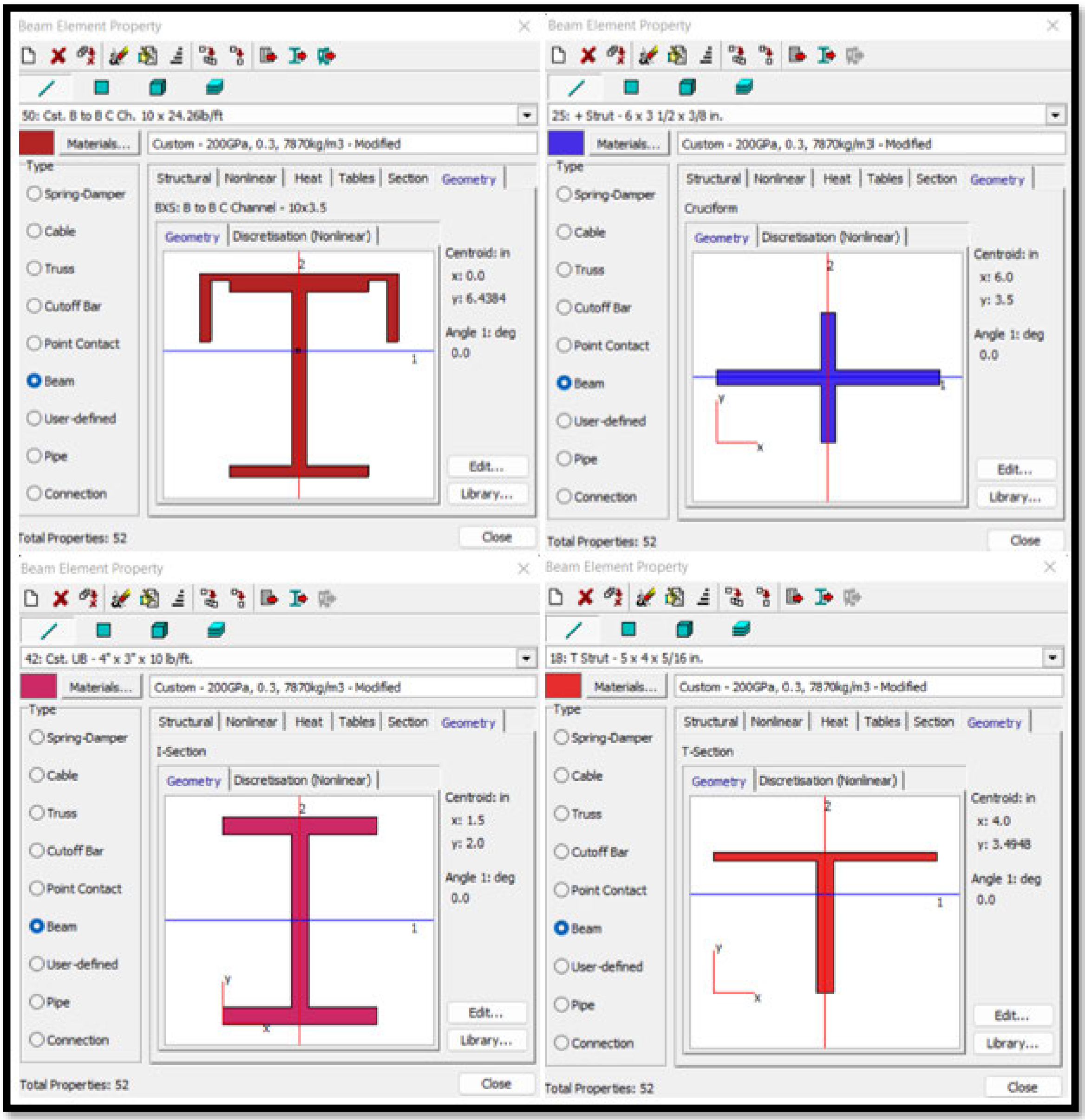


Figure 11 - Examples of Typical Tower Horizontal Beam Cross Sections

DIAGONAL TIE RODS

Forming the truss elements in the lattice structure, the Tie-Rods line each face of the Tower face in opposing diagonal directions. Each of the truss elements are axial only members and do not provide reactions to bending moments. Table 3 details the material properties applied in the model for the Diagonal Tie Rods.

Table 3 - FEA Element Details, Tower Diagonal Tie Rods

Element Property	Element Type	Youngs Modulus		Yield Point		Poisson's Ratio	Density	
		ksi	GPa	psi	MPa		lb/in^3	kg/m^3
Diagonal Tie-Rod	Beam Truss	29008	200	33000	227.5	0.3	0.284	7870

The Diagonal Tie Rods of the tower were modelled using truss elements. As these members in the tower only carry axial loads, it is appropriate to model them with truss elements. All of the Diagonal Tie Rods were of the same material type, with varying lengths and diameters. Figure 12 provides an example of the cross sectional area of typical diagonal tie-rod.

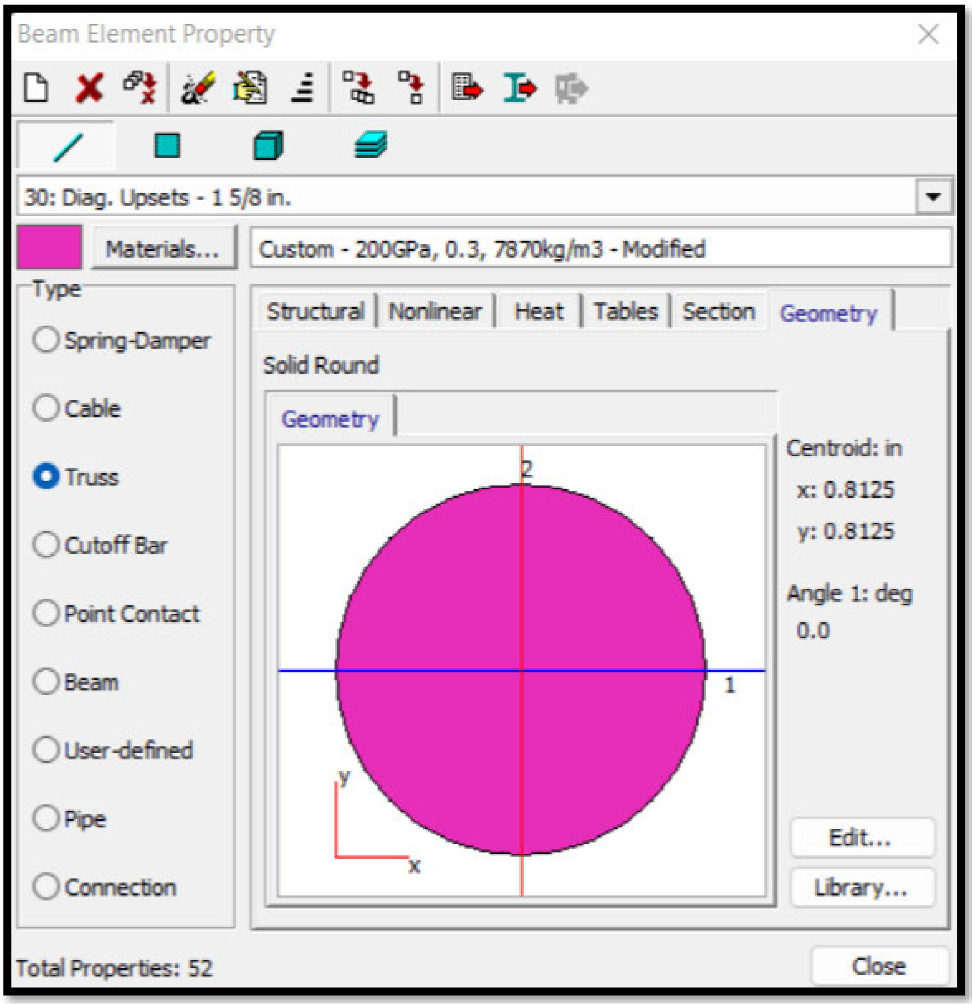


Figure 12 Example of Typical Tower Diagonal Tie-Rod Cross Section

GUY CABLES

While deriving the length of the guy cables is discussed in the Cable Length Solver Section, Table 4 details the properties applied to the model for the guy cable elements.

Table 4 - FEA Element Details, Tower Guy Cables

Element Property	Element Type	Youngs Modulus		Density	
		ksi	GPa	lb/in^3	kg/m^3
Guy Cables 1 to 5	Beam Cable	23043.6 to 24450.4	158.9 to 168.6	0.222	6137.6

All the guy cables were of the same material density, with varying modulus and diameters. Figure 13 provides an example of the cross sectional area of typical guy cable.

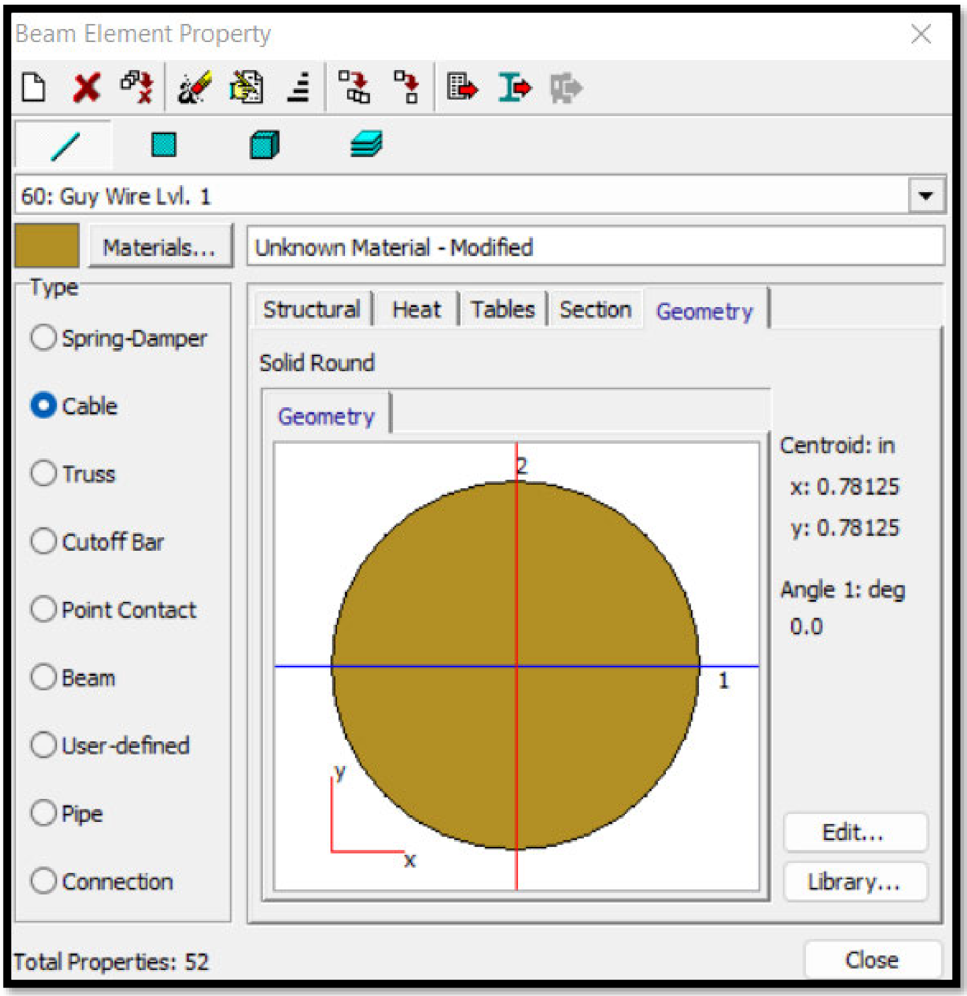


Figure 13 - Example of Typical Guy Cable Cross Section

ANCILLARY EQUIPMENT

Ancillary elements were included to account for parts of the structure which did not contribute to the stiffness matrix but had non-negligible contribution to mass. These included the access ladders and user platforms. The thickness of the elements was adjusted to maintain the correct weight per unit length, however the elements were given a Youngs Modulus of zero (0). This ensured the equipment added mass to the overall structure but did not act as a structural member or contribute to the overall stiffness matrix. Table 5 shows the material properties applied to the ladders and platform assemblies in the model.

Table 5 - FEA Element Details, Tower Ancillary Equipment

Element Type	Youngs Modulus		Yield Point		Poisson's Ratio	Density	
	ksi	GPa	psi	MPa		lb/in^3	kg/m^3
Beam 2 Bar	0	0	0	0	0	0.284321	7870
Plate Tri 3 & Quad 4	0	0	0	0	0	0.284321	7870

Error! Reference source not found. shows a cross section of the ladder and a membrane thickness on the plate element property. These thicknesses were calculated to maintain the desired weight per unit length.

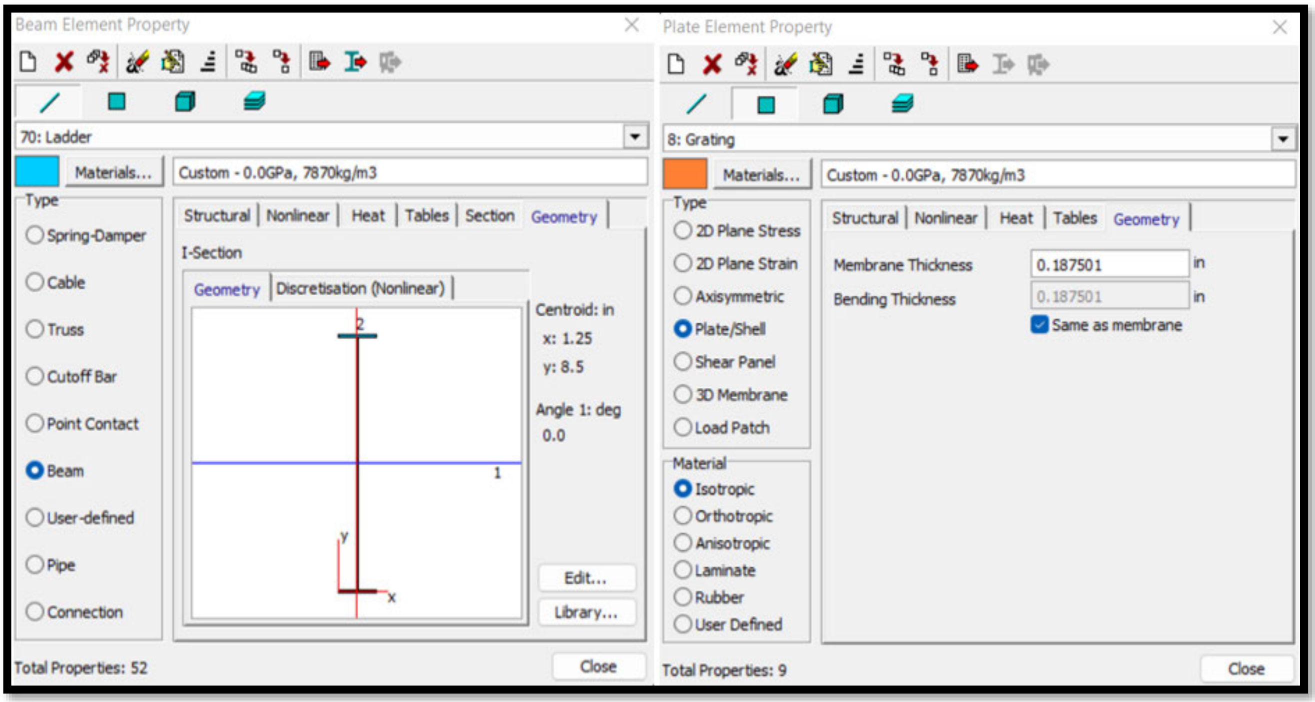


Figure 14 - Ancillary Equipment, Access Ladders & Platform Grating

BASE JOINT – BALL & SOCKET CONFIGURATION

The Base Joint of the Tower was modelled using Hexa20 Brick elements. This was done by creating a cross section of the base section in the y-z plane and meshing that cross section into six (6) Quad8 Plates. These Plates were then copied 20 times around a locally generated cylindrical co-ordinate system, then formed into Hexa20 Brick elements. The Table 6 details the material properties applied to the model for the Tower Base Joint.

Table 6 - FEA Element Details, Tower Base Joint

Element Property	Element Type	Youngs Modulus		Yield Point		Poisson's Ratio	Density	
		ksi	GPa	psi	MPa		lb/in^3	kg/m^3
Base Joint	Brick Hexa20	29008	200	33000	227.5	0.3	0.284	7870

The ball of the joint is mounted in the ground, while the base of the tower is fitted with the socket, as demonstrated in Figure 15. As the Tower deflects, the hardened steel surfaces of the ball and socket allows for a rolling motion, such that the majority of reactions are directed normal to the surfaces.

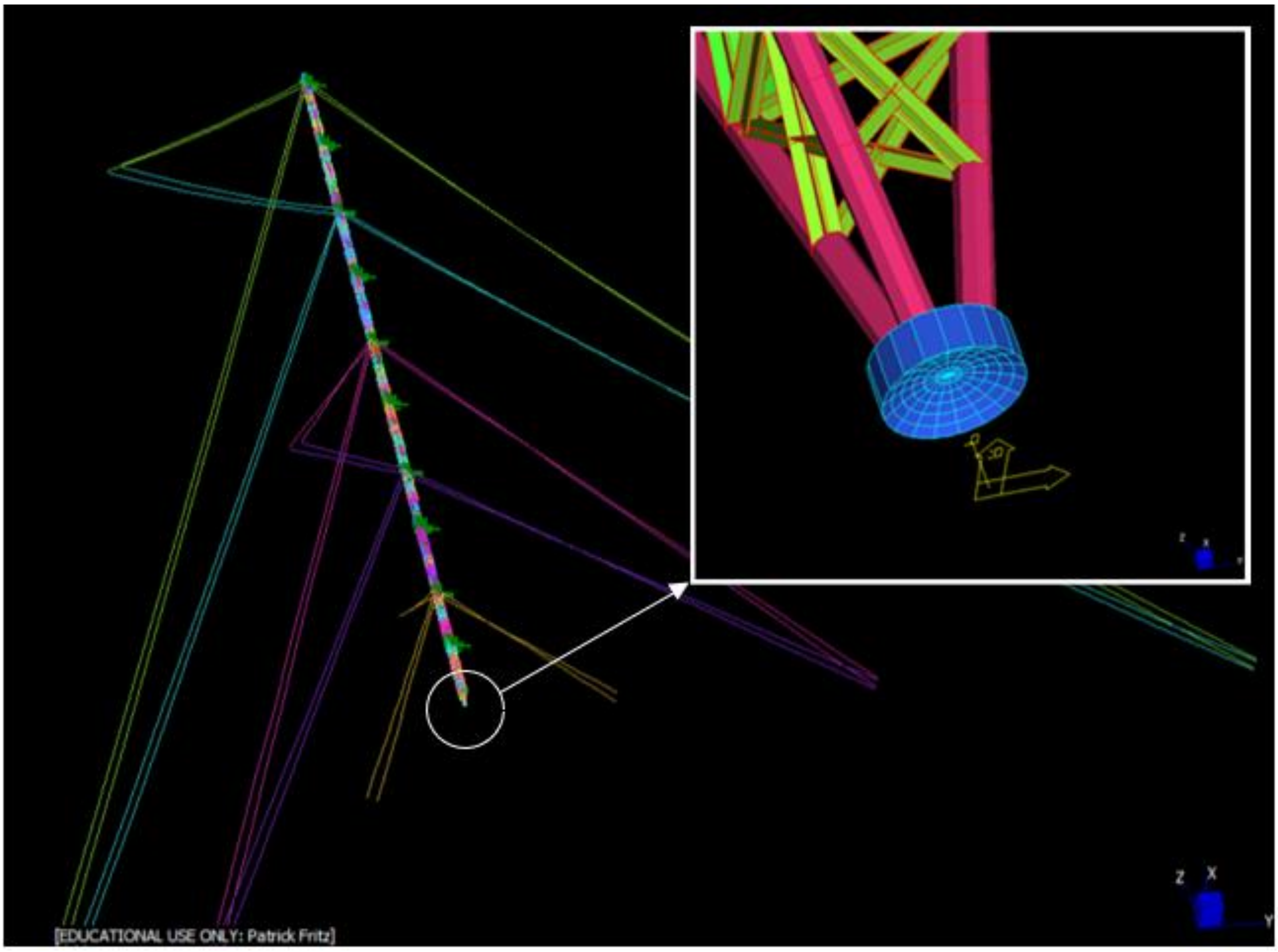


Figure 15 - Tower Base Joint, Ball and Socket Configuration

The lower surface of the socket joint forms a boundary condition for the model, as described in the following Section. It was constructed using a local radial coordinate system, which can also be seen in Figure 15.

BOUNDARY CONDITIONS

GUY CABLES – GROUND ANCHOR RESTRAINT

The guy cables were attached at the anchor support, fixing the 6 degrees of freedom in the global cartesian coordinate system - 3 translational and 3 rotational. The cable could theoretically pivot about the local pin axis at the Ground Anchor, reducing the boundary conditions to 5 fixed degrees of freedom – 3 fixed translational and 2 fixed rotational. However, given the scale of the Tower and cables, there is no appreciable rotation of the end assemblies during Tower displacements. For this reason, all six (6) degrees of freedom (DoF) were fixed at the Ground Anchors.

BASE JOINT – BALL AND SOCKET RESTRAINT

As the Tower deflects, the socket rotates over the surface of the fixed ball. To replicate this restraint system, the surface area was restrained in it radial direction, as shown in Figure 16. This removed the need to model the ball part of the socket altogether.

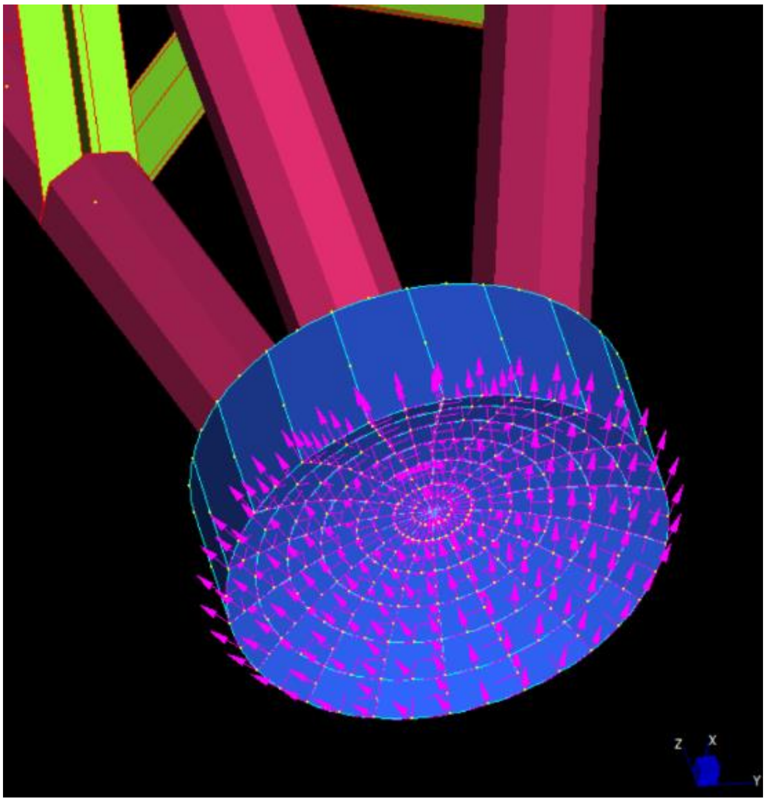


Figure 16 - Tower Base Joint, Fixed Radial DoF

POINT LOADS

Each guy cable has an Open Spelter Socket fitted to one end, and a Hairpin Assembly fitted to the other. The Spelter Sockets attach to the Tower Connection Plates which are welded to the Tower Legs, securing the guy cable to the Tower. Attached to the other end of the guy cable is the Hairpin, which secures the cable to the Ground Anchor and provides the tensioning mechanism.

Both the Spelter Sockets and Hairpin assemblies have non-negligible mass which contribute to the Tower dynamics. The Hairpin effectively acts at the Ground Anchor and was not included in the model. This was deemed appropriate as it acts at the restraint, which is a fixed boundary condition. The Spelter Sockets were represented as translational point loads, which acted at the common node between the guy cable and connection plate, see Figure 17.

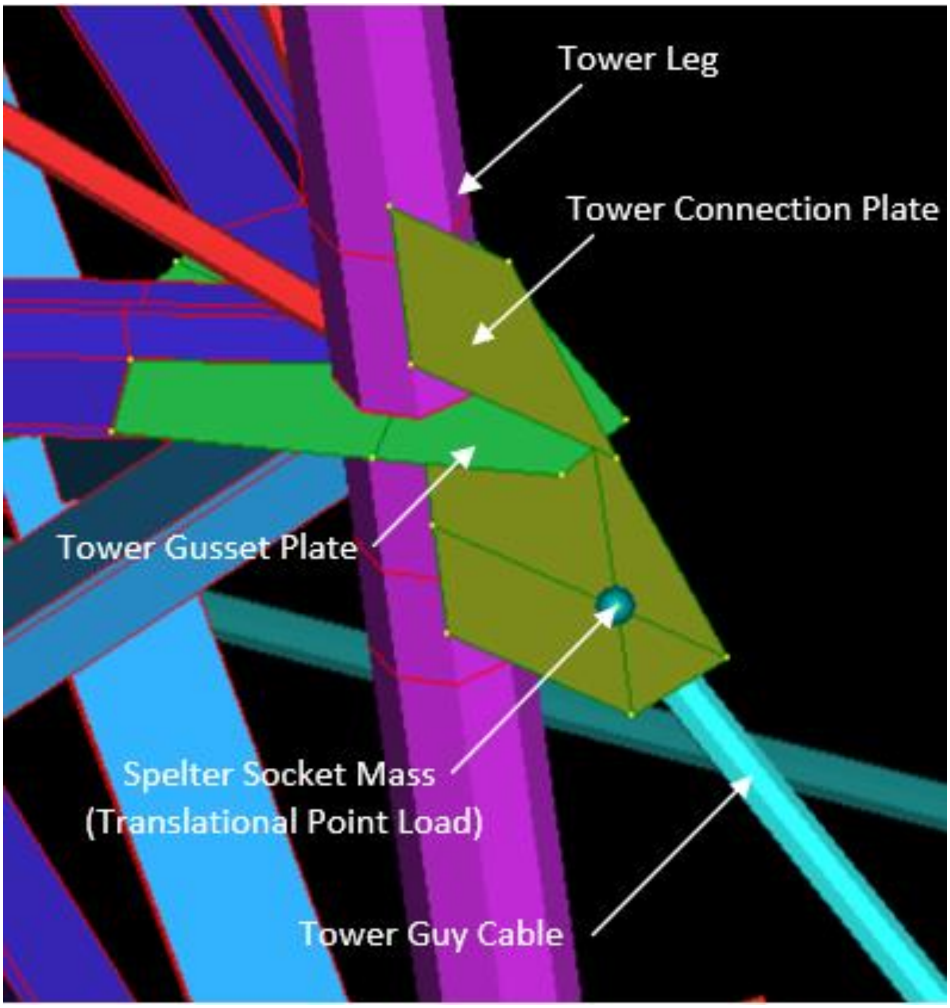


Figure 17 - Tower Connection Plate and Spelter Socket Point Mass

ANTENNA LOADS

The antenna loads were represented as load vectors rather than modelling the actual array. This was done because of both time restraints and vector representation seemed sufficient. In reality, the antenna loads are directed perpendicular with Faces 0-1 and Face 2-0, as halyards supporting the antenna panels are attached to large sheaves on the Tower structure. These are crudely represented as large plate elements which approximate the sheave mass (refer Figures 18 and 19). The tower deflections were anticipated to be in the order of magnitude of inches, so representing the antenna panel loads as vectors was deemed appropriate for the project scope.

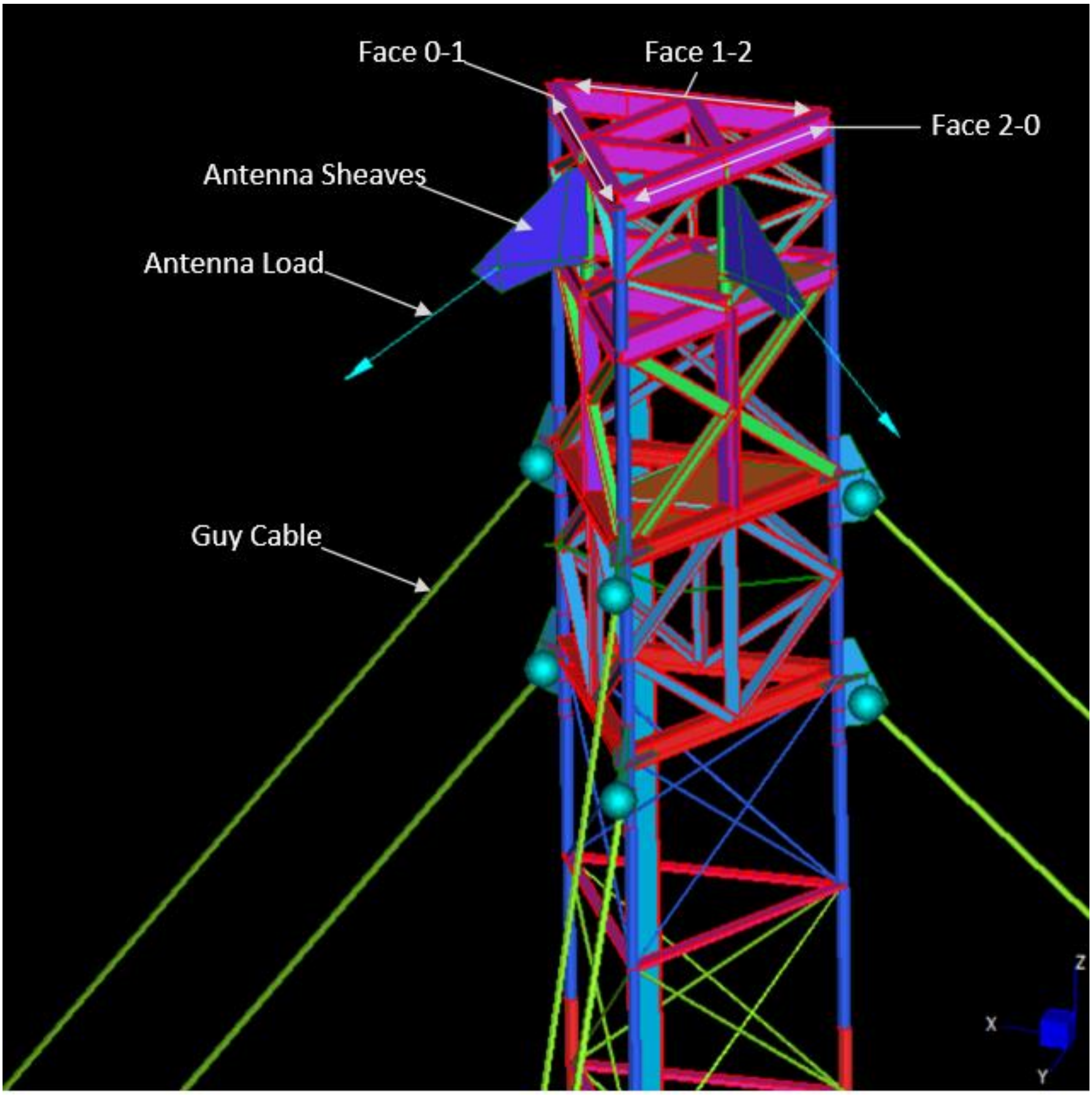


Figure 18 - Antenna Loads as Vectors

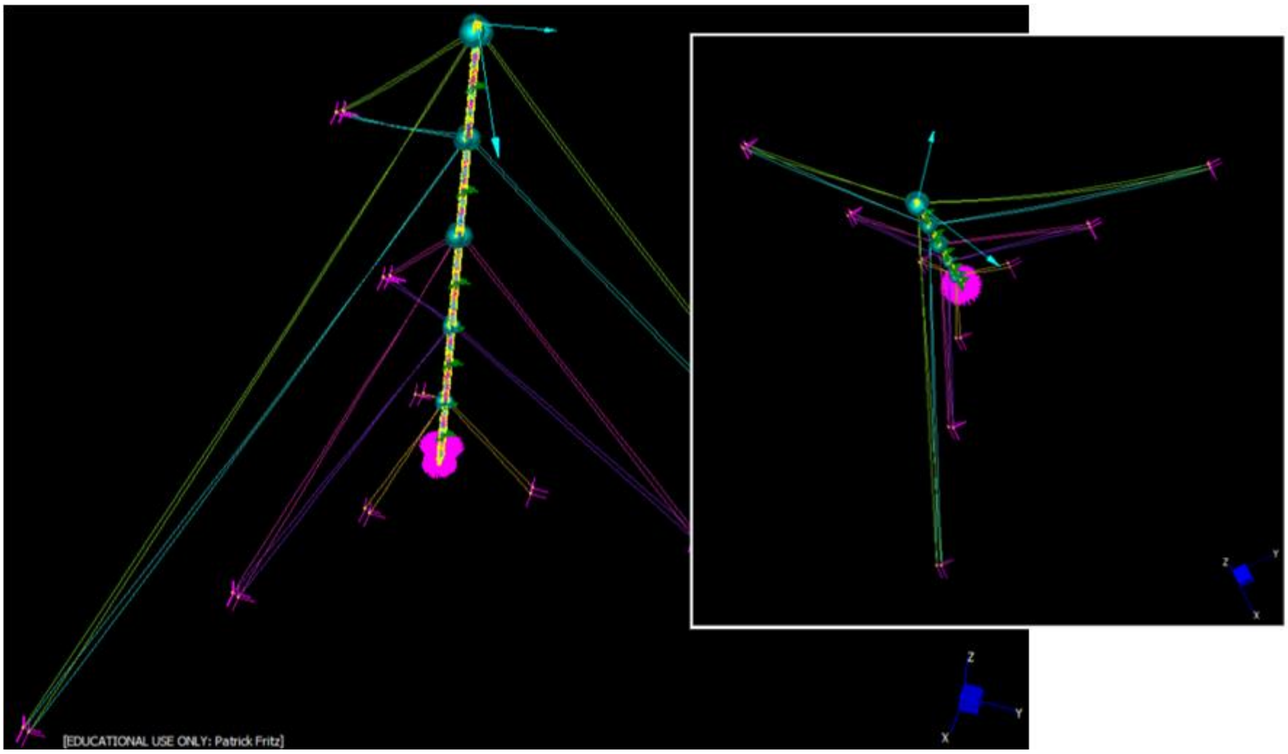


Figure 19 - Tower Antenna Loads

STRAND 7 SOLVER – GEOMETRIC NON-LINEAR

The model is solved using a geometric non-linear solver because of the highly elastic nature of cable elements (Zhang et al. 2019). In a linear-static analysis, the equations of equilibrium are formed on undeformed boundary conditions, before loads are applied. With small deflections boundary conditions and load paths remain constant. However, with large deflections, as with cables, the change in geometry requires new equilibrium equations for the deformed shape (Comino 2022). While material non-linearity is also recognised as being present in large cable structure analysis, the geometric non-linearity is predominant (Pintea & Tarta 2012) and is used for the analysis.

FEA MODEL VALIDATION

Assessing how a model deflects with actual deflection data gained through experimental analysis would be one way to validate a model, as discussed previously. However, alternate methods are often required when these types of validation are not available. For this project, cable tensions for antenna down and antenna up tower states had been provided. This data was used in creating a Cable Length Solver, which iterated on cable lengths using catenary theory described in the Literature Review and further below in the Catenary Equation Application.

CATENARY EQUATION APPLICATION

The following Section describes how the catenary equation was manipulated to assist in developing the Cable Length Solver (refer Figure 20). The outcome of the derivation is an implicit equation that is solved numerically to find the 'a' parameter in catenary equation $y = a\,cosh\left(\frac{x}{a}\right)$.

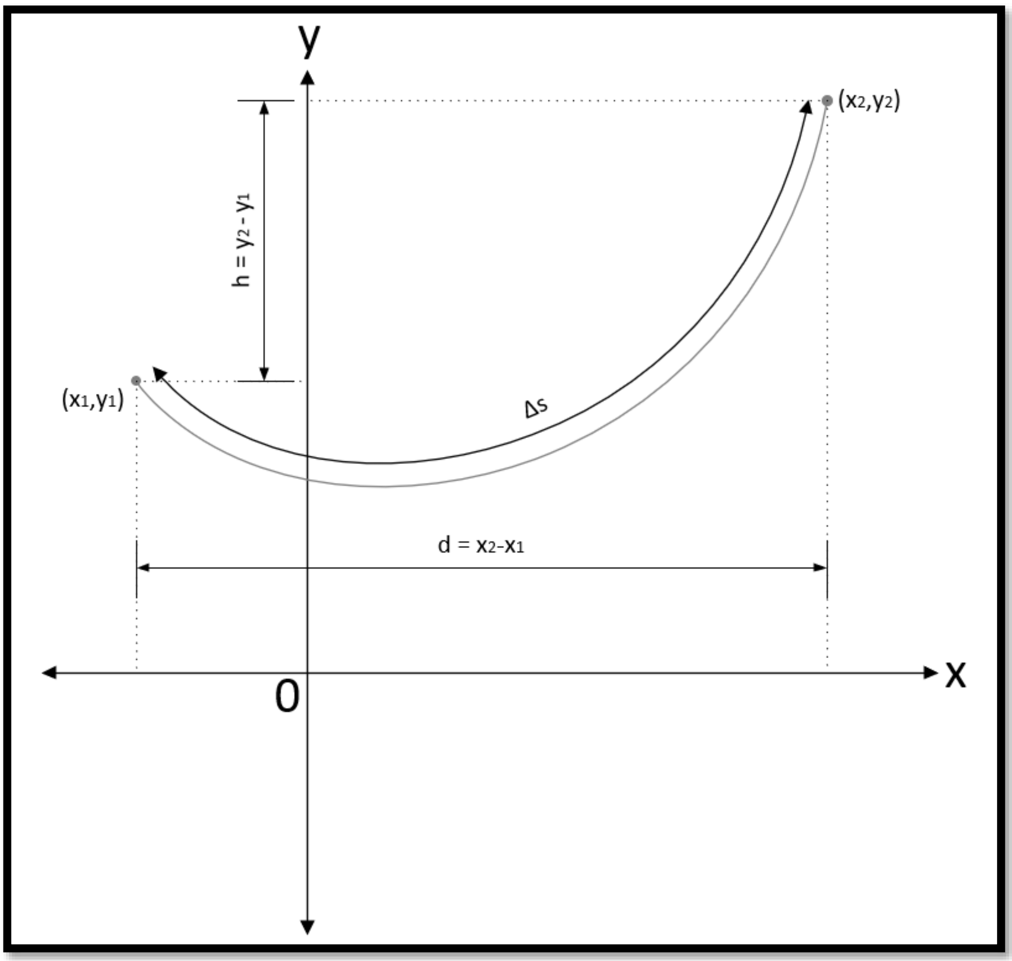


Figure 20 - Catenary Profile

As described in the Literature Review, a cable is mathematically described by the catenary equation $y = a\,cosh\left(\frac{x}{a}\right)$. Figure 20 displays a general profile of a cable structure suspended between two points. It is used to illustrate how the Cable Length Solver was developed to determine cable tensions and reactions at attachment points.

From Figure 2020, it is shown that,

$$x_2 - x_1 = d$$
$$y_2 - y_1 = h$$

Following general form of the catenary,

$$y = a\,cosh\left(\frac{x}{a}\right)$$

Therefore, the height between attachment points is

$$h = a\,cosh\left(\frac{x_2}{a}\right) - a\,cosh\left(\frac{x_1}{a}\right)$$

Using Arc Length Identity

$$ds^2 = dx^2 + dy^2$$

$$\frac{ds^2}{dx^2} = \frac{dx^2}{dx^2} + \frac{dy^2}{dx^2}$$

$$\left(\frac{ds}{dx}\right)^2 = 1 + \left(\frac{dy}{dx}\right)^2$$

$$\frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \;\Rightarrow\; ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx \;\Rightarrow\; \int ds = \int \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx$$

$$s = \int \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx$$

We find 's' in terms of 'a'

$$y = a\,cosh\left(\frac{x}{a}\right) \;\Rightarrow\; \frac{dy}{dx} = \frac{d}{dx}\left(a\,cosh\left(\frac{x}{a}\right)\right) \;\Rightarrow\; \frac{dy}{dx} = sinh\left(\frac{x}{a}\right)$$

Substituting into 's'

$$s = \int \sqrt{1 + \left(\sinh\left(\frac{x}{a}\right)\right)^2}\,dx$$

Using Identity Rule $\Rightarrow \cosh^2(\mathrm{x}) - \sinh^2(\mathrm{x}) = 1 \;\Rightarrow\; \cosh^2(x) = 1 + \sinh^2(x)$

$$s = \int \sqrt{cosh^2\left(\frac{x}{a}\right)}\,dx$$

$$s = \int cosh\left(\frac{x}{a}\right)\ dx$$

Using U − Substitution

$$s = \int cosh^2(u)\ \ dx$$

$$u = \left(\frac{x}{a}\right) \quad \Longrightarrow \quad du = \frac{1}{a}\frac{d}{dx}(x) \quad \Longrightarrow \quad du = \frac{1}{a}\ dx \quad \Longrightarrow \quad dx = a\ du$$

$$s = \int \cosh(u)\ a\ du\ \ = a \int \cosh(u)\ du\ \ =\ \ a \sinh(u) + C$$

$$s = a\ sinh\left(\frac{x}{a}\right)\Big|_{x_1}^{x_2}$$

$$s = a\ sinh\left(\frac{x_2}{a}\right) - a\ sinh\left(\frac{x_1}{a}\right)$$

Summarising,

$$s = a\ sinh\left(\frac{x_2}{a}\right) - a\ sinh\left(\frac{x_1}{a}\right), \quad and$$

$$h = a\ cosh\left(\frac{x_2}{a}\right) - a\ cosh\left(\frac{x_1}{a}\right)$$

′s′and ′h′ are now in terms of ′a′, but also need to solve in terms of additional variable ′d′

$$s^2 - h^2 = \left[a\left(sinh\left(\frac{x_2}{a}\right) - sinh\left(\frac{x_1}{a}\right)\right)\right]^2 - \left[a\left(cosh\left(\frac{x_2}{a}\right) - cosh\left(\frac{x_1}{a}\right)\right)\right]^2$$

Using Identity Rule $\Longrightarrow$ $(a-b)^2 = a^2 - 2ab + b^2$ to expand squared terms

$$s^2 - h^2 = a^2\ \left\{\left[\sinh^2\left(\frac{x_2}{a}\right) - 2\sinh\left(\frac{x_2}{a}\right)\sinh\left(\frac{x_1}{a}\right) + \sinh^2\left(\frac{x_1}{a}\right)\right]\right.$$
$$\left. - \left[\cosh^2\left(\frac{x_2}{a}\right) - 2\cosh\left(\frac{x_2}{a}\right)\cosh\left(\frac{x_1}{a}\right) + \cosh^2\left(\frac{x_2}{a}\right)\right]\right\}$$

Using Identity Rule $\Longrightarrow$ $\cosh^2(x) - \sinh^2(x) = 1 \quad \Longrightarrow \quad -1 = \sinh(x) - \cosh^2(x)$

$$s^2 - h^2 = a^2\left[-1 - 2\sinh\left(\frac{x_2}{a}\right)\sinh\left(\frac{x_1}{a}\right) - 1 + 2\cosh\left(\frac{x_2}{a}\right)\cosh\left(\frac{x_1}{a}\right)\right]$$

$$s^2 - h^2 = a^2\left[2\cosh\left(\frac{x_2}{a}\right)\cosh\left(\frac{x_1}{a}\right) - 2\sinh\left(\frac{x_2}{a}\right)\sinh\left(\frac{x_1}{a}\right) - 2\right]$$

$$s^2 - h^2 = 2a^2\left[\cosh\left(\frac{x_2}{a}\right)\cosh\left(\frac{x_1}{a}\right) - \sinh\left(\frac{x_2}{a}\right)\sinh\left(\frac{x_1}{a}\right) - 1\right]$$

Using Identity Rule $\Longrightarrow$ $\cosh(z_1 - z_2) = \cosh(z_1)\cosh(z_2) - \sinh(z_1)\sinh(z_2)$

$$s^2 - h^2 = 2a^2\left[\cosh\left(\frac{x_2}{a}\right)\cosh\left(\frac{x_1}{a}\right) - 1\right]$$

$$s^2 - h^2 = 2a^2 \left[\cosh\left(\frac{x_2 - x_1}{a}\right) - 1\right]$$

Incorporating $'\mathrm{d}'$ terms $\Longrightarrow$ $\mathrm{x_2 - x_1 = d}$

$$s^2 - h^2 = 2a^2 \left[\cosh\left(\frac{d}{a}\right) - 1\right] \; and\ equivilently\ equals \left[\cosh\left(\frac{2d}{2a}\right) - 1\right]$$

Using Identity Rule $\Longrightarrow$ $\cosh(2\mathrm{z}) = 2\sinh^2(\mathrm{z}) + 1$

$$s^2 - h^2 = 2a^2 \left[\sinh^2\left(\frac{d}{2a}\right) + 1 - 1\right]$$

$$s^2 - h^2 = 4a^2 \left[\sinh^2\left(\frac{d}{2a}\right)\right]$$

Equivalently,

$$\sqrt{s^2 - h^2} = 2a\sinh\left(\frac{d}{2a}\right)$$

As both ‘s’ and ‘h’ are functions of ‘a’, this equation has no explicit solution, but can be numerically solved.

Once solved, the solution for ‘a’ can be used to find the theoretical values of attaching nodes (x_1,y_1) and (x_2,y_2), according to the coordinate system detailed in Figure 20, using hyperbolic identities.

$$s = a\sinh\left(\frac{x_2}{a}\right) - a\sinh\left(\frac{x_1}{a}\right) \; and \; h = a\cosh\left(\frac{x_2}{a}\right) - a\cosh\left(\frac{x_1}{a}\right)$$

Using Hyperbolic Addition Identity Rule $\Longrightarrow$ $\sinh(\mathrm{x}) - \sinh(\mathrm{y}) = 2\cosh\left(\frac{\mathrm{x+y}}{2}\right)\sinh\left(\frac{\mathrm{x-y}}{2}\right)$

$$s = 2a\cosh\left(\frac{\mathrm{x_1 + x_2}}{\mathrm{2a}}\right)\sinh\left(\frac{\mathrm{x_1 - x_2}}{\mathrm{2a}}\right)$$

Using Hyperbolic Addition Identity Rule $\Longrightarrow$ $\cosh(\mathrm{x}) - \cosh(\mathrm{y}) = 2\cosh\left(\frac{\mathrm{x+y}}{2}\right)\cosh\left(\frac{\mathrm{x-y}}{2}\right)$

$$h = 2a\sinh\left(\frac{x_1 + x_2}{2a}\right)\sinh\left(\frac{x_1 - x_2}{2a}\right)$$

Dividing h by s

$$\frac{h}{s} = \frac{\left[2a\sinh\left(\frac{x_1 + x_2}{2a}\right)\sinh\left(\frac{x_1 - x_2}{2a}\right)\right]}{\left[2a\cosh\left(\frac{\mathrm{x_1 + x_2}}{\mathrm{2a}}\right)\sinh\left(\frac{\mathrm{x_1 - x_2}}{\mathrm{2a}}\right)\right]}$$

$$\frac{h}{s} = \tanh\frac{(x_1 + x_2)}{2a}$$

Using Hyperbolic Identity $\Longrightarrow$ $\tanh(x) = \frac{e^{x}-e^{-x}}{e^{x}+e^{-x}}$ and let $x = (x_1 + x_2)$

$$\frac{h}{s} = \frac{e^{\left(\frac{x}{2a}\right)} - e^{-\left(\frac{x}{2a}\right)}}{e^{\left(\frac{x}{2a}\right)} + e^{-\left(\frac{x}{2a}\right)}}$$

$$\frac{h}{s} = \frac{e^{\left(\frac{x}{a}\right)} - 1}{e^{\left(\frac{x}{a}\right)} + 1}$$

$$s\left(e^{\left(\frac{x}{a}\right)} - 1\right) = h\left(e^{\left(\frac{x}{a}\right)} + 1\right) \quad \rightarrow \quad se^{\left(\frac{x}{a}\right)} - s = he^{\left(\frac{x}{a}\right)} + h \quad \rightarrow \quad se^{\left(\frac{x}{a}\right)} - he^{\left(\frac{x}{a}\right)} = h + s$$

$$e^{\left(\frac{x}{a}\right)}(s-h) = h + s \quad \rightarrow \quad e^{\left(\frac{x}{a}\right)} = \frac{h}{(s-h)} + \frac{s}{(s-h)} \quad \rightarrow \quad e^{\left(\frac{x}{a}\right)} = \frac{h+s}{(s-h)}$$

$$\ln\left(e^{\frac{x}{a}}\right) = ln\frac{(h+s)}{(s-h)} \quad \rightarrow \quad \frac{x}{a} = ln\frac{(h+s)}{(s-h)} \quad \rightarrow \quad x = a\,ln\frac{(h+s)}{(s-h)}$$

Incorporating $x = (x_1 + x_2)$

$$x_1 + x_2 = a\,ln\frac{(h+s)}{(s-h)}$$

Substituting into $\Longrightarrow$ $x_2 - x_1 = d$

$$x_2 = d + x_1$$

$$x_1 + (d + x_1) = a\,ln\frac{(h+s)}{(s-h)}$$

$$x_1 = \frac{1}{2}\left(a\,ln\frac{(h+s)}{(s-h)} - d\right)$$

$$x_1 = x_2 - d$$

$$x_2 - (d + x_2) = a\,ln\frac{(h+s)}{(s-h)}$$

$$x_2 = \frac{1}{2}\left(a\,ln\frac{(h+s)}{(s-h)} + d\right)$$

CABLE LENGTH SOLVER

These equations are used to provide the foundations of the Cable Length Solver. When the model is run, all the cable tensions and nodal positions can be extracted. The geometric position of each cable, along with its cable material properties, is used with the above formulations to provide a theoretical cable length which could achieve the objective tension.

The Cable Length Solver is a spread sheet developed and pre-populated with cables material properties, area, unit weight, modulus, and objective tensions. The model data is imported, and each cable has its nodal position extracted, which represents an (x_1, y_1) & (x_2, y_2) coordinate. This is used with the above formulations to iterate on cable length until the objective tension is achieved. These theoretical cable lengths are then exported back into the Strand 7 FEA model, updating the cable elements with the new lengths.

This process is repeated, whereby the model is run using the new cable lengths, the resulting tensions and cable element nodal positions are exported. The solver calculates the required tension by iterating on cable length until the objective tension is obtained. The resulting cable lengths are again exported back into the FEA model, updating the 30 cable element lengths. The model is again run using the geometric non-linear solver and the cable tensions assessed.

PROCESS FLOW

The process flow for iterating on cable length to achieve an objective tension is provided in Figure 21. It details the broad steps used to calculate each of the models 30 guy cable lengths to achieve their objective tension.

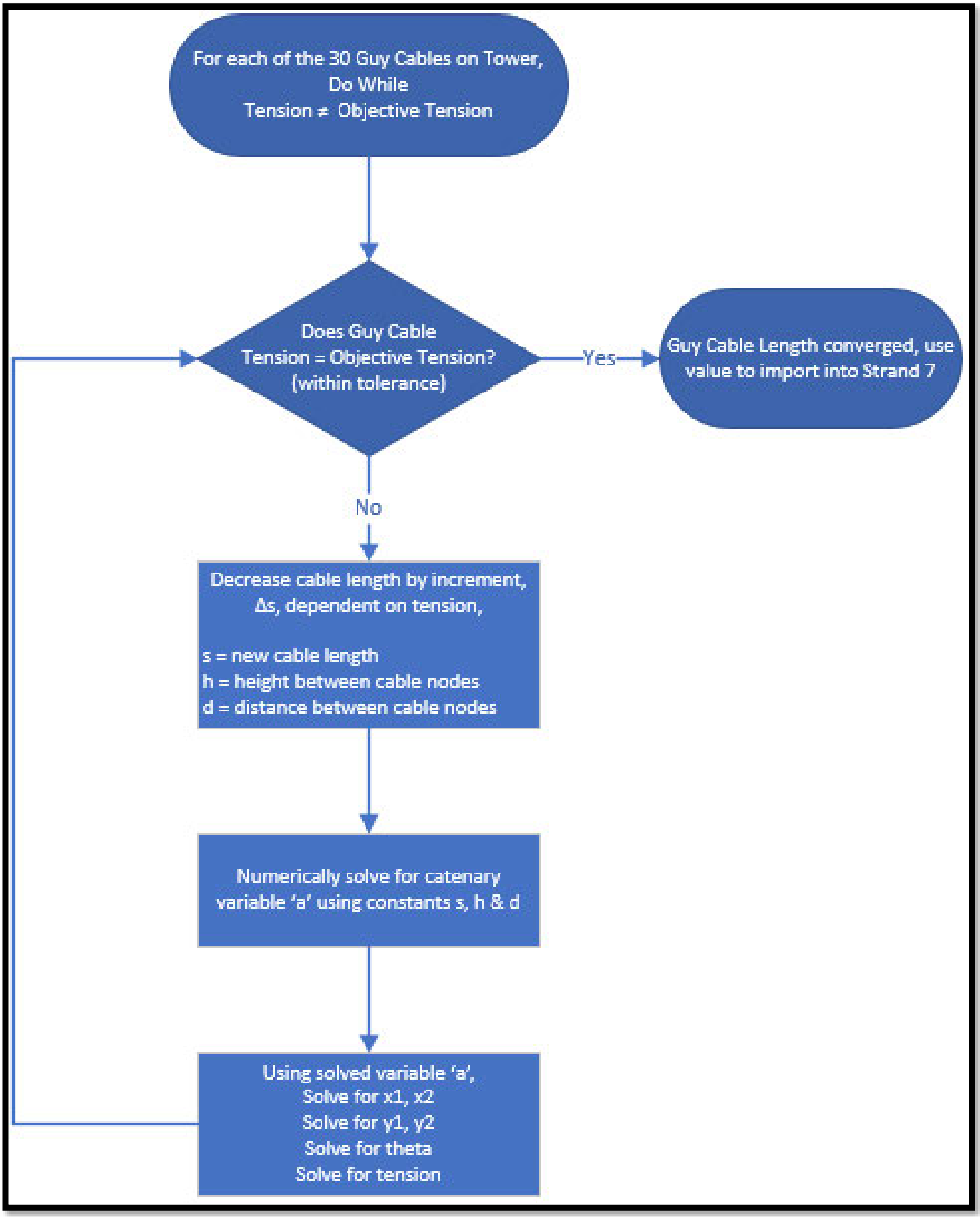


Figure 21 - Guy Cable Length Convergence, Process Flow

The steps summarised in Figure 21 are elaborated below to discuss the method used in deriving their value.

GUY CABLE TENSION = OBJECTIVE TENSION?

Each of the 30 cable tensions were assessed against the objective tensions given in Table 7. If the difference between the two fell outside of a desirable tolerance, the length was reduced by a finitely small increment and used to solve for cables catenary parameter, ‘a’.

SOLVE FOR A

From the Application of Catenary Equation Section, the following equation was derived,

$$\sqrt{s^2 - h^2} = 2a \sinh\left(\frac{d}{2a}\right).$$

From this equation, ‘a’ can be solved iteratively to any desired tolerance. This is done by choosing an upper and lower boundary condition for ‘a’, then using conditions to increment its value until the above equations LHS = RHS converge to the desired tolerance.

SOLVE FOR X

Once the guy cables catenary equation parameter ‘a’ is solved, the corresponding node coordinates are calculated using the derivations detailed in the Application of Catenary Equation Section. From the derivation, it can be shown that,

$$x_1 = \frac{1}{2}\left(a \, ln \frac{(h+s)}{(s-h)} - d\right)$$

$$x_2 = \frac{1}{2}\left(a \, ln \frac{(h+s)}{(s-h)} + d\right)$$

SOLVE FOR Y

Having solved for x_1 and x_2, the values are substituted into the catenary general form,

$$y_1 = a \, cosh\left(\frac{x_1}{a}\right)$$

$$y_2 = a \, cosh\left(\frac{x_2}{a}\right)$$

SOLVE FOR THETA

Tension forces in cables align with the tangent of their profile, so the direction of the support reactions can be calculated by finding the derivative of the cable equation at that point.

$$\frac{\mathrm{dy}}{\mathrm{dx}_1} = \sinh\left(\frac{x_1}{a}\right) \quad \rightarrow \quad \theta_1 = \tan^{-1}\left(\frac{dy}{dx_1}\right)$$

$$\frac{\mathrm{dy}}{\mathrm{dx}_2} = \sinh\left(\frac{x_2}{a}\right) \quad \rightarrow \quad \theta_2 = \tan^{-1}\left(\frac{dy}{dx_2}\right)$$

SOLVE FOR TENSION

Knowing the length of the cable through,

$$s = a\,sinh\left(\frac{x_2}{a}\right) - a\,sinh\left(\frac{x_1}{a}\right),$$

The vertical reactions can be found by integrating the weight of the cable between the low point and each support, as shown in **Error! Reference source not found.**.

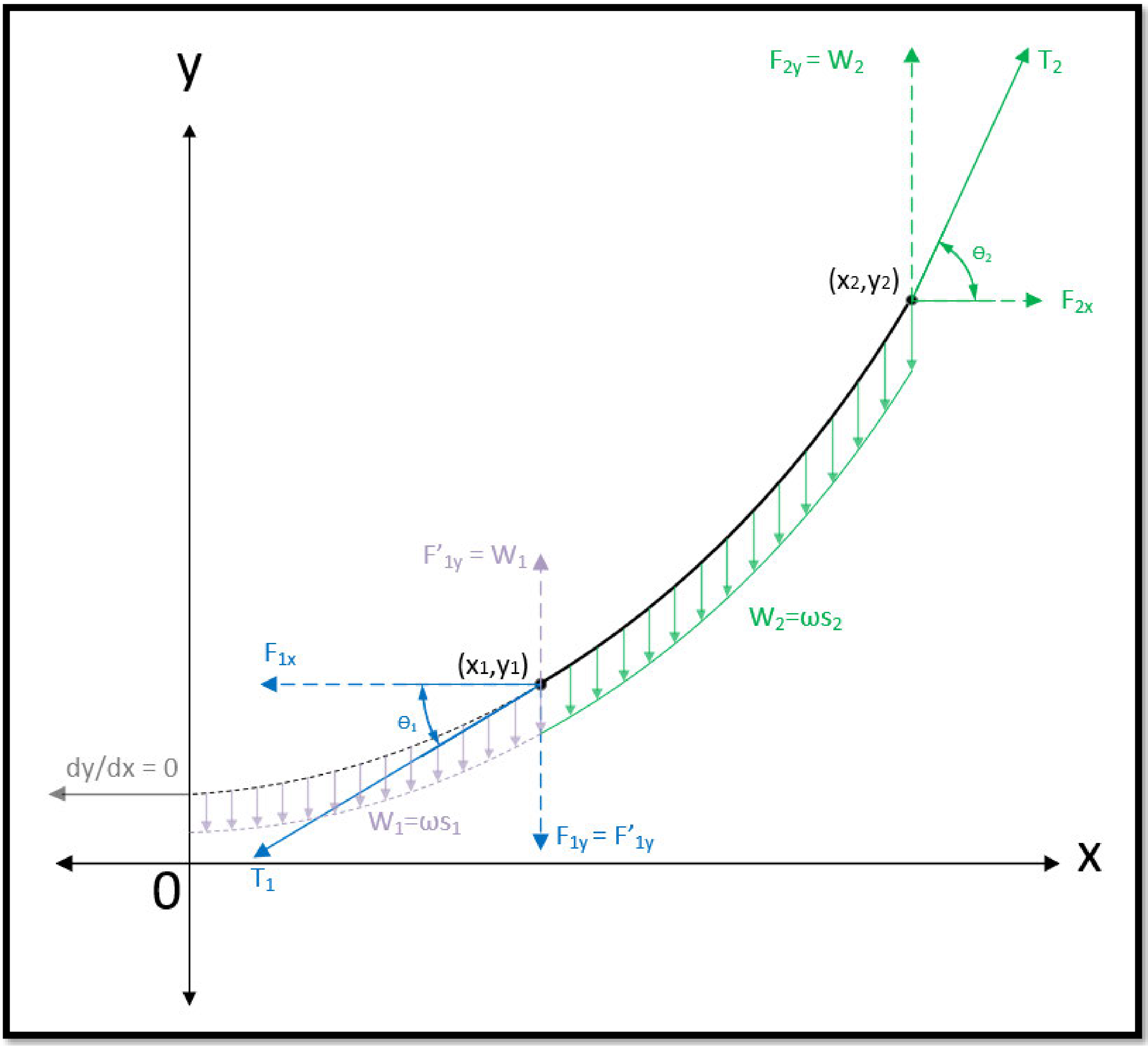


Figure 22 - Calculating Fy Reactions at Supports

With the vertical components, F_{1y} and F_{2y}, now known, the horizontal components are calculated,

$$F_{x_1} = \left(\frac{y_1}{\frac{dy}{dx_1}}\right) \quad and \quad F_{x_2} = \left(\frac{y_2}{\frac{dy}{dx_2}}\right)$$

The tensions at the supports are then calculated,

$$T_1 = \sqrt{{F_{x_1}}^2 + {F_{y_1}}^2} \quad and \quad T_2 = \sqrt{{F_{x_2}}^2 + {F_{y_2}}^2}$$

This process is repeated until all 30 cable tensions fall within 5% of the objective tensions. Once convergence on the initial cable tensions is achieved, a level of confidence in the model was attributed and further analysis conducted. This first stage of achieving cable tension convergence was fundamental to ongoing analysis and applying the Load Cases described in the following Section.

Once an initial convergence on cable tension was achieved, the next stage of the project was to assess various configurations that the tower would be exposed to under varying maintenance procedures. It is common practice to conduct the guy cable replacements under calm forecasted conditions, removing any wind loading. This condition is replicated in the model, where only static environmental conditions are applied.

TOWER LOAD CASES

The HEH Inner Towers each have five (5) Levels where the guy cables attach, termed Attachment Bays. These guy cables are attached to the upper and lower sections of the tower bays, two (2) per lane, extending down to the Ground Anchors, as shown in Figure 23. The Load Cases described below relate to removing the upper three (3) cables at each of the five (5) Attachment Bays.

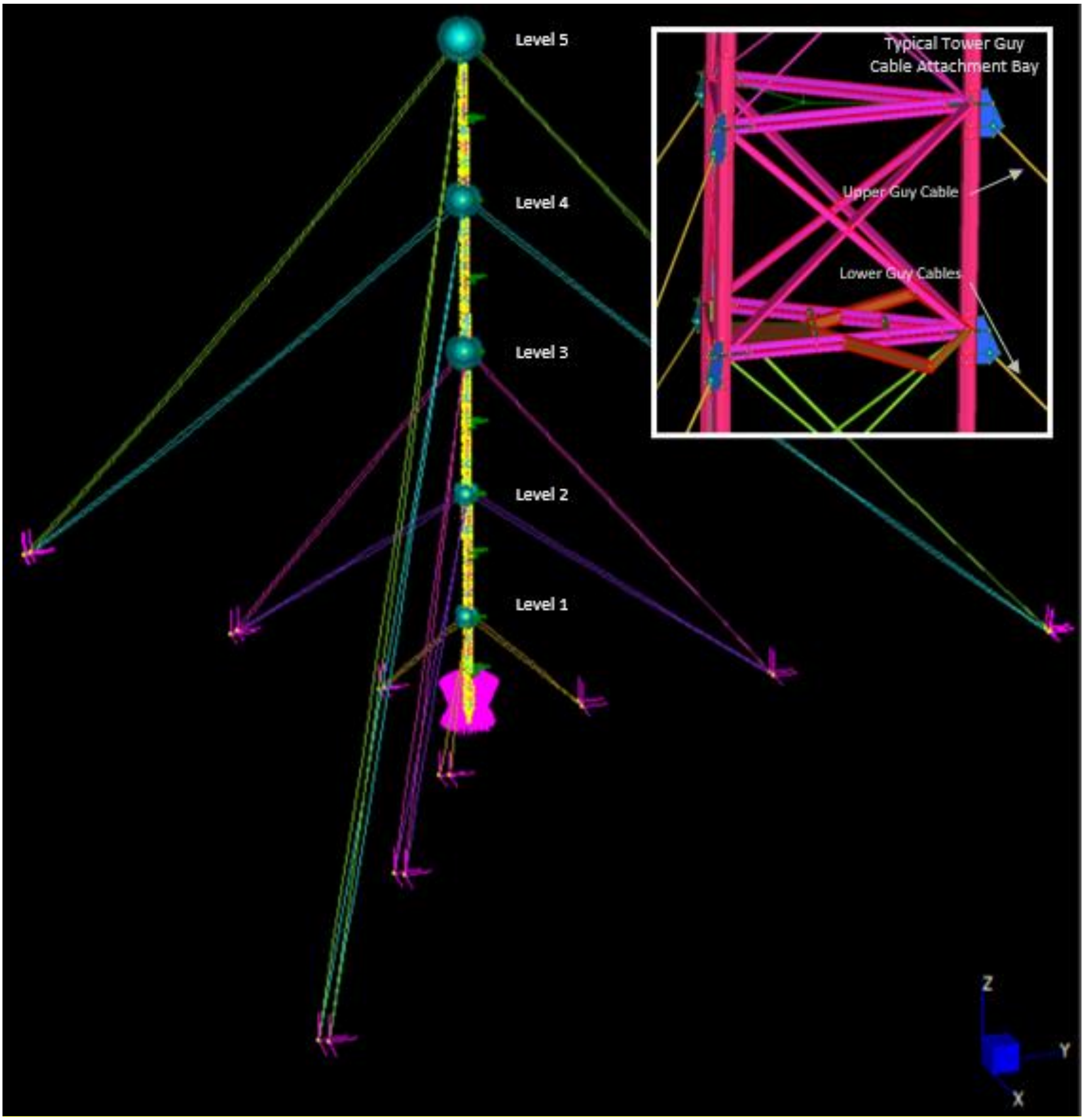


Figure 23 – Tower, showing 30 Guy Cable Attachment Points

Replacing guy cables is conducted in accordance with a local lift plan. The lift plan for replacing an upper guy cable at an Attachment Bay is broadly described as,

1. Of the six (6) guy cables at the affected Tower bay, de-tension the upper three.
2. At the affected Lane, detach the cable from the Ground Anchor and lower cable to the ground. This allows the cable to hang vertically off its Tower support, lying tangent to the ground.
3. Remove the affected cable completely from the Tower structure.
    - Note - The reverse is conducted on installation and is considered equivalent.

These three general steps from the lift plan form the basis for the Load Cases examined within this project. The following Load Cases are conducted on the Tower in two general states, antenna down and antenna up.

1. Load Case 1 – 3 x Guy Cables De-tensioned
2. Load Case 2 – 1 x Guy Cable Hanging
3. Load Case 3 – 1 x Guy Cable Removed

Each of the three (3) upper cables at the five (5) Tower Attachment Bays are subjected to Load Cases 1, 2 & 3. These Load Cases are applied to two different Tower models, one (1) model where the antenna is down, and one (1) model where the antenna is up. This results in 3 (upper cables) x 5 (attachment bays) x 3 (load cases) x 2 (tower states) + 2 (converged down/up) = 92 Tower models which needed to be run to find the required data. Load Case 1, however, does not alter the guy cables between Lanes, as they are all just de-tensioned. This reduces the actual number of load cases to 72.

LOAD CASE 1 – 3 X GUYS DE-TENSIONED

In this load condition, the length of the upper guy cables at Lanes 0, 1 & 2 are increased by 24". This is representative of the situation, where the guy cable length is effectively increased to de-tension them before release. Each guy cable is attached to its Ground Anchor support via a large Hairpin Assembly. This Hairpin Assembly acts like a large turnbuckle and incrementally increases or decreases its length to adjust the guy cable tension. This de-tensioning was simulated in the model by increasing all the applicable cable lengths by 24" and re-running the model.

LOAD CASE 2 – 1 X GUY CABLE HANGING

In this load condition, the affected Level and Lane has its guy cable removed from the Ground Anchor support and is left hanging from the tower. The cable hangs down the Tower and the runs out until it lays tangent to the ground. As detailed previously, the vertical reaction of the upper Tower support will be equal to the weight of the cable between the tangent point (the ground) and the support.

To simulate this condition in the model, a node a was placed 50ft from the base of the affected cable. The cable element was then altered so it attached to the new position. The theoretical length of the cable was then calculated, and model updated, so that it would lay tangent at these coordinates. By doing this, the vertical load from the cable, which the Tower support still reacts against in this condition, could be modelled.

LOAD CASE 3 – 1 X GUY CABLE REMOVED

In this load condition, the affected Level and Lane has its guy cable completely removed. In this condition, the Tower is in its most unsupported and represents the Load Case which was expected to produce the most significant results. To represent this condition in the model, the applicable cable element was just removed.

RISK ASSESSMENT

A project risk assessment has been carried out utilising the standard risk management plan template adopted by Raytheon. An extract is provided in Annex C.

As the project work was largely focused on building, validating, and analysing a FEA model, the hazards and associated risk profile related mainly to desk type work. However, as the intent of the project is to build on a gap in research and provide a foundation for further development, there is an additional dimension of risk which remains beyond the completion of the project. The intent of the project analysis is to help form maintenance procedures, specifying the process of stabilising, tensioning, removing, and installing cables and antenna panels on the tower structures. With the project scope intending to form a basis for future work packages, there is a possibility of introducing post-project risk to the workplace.

While the project is not designing the tower, the work still encompasses examining, testing and analysis of structures. Specific to the project work, there is a duty of care that needs to be addressed to ensure compliance with the Work Health and Safety Act 2011. The Act stipulates that the duties of persons conducting undertakings on structures, need to so far as reasonably practical ensure the design is without risks to the health and safety of exposed persons (Work Health and Safety Act 2011).

Pending the outcomes of the project analysis, maintenance instructions may be drafted to assist in ongoing work. Engineers Australia recommend the development of a safety case to demonstrate safety due diligence, consistent with the WHS legislation (Engineers Australia 2014, p. 4). Within the Safety Guideline Case, Engineers Australia make an important distinction between preventing all hazardous events, and taking all reasonable, practical precautions to eliminate risk so far as is reasonably practical (SFAIRP) (2014, p. 6). In addition to maintaining compliance with the WHS legislation, engineers are also obliged to consider these aspects as part of their professional practice. The Engineers Australia’s Code of Ethics stipulates such practices and behaviours, and it is incumbent on the engineer to act accordingly (Engineers Australia 2019). These considerations will be incorporated into any future work packages.

PROJECT RESTRAINTS

There are various restraints which could impact the project, with the associated risks identified in Annex C. These restraints have been categorised into three (3) broad classes, Hardware, Software, Human. Each of these is discussed briefly in turn.

HARDWARE

Although the data classification on the information used to generate the model was kept to a minimum, as a precaution none of it was transferred from the work issued laptop. External software couldn’t be installed on the work issued laptop, so a separate standalone laptop was sourced to run the Strand 7 software. Due to licencing restrictions on the student version of Strand 7 it could only be run on a single piece of hardware. To reduce the risk of hardware restraints impacting the project, acquiring a standalone laptop was deemed the most suitable option.

SOFTWARE

Microsoft Excel was used to formulate various spreadsheets, most importantly the Cable Length Solver. Other spreadsheets were required to conduct the analysis, which required sorting and plotting various aspects in various ways. As the baked in functions of Excel could not achieve the required iteration process, Visual Basic for Applications (VBA) code needed to be developed and run.

To conduct the project, having consistent access to the STRAND7 FEA software was critical. While there are other software packages that could conduct the non-linear analysis, project specifications detailed it as a requirement to ensure consistency across other Company projects. While the University of Southern Queensland provides access to this software, a student licence was instead gained through the provider to remove any third party involvement.

HUMAN

Undertaking and completing this project could not have been conducted without the tutoring and mentorship of project supervisor, Mr Stephen Mitchell. His engineering expertise and willingness to tutor and impart his knowledge was critical in conducting this project. Every aspect of the project had an element of learning involved. From developing an understanding of catenary theory and how to apply it in a practical application, to developing the skillsets to use an unfamiliar FEA software package in modelling a real world problem. Every project element was coupled with an element of tutoring, which was critical in completing the project.

TIMELINES

A Project Plan Timeline was carried out, an extract provided in Annex D - Project Plan Timeline. While most of the milestones were achieved, the data extraction and analysis took a lot longer than anticipated. To get the required data, very time onerous processes needed to be conducted. Sorting the elements into the required groups, extracting, further sorting and data plotting all took considerably more time than anticipated. As such, the Project was not able to incorporate some of the other aspects that had been intended, such as wind loading. Through the Analysis and Findings Section, however, it is shown that the model may require some further refinement and validation, which if applicable should be carried out prior to further loadings.

ANALYSIS & FINDINGS

The following analysis assesses the deflections and stresses affecting the tower while replacing the upper guy wires from the Attachment Bays. Initially, Tower deflection in both x-z and y-z planes is measured while under the three different Load Cases. The Load Cases which cause out of tolerance conditions are identified, along with the Load Cases which cause the greatest tower displacements.

Tower forces and stresses are then assessed. The tower is separated into three (3) groups for analysis, the Legs, the Horizontal Beams and the Diagonal Tie-Rods. Each group is provided with two (2) tables, one table indicates the peak stress for the applicable Load Case, and the other measures that peak against the material yield point to provide a Factor of Safety (FoS).

GUY CABLE TENSION CONVERGENCE

Field tests had provided the below information on cable tensions that were measured on a Tower with both an antenna down, and antenna up. The two different objective tensions are provided in Table 7. Note that these tensions are taken from the Hairpin assembly, or the lower end of the cable end.

Table 7 - Tower Guy Cable Objective Tensions, Antenna Down & Up

Tower Guy Cable Objective Tensions			
Tower Details	Antenna Down	Antenna Up	
	All Lanes	Lane 0	Lane 1&2
Level 5	169800	133900	192800
Level 4	79600	76960	80600
Level 3	77400	79800	74700
Level 2	41100	41700	40500
Level 1	33300	32800	32900

For the antenna down tensions, all the guy lanes have the same tension at each Level as the Tower loading is symmetric. With the antenna up tensions, however, an increase tension in Lanes 1 & 2 is apparent. This is to counteract the additional forces imparted by the antenna loads, which have horizontal components pulling against Lanes 1 & 2. Of interest, Level 3 also has a higher tension then Level 4 in Lane 0, which relates to the ‘s’ shape profile the towers exhibit, discussed further in the Deflections Section.

As discussed earlier in the Methodology, Load Cases 1, 2 & 3 are applied to two Tower models, antenna down and antenna up. Before applying any Load Cases, confidence in the model needed to be attained. This was done by using a Cable Length Solver, which used model data to calculate the theoretical cables lengths required to achieve the objective tensions. This process of running the model, extracting nodal positions, calculating theoretical free lengths, reimporting cable lengths, running the model and assessing the tensions was conducted approximately six (6) times on both tower models before convergence was achieved and cable tensions fell within the 5 % of the objective tension.

CABLE TENSION CONVERGENCE ERROR

Table 8 provides the final tensions that were derived from the model. End 2 tensions represent tensions at the ground anchor and are the ones used to measure objective tension against.

Table 8 - Tower Model Guy Cable Tension Error

Tower Details			Antenna Down				Antenna Up			
			Tension (kips)			Error	Tension (kips)			Error
			End 1	End 2	Objective		End 1	End 2	Objective	
Lane 2	Level 5	Upper	203178	167839	169800	1.17%	227327	191992	192800	0.42%
		Lower	202671	167612	169800	1.31%	226298	191242	192800	0.81%
	Level 4	Upper	90747	78861	79600	0.94%	92568	80683	80600	0.10%
		Lower	90515	78752	79600	1.08%	92539	80777	80600	0.22%
	Level 3	Upper	82992	75113	77400	3.04%	80170	72291	74700	3.33%
		Lower	82920	75154	77400	2.99%	80109	72343	74700	3.26%
	Level 2	Upper	42980	40346	41100	1.87%	42416	39782	40500	1.80%
		Lower	42941	40368	41100	1.81%	42384	39811	40500	1.73%
	Level 1	Upper	33805	32822	33300	1.46%	33774	32792	32900	0.33%
		Lower	33797	32862	33300	1.33%	33727	32793	32900	0.33%
Lane 1	Level 5	Upper	203179	167840	169800	1.17%	227128	191793	192800	0.53%
		Lower	202663	167604	169800	1.31%	226473	191417	192800	0.72%
	Level 4	Upper	90749	78863	79600	0.93%	92666	80780	80600	0.22%
		Lower	90512	78749	79600	1.08%	92458	80695	80600	0.12%
	Level 3	Upper	83000	75121	77400	3.03%	80189	72309	74700	3.31%
		Lower	82914	75148	77400	3.00%	80092	72326	74700	3.28%
	Level 2	Upper	42985	40351	41100	1.86%	42419	39785	40500	1.80%
		Lower	42938	40365	41100	1.82%	42381	39808	40500	1.74%
	Level 1	Upper	33822	32839	33300	1.40%	33740	32757	32900	0.44%
		Lower	33781	32846	33300	1.38%	33762	32828	32900	0.22%
Lane 0	Level 5	Upper	203182	167843	169800	1.17%	168803	133461	133900	0.33%
		Lower	202669	167610	169800	1.31%	168363	133301	133900	0.45%
	Level 4	Upper	90738	78852	79600	0.95%	88005	76119	76960	1.11%
		Lower	90502	78739	79600	1.09%	87779	76016	76960	1.24%
	Level 3	Upper	83049	75170	77400	2.97%	85841	77962	79800	2.36%
		Lower	82968	75203	77400	2.92%	85757	77992	79800	2.32%
	Level 2	Upper	42983	40350	41100	1.86%	43527	40893	41700	1.97%
		Lower	42940	40367	41100	1.82%	43466	40893	41700	1.97%
	Level 1	Upper	33785	32803	33300	1.52%	32607	31625	32800	3.72%
		Lower	33760	32826	33300	1.44%	32557	31623	32800	3.72%

TOWER DEFLECTIONS

As discussed in the Methodology, field data provided guy wire tensions for the Tower in both antenna down and antenna up states. Tolerances are also provided for both antenna states and are given with respective Positions A and Position B on the tower, as shown in Figure 24. With respect to the models global cartesian coordinate system, Position A aligns with the models x-axis, while Position B aligns with the models y-axis.

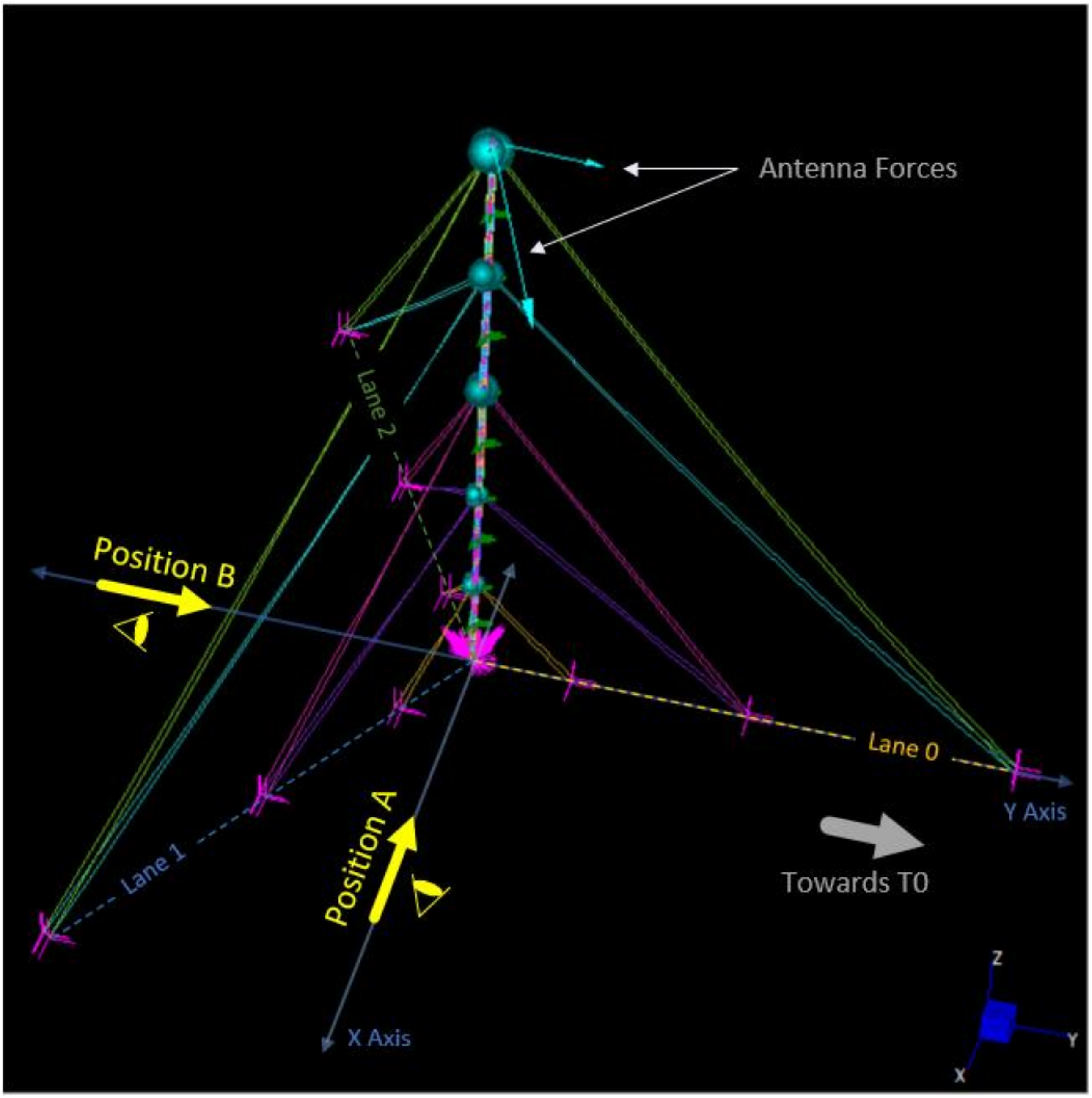


Figure 24 - Tower Deflections, Position A & Position B Reference

The design drawings offer tolerances for the tower deflections; however, they assume the tower is in a fully supported, as-designed state. This is not representative of the tower when undergoing guy wire maintenance, where cables are being de-tensioned (Case 1), left in a hanging state (Case 2), or removed altogether (Case 3). While it is unknown if these tolerances were ever intended to be used for the purposes of guy wire maintenance, they provided a tolerance to which the tower model could be assessed against. Tolerances for tower deflection in both antenna states, at each level, is provided in Table 9.

When the antenna is down, the tower profile is intended to be aligned with the local z-axis as indicated by a nominal value of zero (0) for both Position A and Position B. When the antenna is up, the tower exhibits an ‘s’ type profile when viewed from Position A, as indicated by the antenna up nominal values in Table 9. As shown at Level 5, the tower is leaning in towards T-0 by 23.75”. This deflection is caused by the antenna loads, which pull the tower towards the centre of the array. To counter this antenna force, it can be observed that the objective tensions in Lanes 1 & 2 are higher than the objective tensions in Lane 0, refer Table 8.

Table 9 - Maximum Allowable Tower Deflection

Maximum Allowable Tower Deflection								
Tower Level & Height (ft)	Antenna Down				Antenna Up			
	Position A Y-Axis Deflection (in)		Position B X-Axis Deflection (in)		Position A Y-Axis Deflection (in)		Position B X-Axis Deflection (in)	
	Nominal	± Tolerance	Nominal	± Tolerance	Nominal	± Tolerance	Nominal	± Tolerance
Level 5 (1177.4')	0	± 3	0	± 3	23.75	± 3	0	± 3
Level 4 (911.5')	0	± 2.25	0	± 2.25	1.75	± 2.25	0	± 2.25
Level 3 (655.0')	0	± 1.75	0	± 1.75	-1.5	± 1.75	0	± 1.75
Level 2 (408.0')	0	± 1.25	0	± 1.25	-0.25	± 1.25	0	± 1.25
Level 1 (189.5')	0	± 1.25	0	± 1.25	0	± 1.25	0	± 1.25

TOWER DEFLECTION DATA POST PROCESSING

To measure tower deflection against the tolerances, multipoint links in the model were created. To achieve this, slave nodes were placed up the centre of the tower (z-axis) at the same heights as those given in Table 8. Each slave node was then linked to three master nodes, one on each of the three surrounding legs at the same height. A multipoint link was then created between these nodes, such that the slave node interpolated the translational values of the master nodes. These slave nodes were placed into a group so once the model Load Cases were run, the deflection data could be extracted. Using this multipoint link method allowed the use of nodes to measure deflection without introducing any elements which would contribute to the mass and stiffness matrix of the tower.

The deflection data provided by the reference nodes was assessed and plotted against the nominal values. Table 10 shows the three (3) Load Cases being applied on each of the Lanes, at each of the Levels. The numeric value indicates the greatest tower deflection from the nominal values provided in Table 9. The green box indicates the deflection is within tolerance, amber box indicates that the tower deflection exceeds tolerance and red box indicates the tower has exceeded tolerance and is the greatest deflection for any Load Case on any Lane, on any Level.

When viewing Case 1 in both antenna states, on each Level there is no change in deflection between Lanes 0, 1 & 2. This is because during Case 1, all three (3) cables at the affected Level are de-tensioned. There is no actual differences when viewing Lane 0, 1 & 2 as they are all de-tensioned, in comparison with Case 2 & 3, where each lane successively has its guy cable left hanging (Case 2), then removed (Case 3).

Table 10 - Tower Deflections (Inch)

TOWER DEFLECTIONS (Inch)		No Antenna						Antenna Installed					
		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)	
		Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis
Level 5	Lane 0	-0.261	0.009	-28.548	0.431	-28.765	0.432	-10.645	0.004	-42.311	0.194	-42.756	0.195
	Lane 1	-0.261	0.009	13.521	-24.702	13.629	-24.891	-10.645	0.004	7.775	-19.505	7.771	-19.667
	Lane 2	-0.261	0.009	14.252	24.293	14.362	24.481	-10.645	0.004	8.852	19.298	8.847	19.458
Level 4	Lane 0	-0.258	0.008	-10.554	0.098	-10.582	0.098	-18.380	-0.022	-21.367	0.069	-21.438	0.069
	Lane 1	-0.258	0.008	4.893	-9.016	4.908	-9.040	-18.380	-0.022	-16.926	-8.913	-16.911	-8.934
	Lane 2	-0.258	0.008	5.062	8.919	5.076	8.943	-18.380	-0.022	-16.877	8.771	-16.862	8.793
Level 3	Lane 0	-0.258	0.008	-2.659	0.044	-2.682	0.044	-18.537	0.004	-18.292	0.055	-18.298	0.055
	Lane 1	-0.258	0.008	1.207	-2.280	1.219	-2.301	-18.537	0.004	-18.672	-2.339	-18.678	-2.359
	Lane 2	-0.258	0.008	1.286	2.231	1.298	2.251	-18.537	0.004	-18.679	2.296	-18.684	2.317
Level 2	Lane 0	-0.259	0.008	-1.155	0.018	-1.165	0.019	-18.513	0.001	-18.442	0.021	-18.441	0.022
	Lane 1	-0.259	0.008	0.611	-1.040	0.616	-1.048	-18.513	0.001	-18.552	-1.057	-18.554	-1.066
	Lane 2	-0.259	0.008	0.644	1.018	0.649	1.027	-18.513	0.001	-18.554	1.039	-18.556	1.048
Level 1	Lane 0	-0.259	0.008	-0.258	0.008	-0.258	0.008	-18.509	0.000	-18.509	0.004	-18.509	0.004
	Lane 1	-0.259	0.008	-0.259	-0.095	-0.259	-0.100	-18.509	0.000	-18.510	-0.095	-18.510	-0.100
	Lane 2	-0.259	0.008	-0.259	0.089	-0.259	0.093	-18.509	0.000	-18.510	0.090	-18.510	0.095

Legend

- (Green) Within Tolerance — Value equals deviation from nominal
- (Amber) Exceeds Tolerance — Value equals deviation from nominal
- (Red) Exceeds Tolerance - Maximum Antenna Down/Up — Value equals deviation from nominal

Table 11 compares the tower deflections with the tolerances provided in Table 9. The numeric value indicates how many multiples of the tolerance that the deflection exceeds nominal by.

Table 11 - Tower Deflection, Multiple of Tolerance

TOWER DEFLECTIONS (Multiple of Tolerance)		No Antenna						Antenna Installed					
		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)	
		Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis	Pos (A) Y-Axis	Pos (B) X-Axis
Level 5	Lane 0	0.087	0.003	9.516	0.144	9.588	0.144	3.548	0.001	14.104	0.065	14.252	0.065
	Lane 1	0.087	0.003	4.507	8.234	4.543	8.297	3.548	0.001	2.592	6.502	2.590	6.556
	Lane 2	0.087	0.003	4.751	8.098	4.787	8.160	3.548	0.001	2.951	6.433	2.949	6.486
Level 4	Lane 0	0.086	0.003	3.518	0.033	3.527	0.033	6.127	0.007	7.122	0.023	7.146	0.023
	Lane 1	0.086	0.003	1.631	3.005	1.636	3.013	6.127	0.007	5.642	2.971	5.637	2.978
	Lane 2	0.086	0.003	1.687	2.973	1.692	2.981	6.127	0.007	5.626	2.924	5.621	2.931
Level 3	Lane 0	0.086	0.003	1.519	0.015	1.533	0.015	6.179	0.001	6.097	0.018	6.099	0.018
	Lane 1	0.086	0.003	0.402	1.303	0.697	1.315	6.179	0.001	6.224	1.336	6.226	1.348
	Lane 2	0.086	0.003	0.429	1.275	0.742	1.286	6.179	0.001	6.226	1.312	6.228	1.324
Level 2	Lane 0	0.086	0.003	0.385	0.006	0.388	0.006	6.171	0.000	6.147	0.007	6.147	0.007
	Lane 1	0.086	0.003	0.204	0.347	0.205	0.349	6.171	0.000	6.184	0.352	6.185	0.355
	Lane 2	0.086	0.003	0.215	0.339	0.216	0.342	6.171	0.000	6.185	0.346	6.185	0.349
Level 1	Lane 0	0.086	0.003	0.086	0.003	0.086	0.003	6.170	0.000	6.170	0.001	6.170	0.001
	Lane 1	0.086	0.003	0.086	0.032	0.086	0.033	6.170	0.000	6.170	0.032	6.170	0.033
	Lane 2	0.086	0.003	0.086	0.030	0.086	0.031	6.170	0.000	6.170	0.030	6.170	0.032

Legend

- (Green) Within Tolerance — 0 < Deflection ≤ Tolerance
- (Amber) Deflection exceeds 1 x Tolerance — Value equals multiple of tolerance
- (Red) Deflection exceeds 10 x tolerance — Value equals multiple of tolerance

Each of the Load Cases had the data plotted to give a visualisation of the tower deflection. The following Figures represent load cases which produced the most interesting and excessive deflections. The Figure plots contain two dashed lines and three solid lines. The dashed lines represent the deflection tolerances. The solid lines represent the tower profile when each of its Lanes is affected by the applicable Load Case.

TOWER DEFLECTION - ANTENNA DOWN SUMMARY

With the antenna down and no Load Cases applied, the tower is closely aligned with the local z-axis as there is a balance of forces in the x-y plane supporting the tower, refer Figure 25.

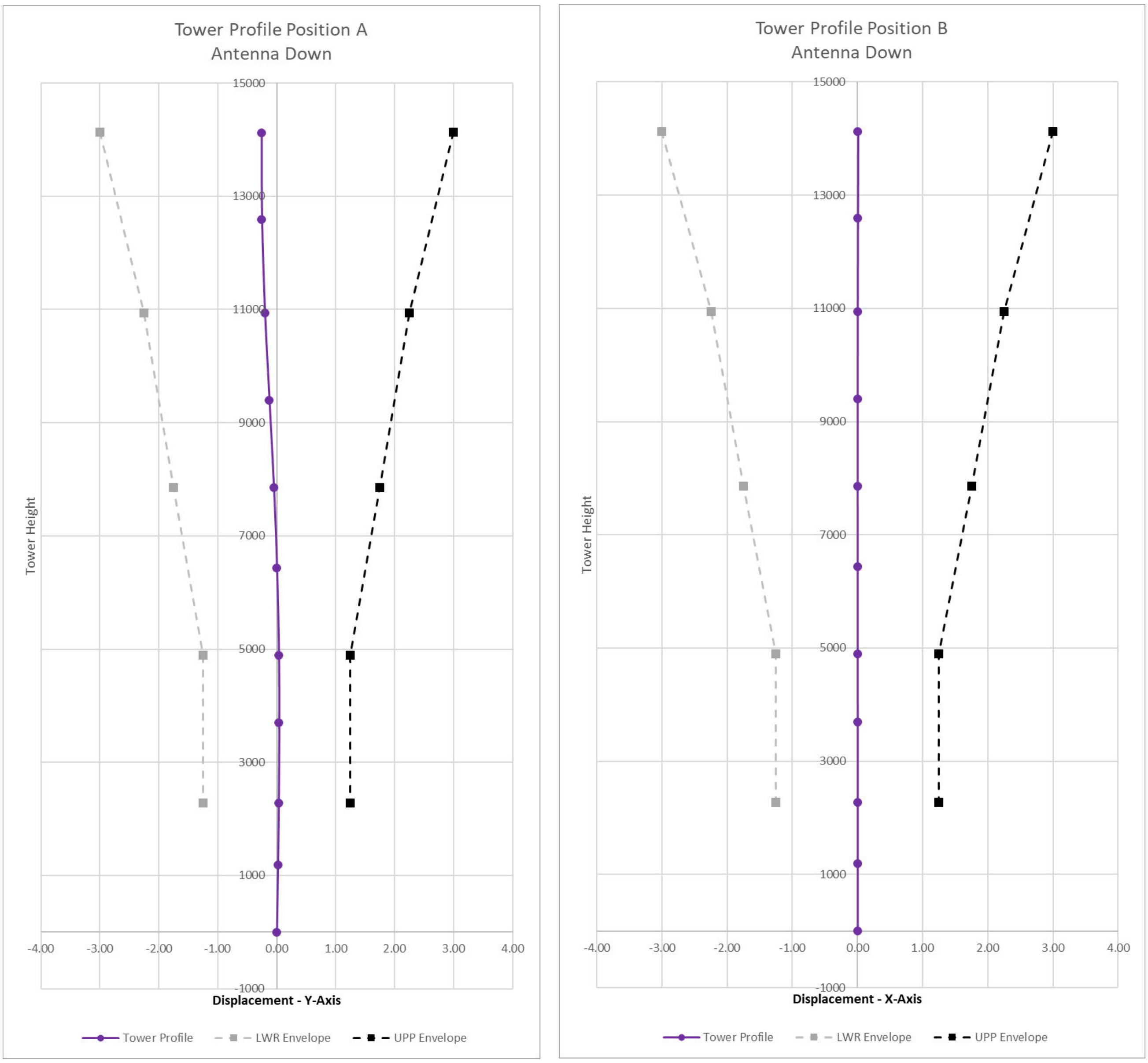


Figure 25 - Tower Deflection - Antenna Down, No Load Case Applied

When subjected to Load Case 1, there is little change in tower deflections. While each level is successively de-tensioned, there is no imbalance of forces in the x-y plane and the tower deflection remains relatively unchanged.

When subjected to Load Case 2 & 3, the greatest deflection with respect to Position A occurs when Lane 0 guy cable is removed from Level 5, refer Figure 26. The greatest deflection with respect to Position B occurs when Lane 1 guy cable is removed from Level 5, although the deflection is essentially the same when Lane 2 is removed. As the objective tensions on all three (3) Lanes are the same when the antenna is down, when each lane is successively removed the tower leans into opposing lanes due to the imbalance of forces. Deflection behaviour like this is expected as there is an asymmetric load applied, however the magnitude of deflection is of importance. The effects of the load imbalance become more pronounced at Level 5, where there are no cables above to provide support.

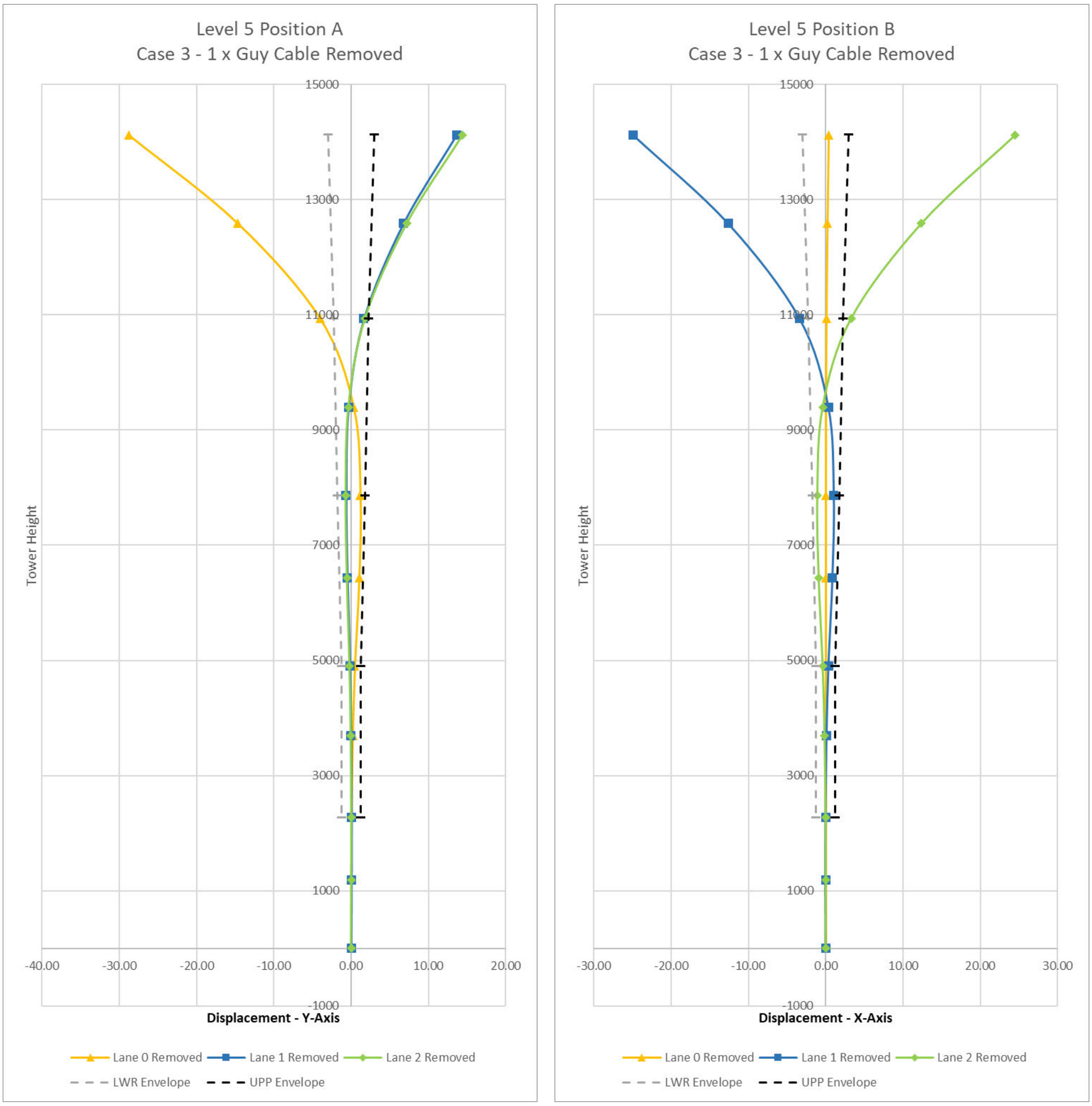


Figure 26 - Tower Deflection - Antenna Down, Level 5 Case 3

As shown in Figure 27, when there are guy cables above the affected level to assist in supporting tower structure, a bowing effect is produced instead, although the magnitude of deflection is less than that at Level 5. As lower Levels are affected, the tower profile follows the same general pattern shown in Figure 27, with lessening degrees of deflection.

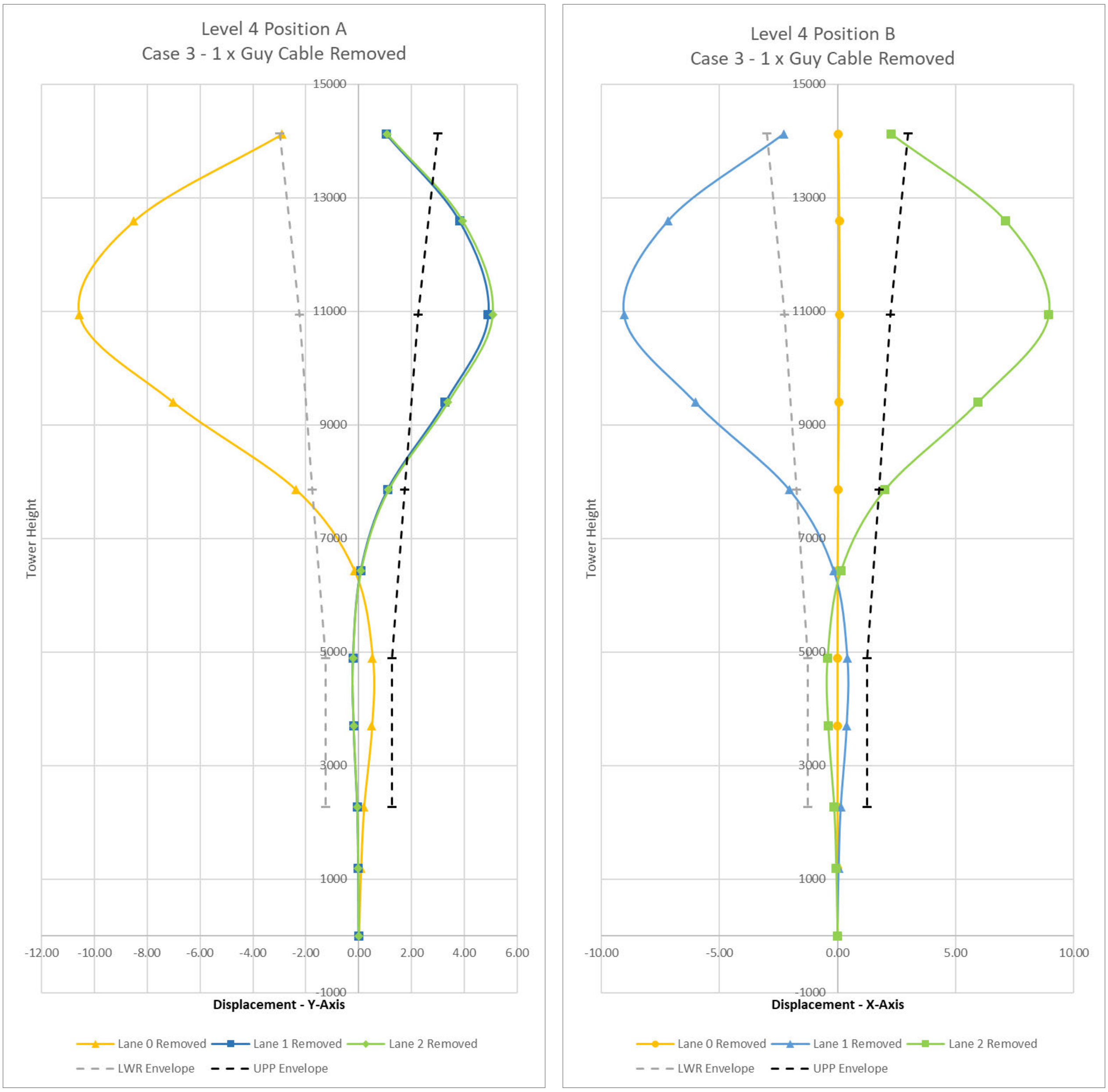


Figure 27 - Tower Deflection - Antenna Down, Level 4 Case 3

TOWER DEFLECTION - ANTENNA UP SUMMARY

With the antenna up and no load cases applied, the tower is aligned with the local z-axis when viewed from Position B, but displays an ‘s’ type profile when viewed from Position A, refer Figure 28. This deflection is caused by the antenna loads, which pull the tower towards the centre of the array. To counter this antenna force, it can be observed that the objective tensions in Lanes 1 & 2 are higher than the objective tensions in Lane 0, refer Table 8.

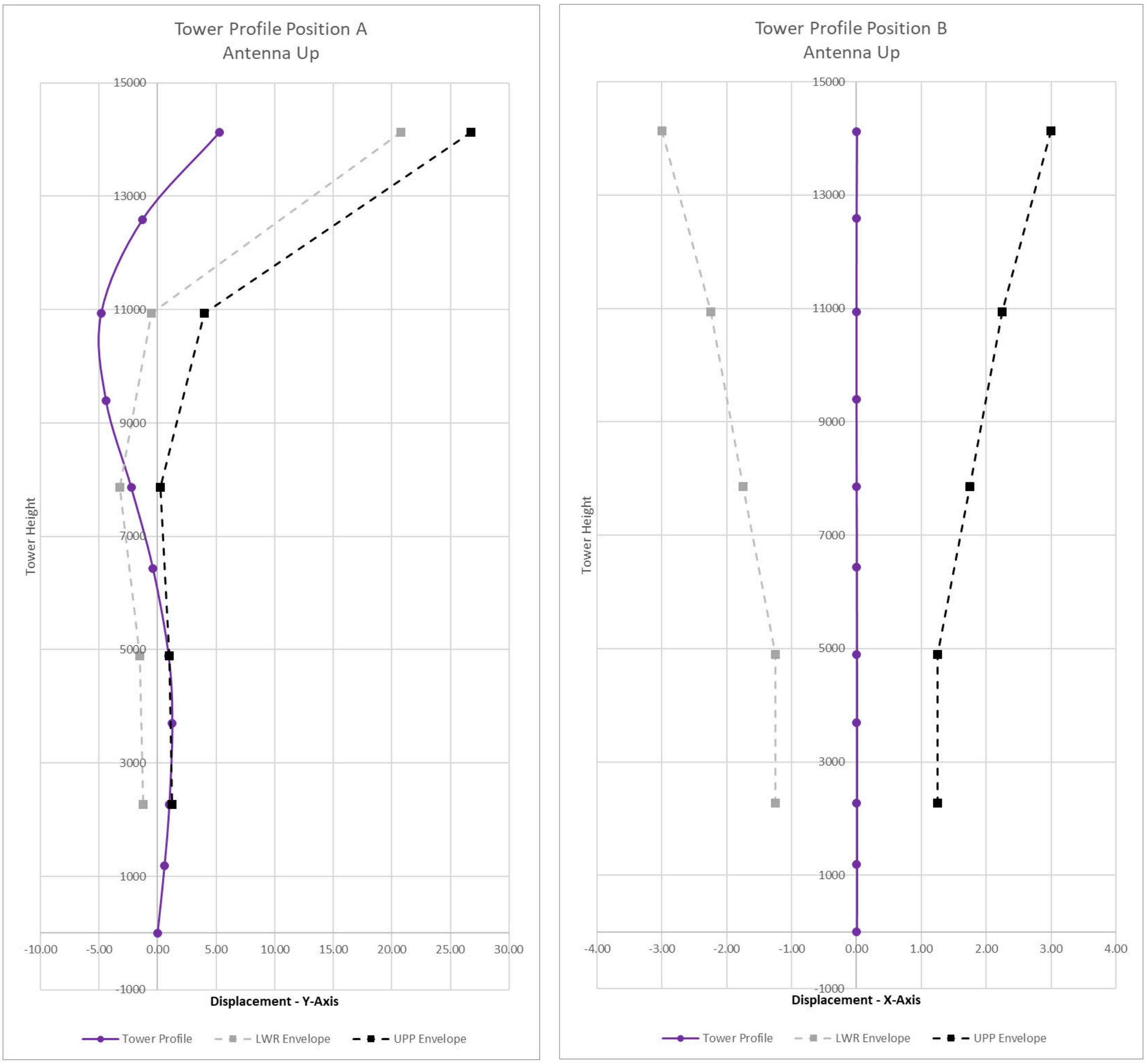


Figure 28 - Tower Deflections - Antenna Up, No Load Case Applied

As shown, Level 5 is out of tolerance in this state, which requires further investigation. It is unknown if this is representative or is possibly due to how the antenna load is represented. These points are discussed in the Considerations Section.

As was the case with the antenna down, when the tower is subjected to Load Case 1, there is little change in tower deflections from the original ‘s’ profile. While each level is successively de-tensioned, no further imbalance of forces in the x-y plane is introduced and deflections are relatively maintained.

When subjected to Load Case 2 & 3, the greatest deflection with respect to Position A occurs when Lane 0 guy cable is removed from Level 5, refer Figure 29. The greatest deflection with respect to Position B occurs when Lane 1 guy cable is removed from Level 5, although the deflection is essentially the same when Lane 2 is removed. The yellow profile in the LH image (Position A) shows the tower in the negative y-axis, creating the greatest deflection from nominal. When the antenna is up, the tensions in Lanes 1 & 2 are greater than those in Lane 0 to account for the antenna load. When Lane 0 is removed, it is no longer contributing to opposing these increased tensions in Lanes 1 & 2. For this reason, all levels exhibit the greatest deflection when Lane 0 is removed, relative to Lanes 1 & 2.

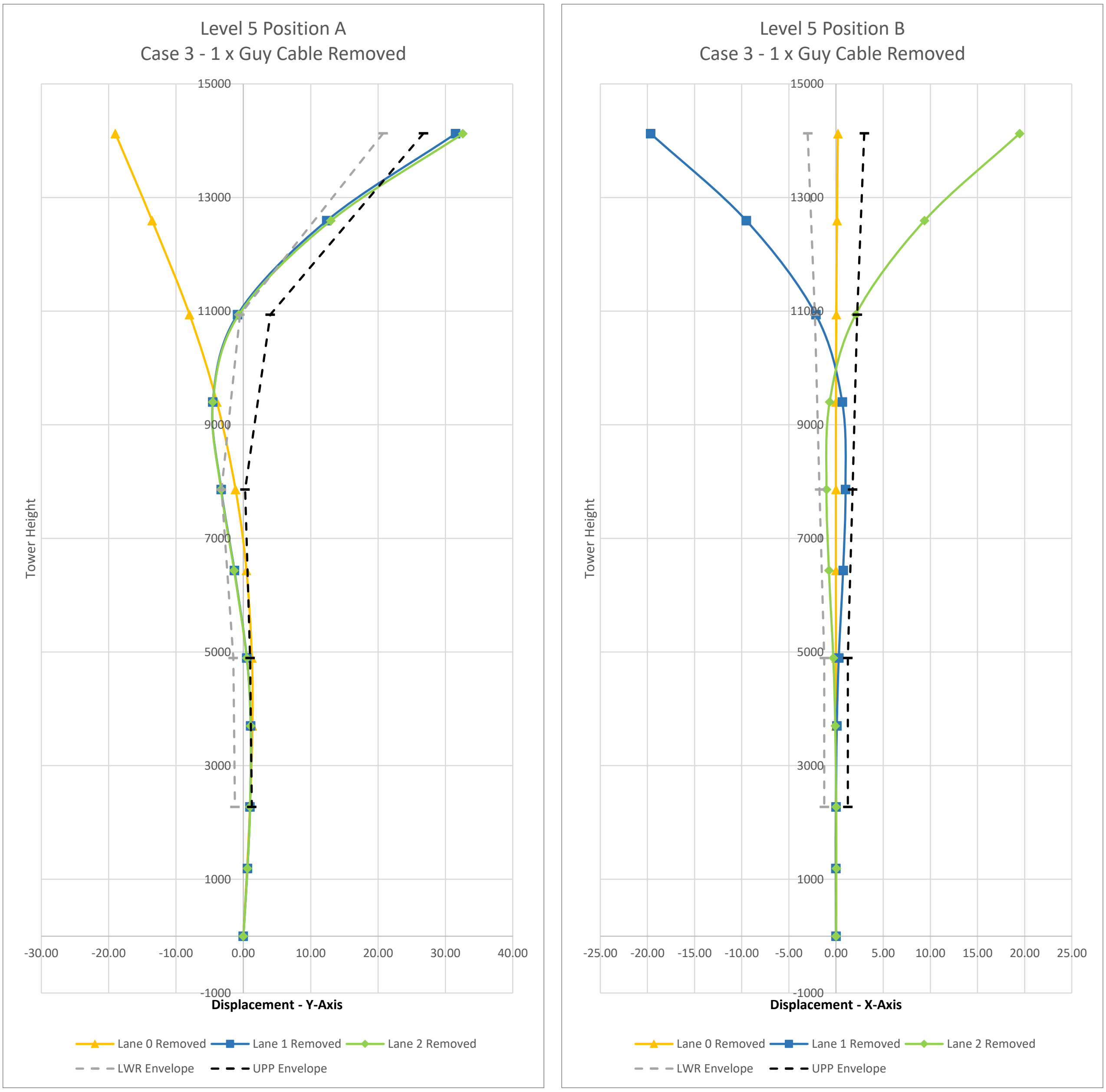


Figure 29 - Tower Deflection - Antenna Up, Level 5 Case 3

As shown in Figure 30, when there are guy cables above the affected level to assist in supporting the tower structure, a bowing effect is produced although the magnitude of deflection is less that that at Level 5. As lower Levels are affected, the tower profile follows the same general pattern shown in Figure 30, with lessening degrees of deflection.

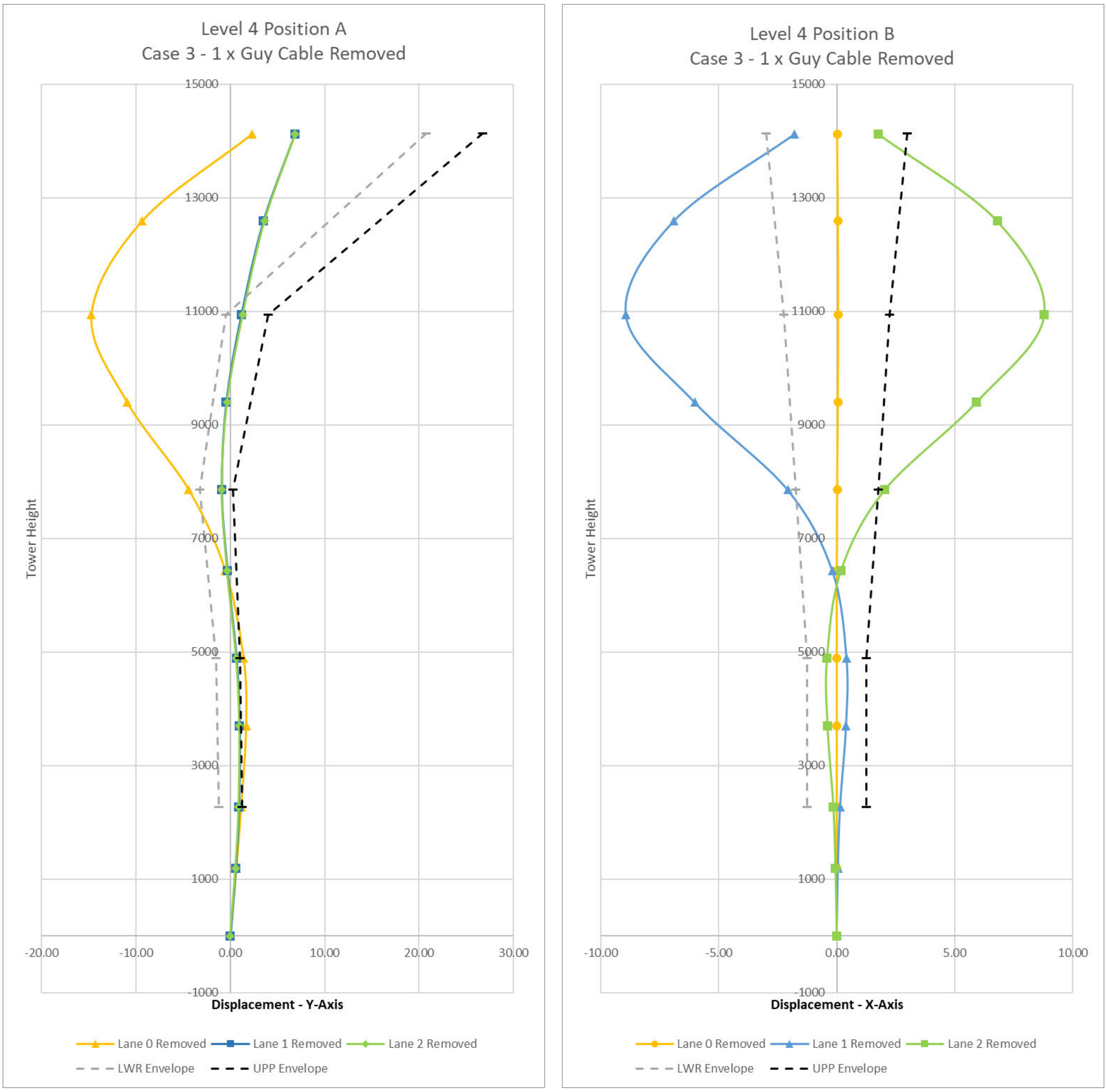


Figure 30 - Tower Deflections - Antenna Up, Level 4 Case 3

TOWER FORCES & STRESSES

To assess the forces and stresses in the tower, the model needed to be separated into groups so specific areas could have their information extracted. To do this, the tower was grouped into its three main structural components; the Legs, Horizontal Members, and Diagonal Tie-Rods. When the model is solved, tens of thousands of data points are created. By using Beam IDs and model Groups, any of the tower groups were able to be systematically assessed. The Leg and guy cable parameters were grouped using Beam IDs, while the Horizontal Members and Diagonal Tie-Rods were grouped using the Groups function in Strand 7. Once the required data was extracted from Strand 7, the data was further manipulated for analysis in another spreadsheet, explained in more detail in the below Sections.

TOWER LEGS

The Tower Leg analysis measured axial force, bending moment 1 (primary axis), bending moment 2 (secondary axis), maximum axial force, minimum fibre stress and maximum fibre stress. The fibre stresses were the main focus of the analysis, as it represents the net stress within the member and when measured against a materials yield strength, can most closely approximate a safety margin.

TOWER LEG DATA POST PROCESSING

The Tower Legs were designated with Beam IDs. Each beam is comprised of two nodes which make up its beam ends. When the model is run, each of these nodes is imparted with data, such as displacement, forces, stresses, which is extracted for analysis.

Figure 31 shows an extract from the force/moment tab in the Strand 7 result file, where the required parameter tab is selected, the applicable beam end is selected, then the necessary columns are selected to display the information that is to be extracted. The ID column is then used to sort the beams in ascending order, where the tower leg information is extracted for further analysis.

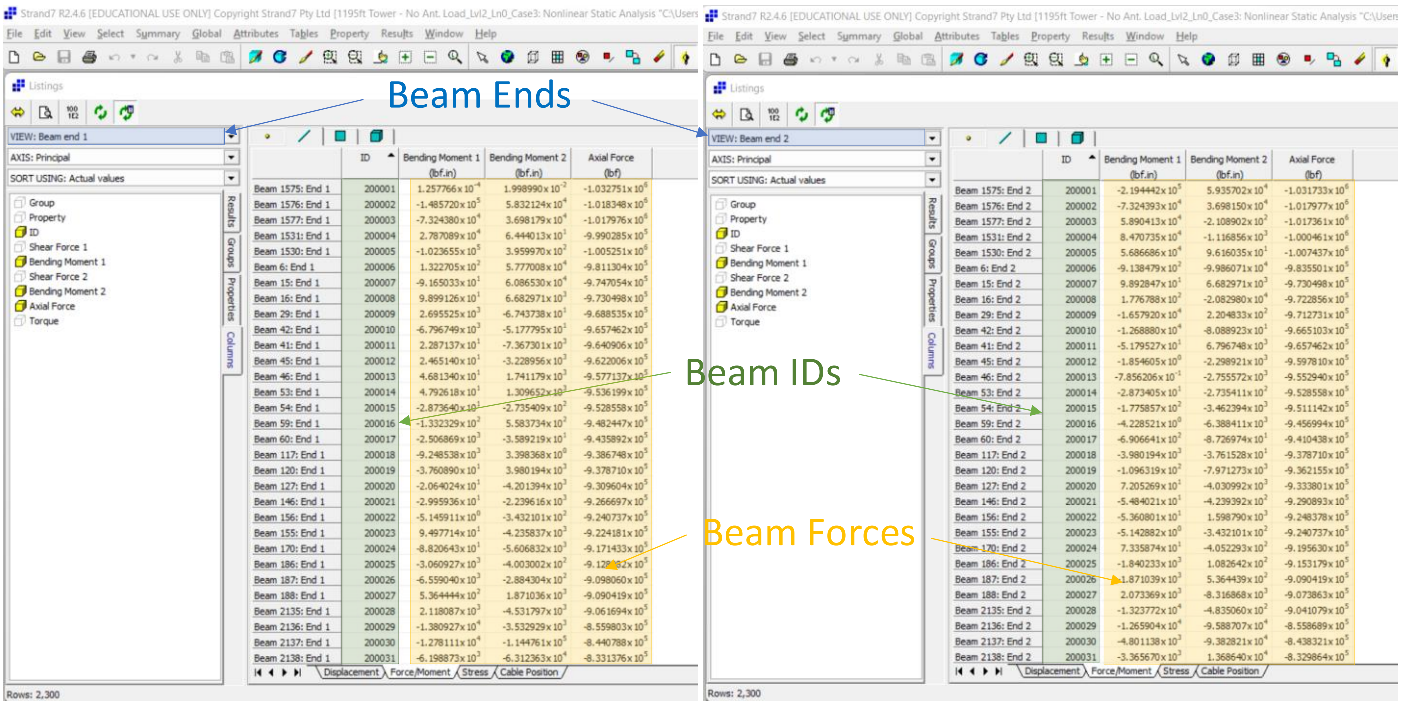


Figure 31 - Tower Leg Stress, Use of Beam IDs

Once the data was imported into another spreadsheet, the Beam IDs were again used to separate the information into individual legs. This allowed each leg to be assessed under each Load Case. The axial force, bending moments, axial stress, and fibre stresses on each leg, under each Load Case were then plotted against tower height.

As mentioned, fibre stresses were the focus of the analysis, however the other parameters were extracted, analysed, and plotted as they contribute to fibre stresses and help explain behaviour. As each Load Case is applied to each Lane at each Level, a peak compressive and peak tensile stress within the tower legs is produced. These are represented by the minimum and maximum fibre stresses, which are used to populate Table 12.

This Table provides four (4) columns for each tower state, antenna down and antenna up. Column one (1) represents the peak leg fibre stresses when the tower is in its ‘As Designed’ state, or when no load cases are being applied. Columns two (2) to four (4) represent Load Case 1, 2 & 3, respectively. As each Level had its respective Lanes subjected to Load Cases 1, 2 & 3, the peak fibre stresses in the Tower Legs were extracted and populates Table 12.

The numeric value indicates the peak fibre stress experienced, σ_{peak}, during each of the Load Cases. The Tower Leg material has a yield strength σ_{yield}, of 45000psi (310.3MPa). Within Table 12, a green box indicates the peak stress, σ_{peak}, measured was less than 25% of yield stress, σ_{yield}. Equivalently, a green box indicates $\sigma_{peak} < 0.25\,\sigma_{yield}$. Similarly, an amber box indicates $0.25\,\sigma_{yield} < \sigma_{peak} < 0.40\,\sigma_{yield}$ and a red box indicates $0.40\,\sigma_{yield} < \sigma_{peak} < \sigma_{yield}$.

In the 'as designed' columns, all the peak fibre stresses are the same as the tower is not being subjected to any Load Cases. In the Load Case 1 columns, each Level has the same peak fibre stresses across Lanes, as the Load Case de-tensions all three (3) guy cables.

Table 12 - Tower Legs Stress (MPa)

TOWER LEG STRESS (MPa)		Antenna Down								Antenna Up							
		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		As Designed		Case 1 (3 x Detensioned)		Case 2 (1x Hanging)		Case 3 (1 x Removed)	
		Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)
Level 5	Lane 0	-107.419	53.605	-111.037	19.345	-108.218	43.557	-107.000	52.483	-127.661	26.002	-124.043	21.975	-119.306	22.834	-118.028	22.647
	Lane 1	-107.419	53.605	-111.037	19.345	-108.556	44.760	-107.335	53.586	-127.661	26.002	-124.043	21.975	-132.796	65.965	-131.215	74.811
	Lane 2	-107.419	53.605	-111.037	19.345	-108.639	44.778	-107.419	53.605	-127.661	26.002	-124.043	21.975	-134.598	65.978	-133.012	74.823
Level 4	Lane 0	-107.419	53.605	-113.103	22.717	-112.866	23.089	-112.440	23.105	-127.661	26.002	-125.727	26.031	-143.264	25.817	-143.799	25.812
	Lane 1	-107.419	53.605	-113.103	22.717	-112.459	22.542	-112.033	22.540	-127.661	26.002	-125.727	26.031	-124.174	26.371	-123.757	26.388
	Lane 2	-107.419	53.605	-113.103	22.717	-112.465	21.240	-112.040	22.536	-127.661	26.002	-125.727	26.031	-124.162	26.354	-123.744	26.370
Level 3	Lane 0	-107.419	53.605	-111.037	22.725	-111.378	22.623	-111.103	22.623	-127.661	26.002	-123.838	26.037	-124.258	26.109	-123.980	26.111
	Lane 1	-107.419	53.605	-111.037	22.725	-110.957	22.781	-110.682	22.783	-127.661	26.002	-123.838	26.037	-122.925	26.073	-122.631	26.075
	Lane 2	-107.419	53.605	-111.037	22.725	-110.992	22.784	-110.717	22.786	-127.661	26.002	-123.838	26.037	-122.686	26.092	-122.398	26.094
Level 2	Lane 0	-107.419	53.605	-113.477	22.707	-113.334	22.694	-113.227	22.694	-127.661	26.002	-126.022	26.009	-125.080	26.019	-124.998	26.019
	Lane 1	-107.419	53.605	-113.477	22.707	-113.669	22.714	-113.566	22.715	-127.661	26.002	-126.022	26.009	-126.205	25.997	-126.101	25.997
	Lane 2	-107.419	53.605	-113.477	22.707	-113.754	22.715	-113.648	22.715	-127.661	26.002	-126.022	26.009	-126.275	26.016	-126.168	26.016
Level 1	Lane 0	-107.419	53.605	-118.947	22.704	-119.534	22.704	-119.527	22.704	-127.661	26.002	-130.393	26.007	-129.719	26.007	-129.647	26.007
	Lane 1	-107.419	53.605	-118.947	22.704	-119.709	22.704	-119.703	22.704	-127.661	26.002	-130.393	26.007	-130.687	26.008	-130.658	26.008
	Lane 2	-107.419	53.605	-118.947	22.704	-119.939	22.704	-119.931	22.704	-127.661	26.002	-130.393	26.007	-131.307	26.007	-131.298	26.007

Legend

- Stress < 25% Yield Stress; Value equals stress (Mpa)
- 25% < Stress < 40% Yield Stress; Value equals stress (Mpa)
- Stress > 40% Yield Stress; Value equals stress (Mpa)

$$1psi = 0.0068947573MPa$$

$$\sigma_{YieldPoint} = 45000psi = 310.3MPa$$

A factor of safety (FoS) is calculated as the ratio of yield strength, σ_{yield}, and applied, or peak stress, σ_{peak}. Equivalently, $FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$. Within Table 13, a green box indicates the Factor of Safety, FoS, was greater than ten (10). Equivalently, a green box indicates FoS > 10. Similarly, an amber box indicates 10 > FoS > 2.5 and a red box indicates FoS < 2.5.

Table 13 - Tower Leg Stress, Factor of Safety (FoS)

TOWER LEG STRESS (FoS)		Antenna Down								Antenna Up							
		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)	
		Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)
Level 5	Lane 0	2.888	5.788	2.794	16.039	2.867	7.123	2.900	5.912	2.430	11.932	2.501	14.119	2.601	13.588	2.629	13.700
	Lane 1	2.888	5.788	2.794	16.039	2.858	6.932	2.891	5.790	2.430	11.932	2.501	14.119	2.336	4.703	2.365	4.147
	Lane 2	2.888	5.788	2.794	16.039	2.856	6.929	2.888	5.788	2.430	11.932	2.501	14.119	2.305	4.703	2.333	4.147
Level 4	Lane 0	2.888	5.788	2.743	13.658	2.749	13.438	2.759	13.428	2.430	11.932	2.468	11.919	2.166	12.018	2.158	12.020
	Lane 1	2.888	5.788	2.743	13.658	2.759	13.764	2.769	13.765	2.430	11.932	2.468	11.919	2.499	11.765	2.507	11.758
	Lane 2	2.888	5.788	2.743	13.658	2.759	14.607	2.769	13.768	2.430	11.932	2.468	11.919	2.499	11.773	2.507	11.766
Level 3	Lane 0	2.888	5.788	2.794	13.653	2.786	13.715	2.793	13.715	2.430	11.932	2.505	11.916	2.497	11.884	2.503	11.883
	Lane 1	2.888	5.788	2.794	13.653	2.796	13.619	2.803	13.618	2.430	11.932	2.505	11.916	2.524	11.900	2.530	11.899
	Lane 2	2.888	5.788	2.794	13.653	2.795	13.618	2.802	13.616	2.430	11.932	2.505	11.916	2.529	11.891	2.535	11.890
Level 2	Lane 0	2.888	5.788	2.734	13.664	2.738	13.672	2.740	13.672	2.430	11.932	2.462	11.929	2.481	11.925	2.482	11.924
	Lane 1	2.888	5.788	2.734	13.664	2.730	13.659	2.732	13.659	2.430	11.932	2.462	11.929	2.458	11.935	2.460	11.935
	Lane 2	2.888	5.788	2.734	13.664	2.727	13.659	2.730	13.659	2.430	11.932	2.462	11.929	2.457	11.926	2.459	11.926
Level 1	Lane 0	2.888	5.788	2.608	13.666	2.596	13.665	2.596	13.665	2.430	11.932	2.379	11.930	2.392	11.930	2.393	11.930
	Lane 1	2.888	5.788	2.608	13.666	2.592	13.666	2.592	13.666	2.430	11.932	2.379	11.930	2.374	11.930	2.375	11.930
	Lane 2	2.888	5.788	2.608	13.666	2.587	13.666	2.587	13.666	2.430	11.932	2.379	11.930	2.363	11.930	2.363	11.930

Legend

- (green) FoS > 10, Value equals FoS
- (amber) 2.5 < FoS ≤10, Value equals FoS
- (red) 0 < FoS ≤ 2.5, Value equals FoS

$$Factor\ of\ Saftey = \frac{Material\ Strength}{Design\ Load}$$

TOWER LEG STRESSES - ANTENNA DOWN SUMMARY

With the antenna down, the peak compressive stresses occur at the very base of the model, where the Leg and Base Joint interface, peaking at around 120MPa (refer Figure 32). These peaks are under 40% of yield strength, but also thought to require model refinement to better understand accuracy.

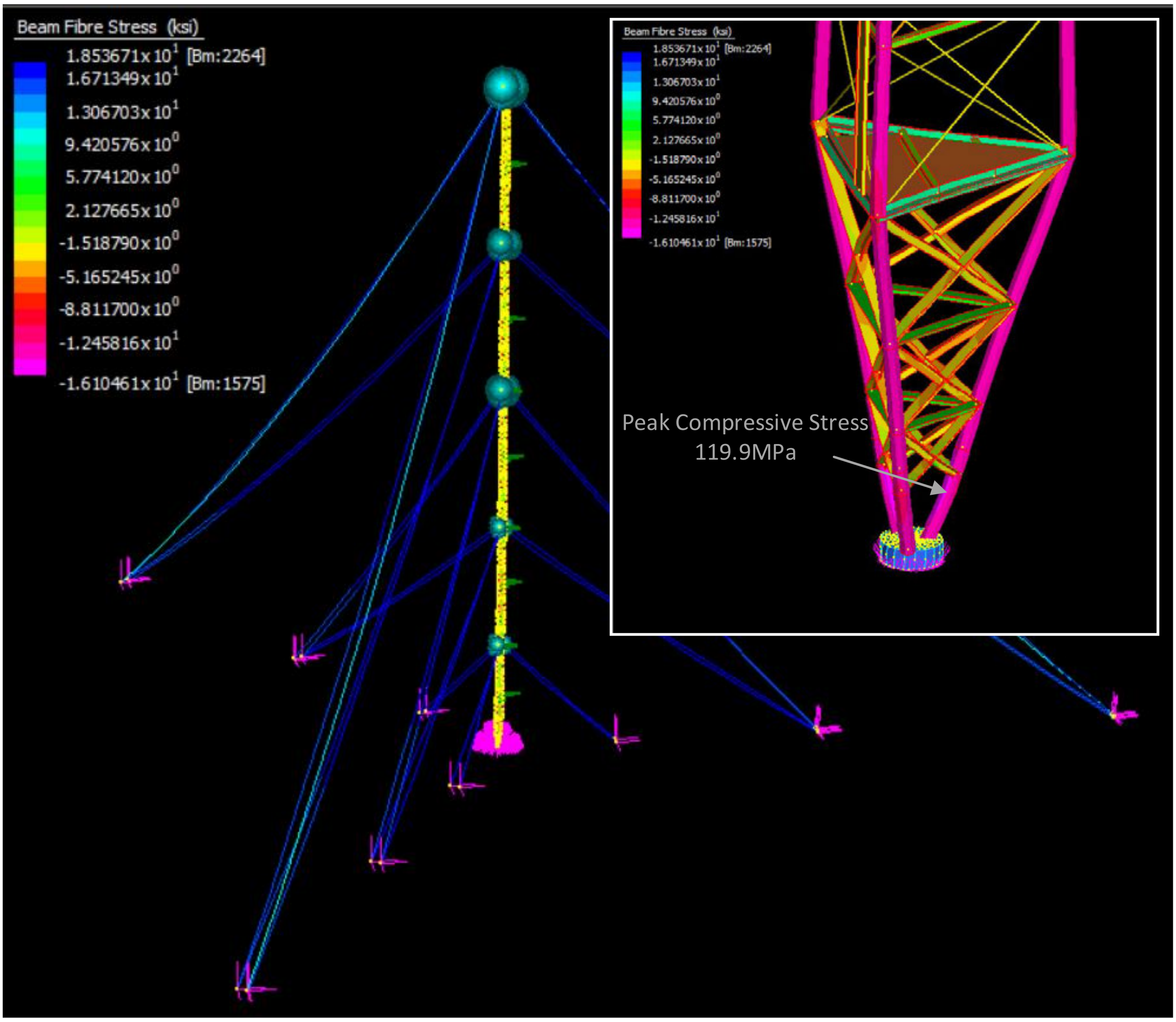


Figure 32 - Tower Leg Stresses, Antenna Down, Level 5 Lane 2

As can be seen in Figure 33, the peak compressive stress sits at the base of the tower which is a similar characteristic in all Load Cases.

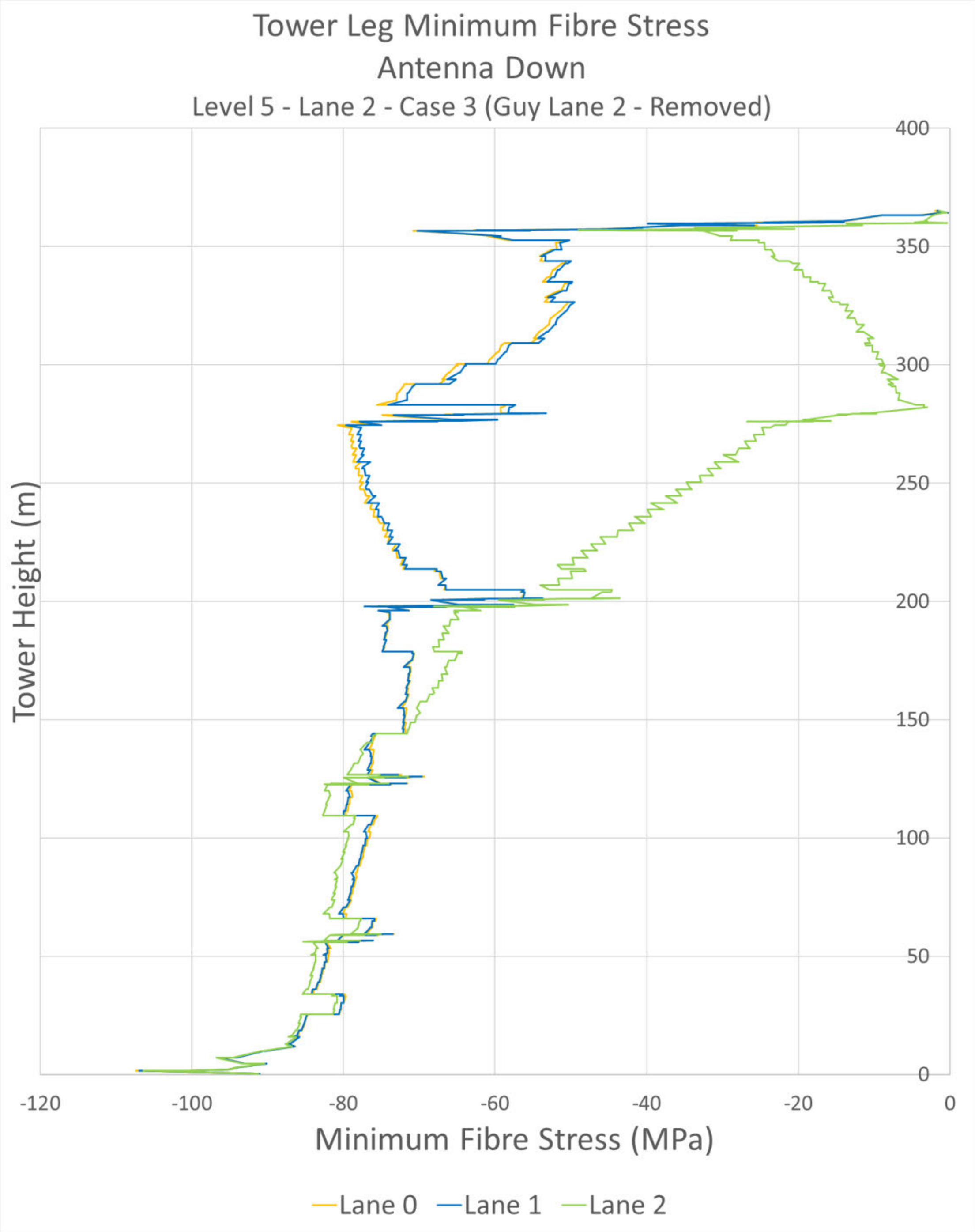


Figure 33 - Tower Leg Stress Plot, Antenna Down, Level 5, Lane 2, Case 3

It is assumed the peak is a representative peak stress and a FoS is calculated,

$$FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS = \frac{310.3MPa}{119.9MPa} = 2.6$$

All the tensile stresses in an antenna down state exceed a safety factor of 5 and are not considered further, refer Table 13.

TOWER LEG STRESSES - ANTENNA UP SUMMARY

With the antenna up, Lane 0 is in a general state of increased compression with respect to Lanes 1 & 2 (Figure 34). This is due to the antenna loads which pull the Tower towards the array centre and into Lane 0. Even without applying any Load Cases, there are appreciable compressive stresses in Lane 0 Leg. As shown in Figure 34, without Load Cases applied the peak compressive stresses occur in Lane 0 at the interface of the Leg and Base Joint, peaking at around 128MPa.

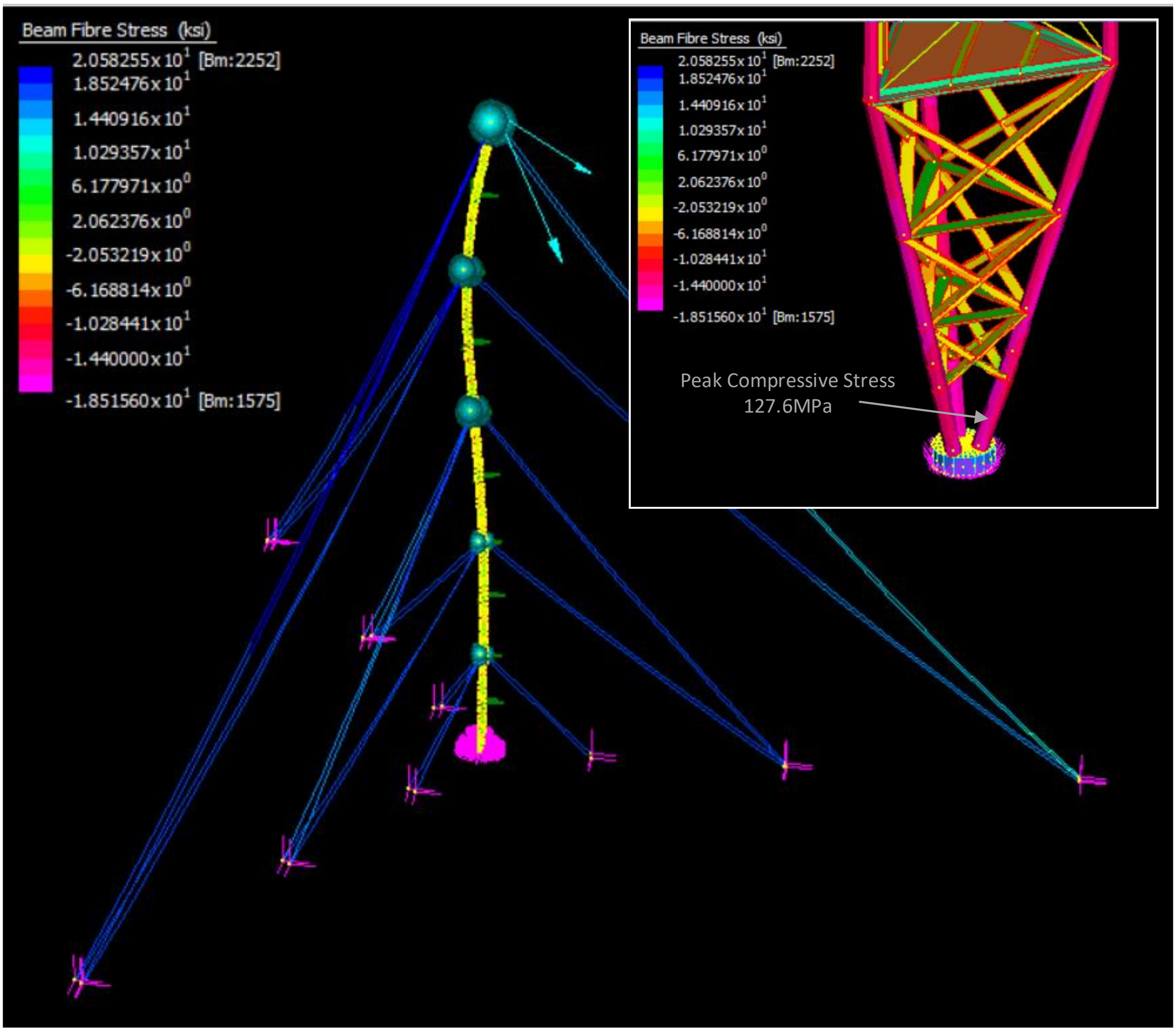


Figure 34 - Tower Leg Stresses, Antenna Up, No Load Cases Applied

Figure 35 provides the compressive stress plot for the Tower without any Load Cases applied. As can be seen, there is a peak of 127.6MPa in Lane 0, where the Leg and Base Joint interfaces. The compressive stress in Lane 0 Leg again increases in the Level 4 area, where the Tower exhibits local bending as a result of its ‘s’ profile. This ‘s’ profile is further exacerbated when applying Load Cases, where the Tower is successively loaded asymmetrically.

Figure 35 - Tower Leg Stress Plot, Antenna Up - No Load Cases Applied

As can be seen by see in Figure 35, the peak compressive stress occurs at the base of the Tower, with a peak of 127.6MPa. The FoS in this state is calculated as,

$$FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS = \frac{310.3MPa}{127.6MPa} = 2.4$$

While there are appreciable compressive stresses in the Tower Legs without Load Cases being applied, the tensile stresses were negligible with a safety factor exceeding 11.9, refer Table 13. These will not be considered further.

When Load Cases are applied, the peak compressive stress occurs when applying Load Case 3 to Lane 0 on Level 4, with a peak stress of 143.8MPa, refer Table 12. This peak occurs at Level 4, on Lane 0 Leg at the guy cable Attachment Bays, as illustrated in Figure 36.

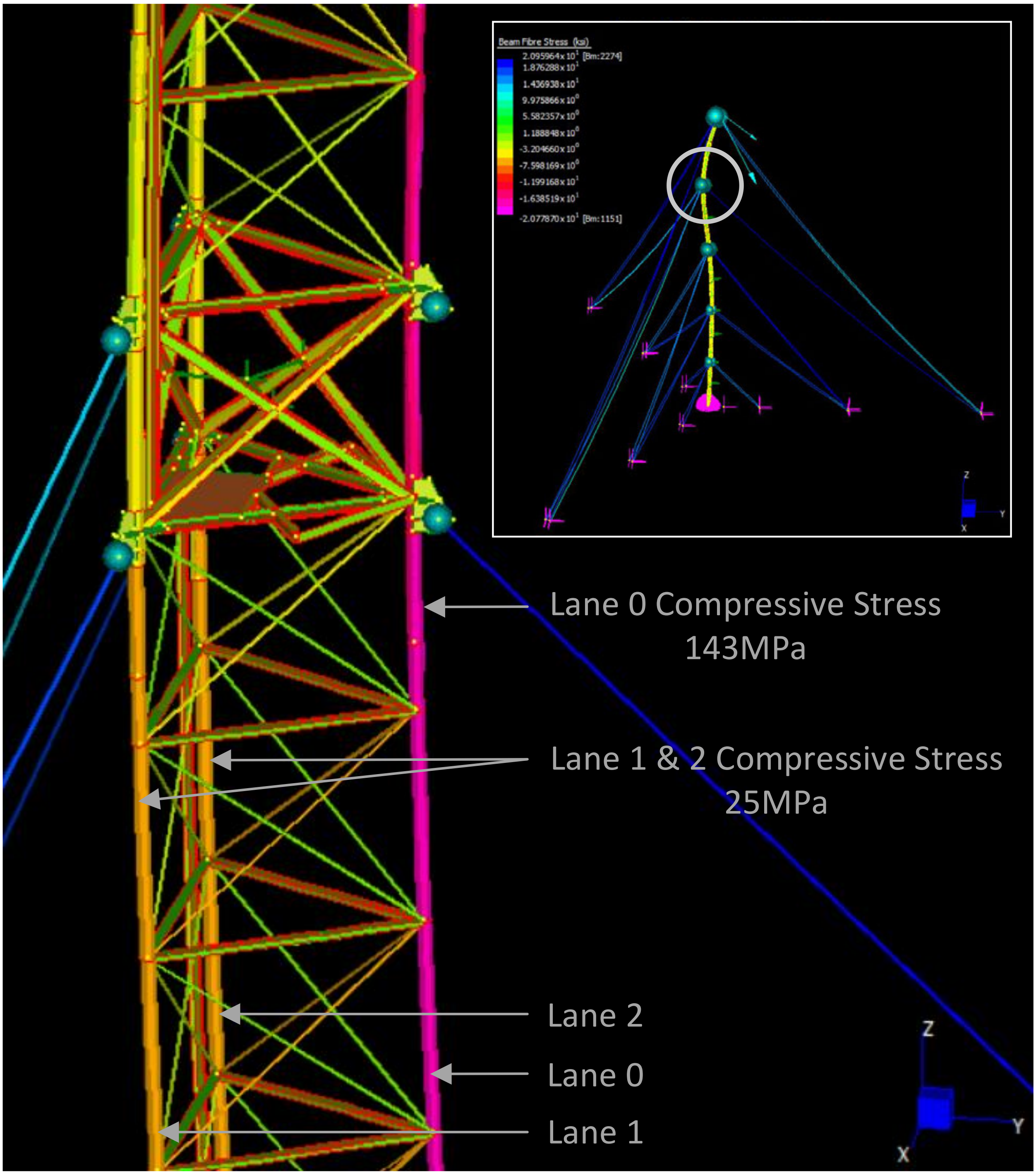


Figure 36 - Tower Leg Stress, Antenna Up - Level 4, Lane 0, Load Case 3

As shown in Figure 34, the general Tower profile already exhibits a ‘s’ shape. Once Level 4, Lane 0 guy cable is removed the Tower deflects further, creating a local buckling type effect which compresses the Leg.

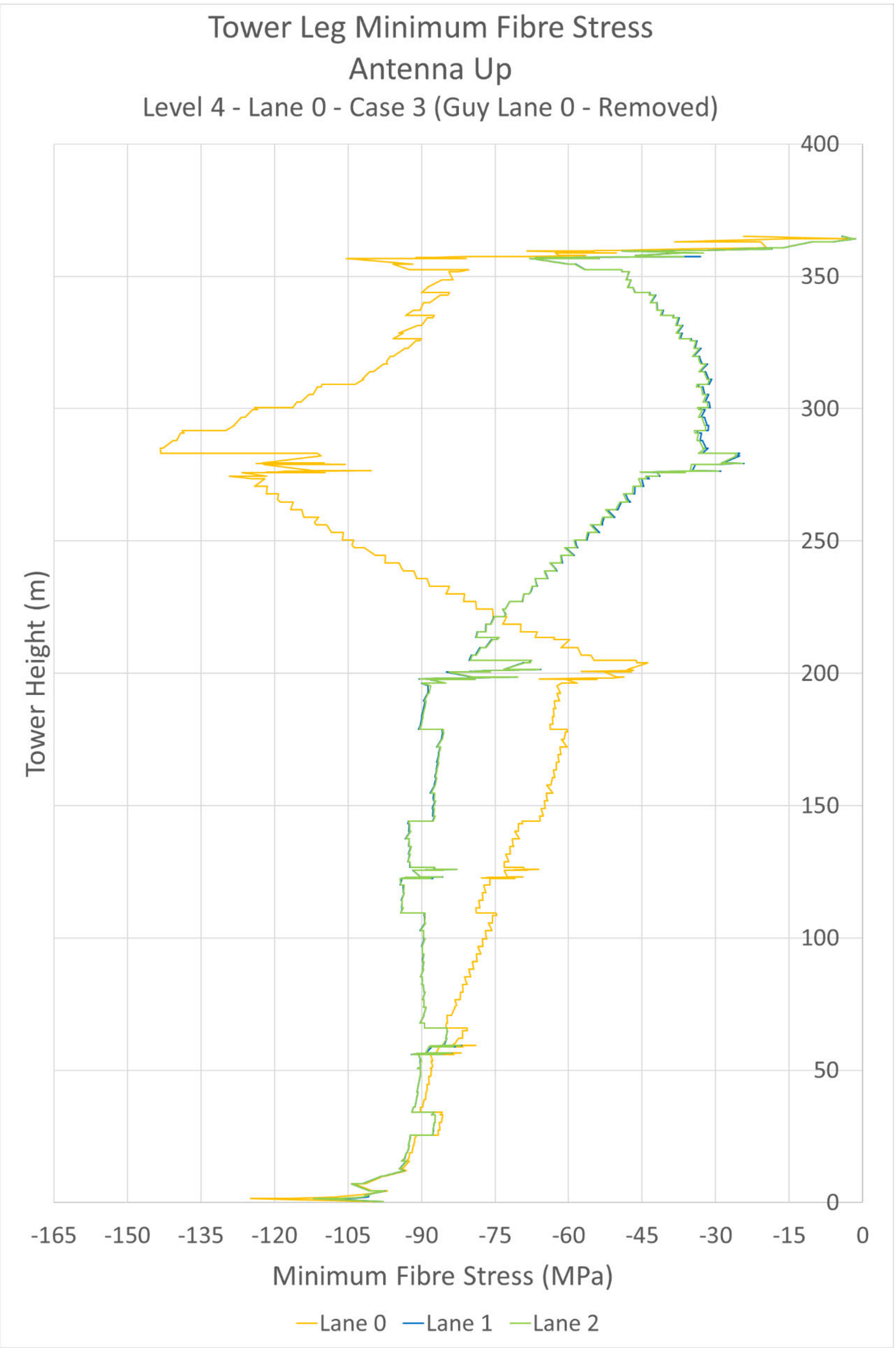


Figure 37 - Tower Leg Stress Plot, Antenna Up - Level 4, Lane 0, Case 3

Figure 37 shows the peak compressive stress at Level 4 on Lane 0 of 143.8MPa. The FoS is calculated as,

$$FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS = \frac{310.3MPa}{143.8MPa} = 2.2$$

While tensile stresses were not appreciable in an antenna down state, the modelling suggests they may need to be considered when the antenna is up. On removing Lanes 1 or 2 at Level 5, the tensile forces in the respective Legs are approximately 75MPa, as shown in Figure 38 and Figure 39.

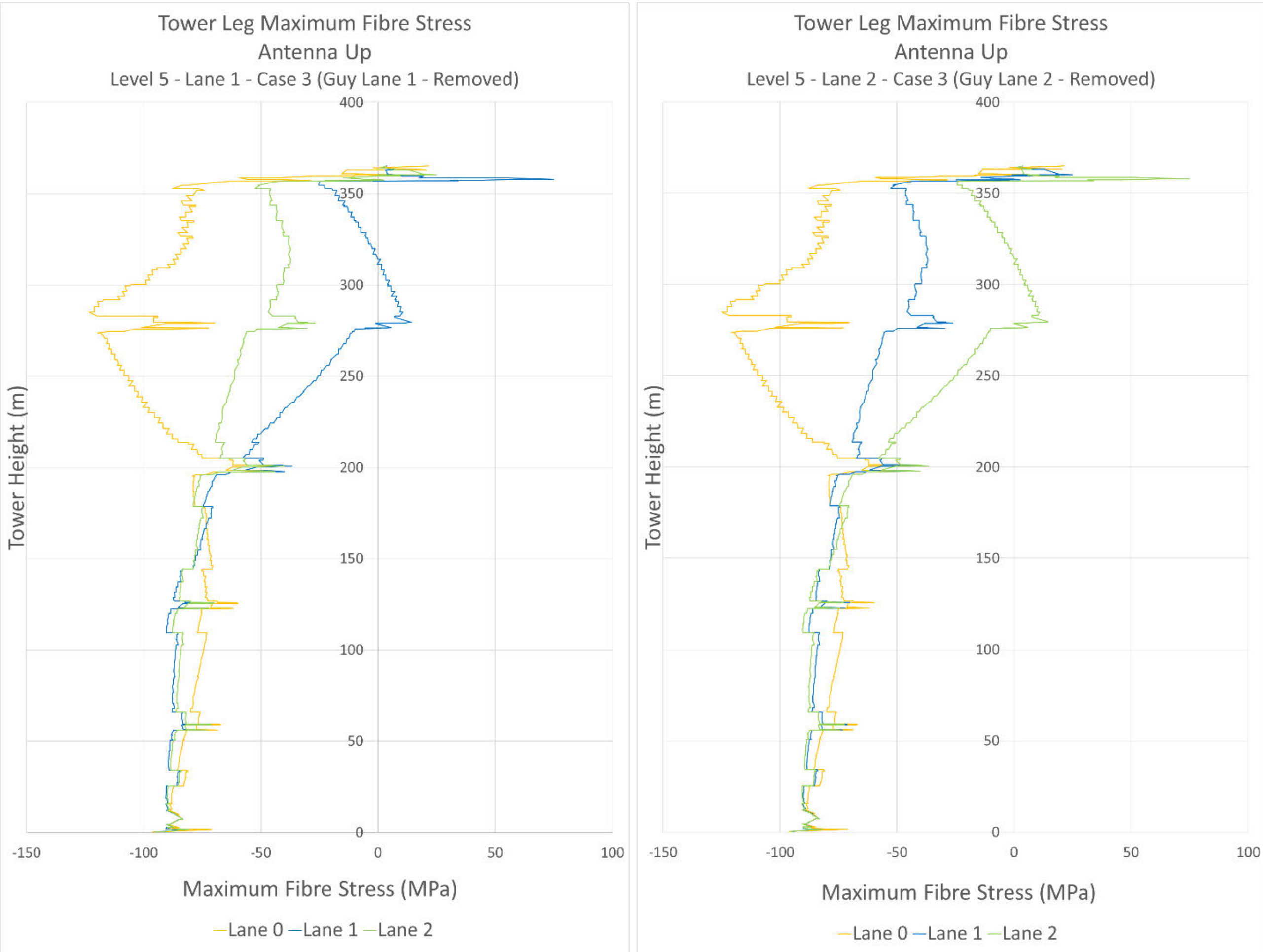


Figure 38 - Tower Leg Stress Plots, Antenna Up - Level 5, Lanes 1 & 2, Load Case 3

Both peak tensile stresses at Level 5 on Lanes 1 & 2 are calculated at 74.8MPa. The FoS is calculated as,

$$FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS = \frac{310.3MPa}{74.8MPa} = 4.1$$

What can also be seen in these plots is that immediately below the peak tensile stress, the Leg goes back into compression. As shown in Figure 39, this behaviour appears to be the result of the antenna loads acting above the Level 5 guy cable forces. The horizontal component of the antenna load acts to lever the section of tower above Level 5 away, while the vertical components of the guy cable forces act to pull the tower down into the ground. When Lanes 1 or 2 are removed, this imbalance is most pronounced, as the applicable guy cable is no longer there to oppose the antenna load.

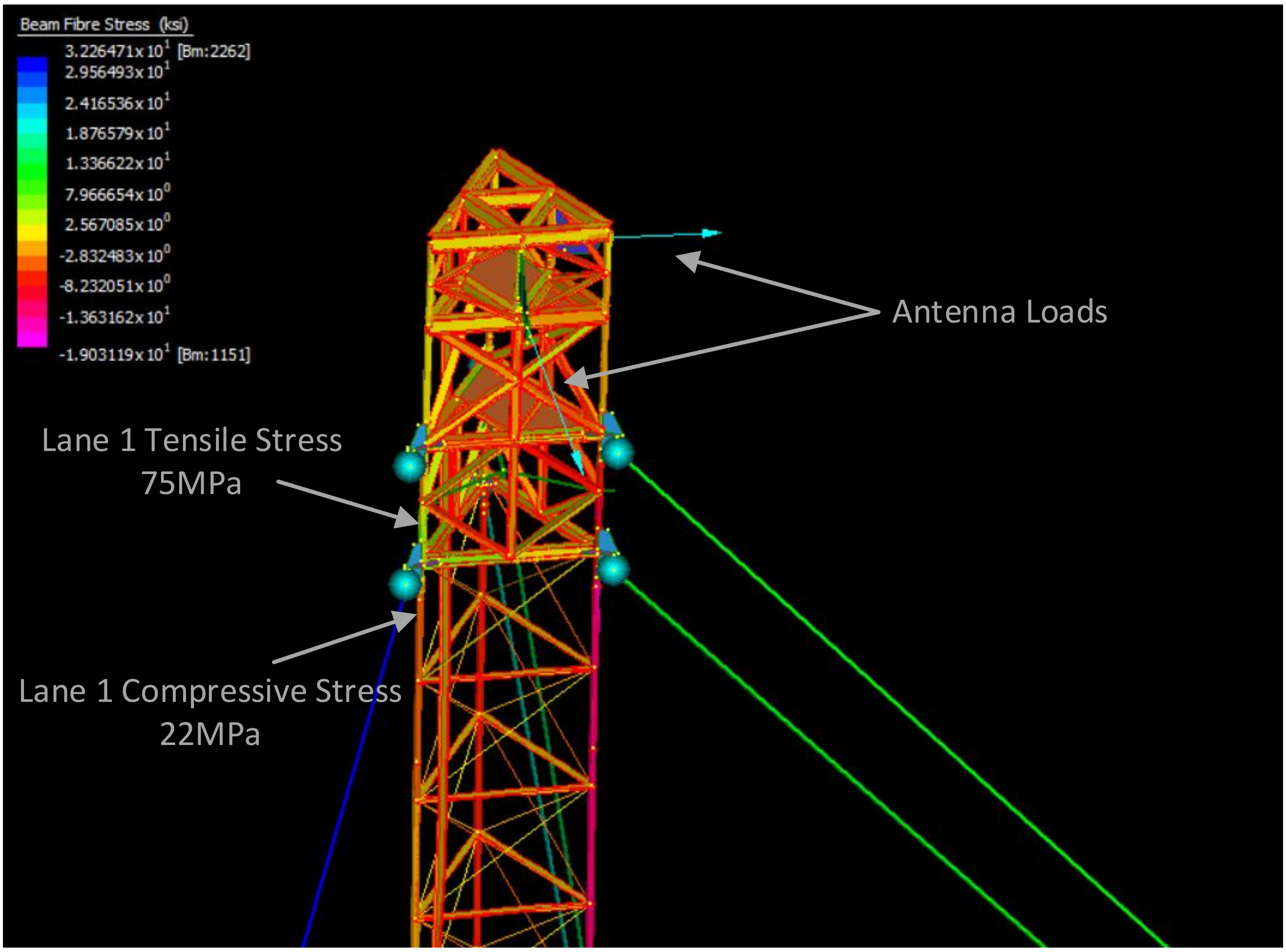


Figure 39 - Tower Leg Stress, Antenna Up - Level 5, Lane 1, Case 3

TOWER HORIZONTAL MEMBERS

The Tower Horizontal Member analysis measured axial force, bending moment 1 (primary axis), bending moment 2 (secondary axis), maximum axial force, minimum fibre stress and maximum fibre stress. The fibre stresses were the focus of the analysis, as it represents the net stress within the member and when measured against the materials yield strength, can most closely approximate a safety margin.

TOWER HORIZONTAL MEMBERS POST PROCESSING

The Horizontal Members were designated using Groups within Strand 7. Each beam is comprised of two nodes which make up its beam ends. When the model is run, each of these nodes is imparted with data, such as displacement, forces and stresses, which is extracted for analysis.

Figure 40 shows an extract from the force/moment tab in the Strand 7 result file, where the Groups tab is selected, then the necessary columns are selected to display the information that is to be extracted. Selecting the required Group eliminates all other model elements from the selectable window, allowing the required parameter to be extracted and imported into another spreadsheet for analysis.

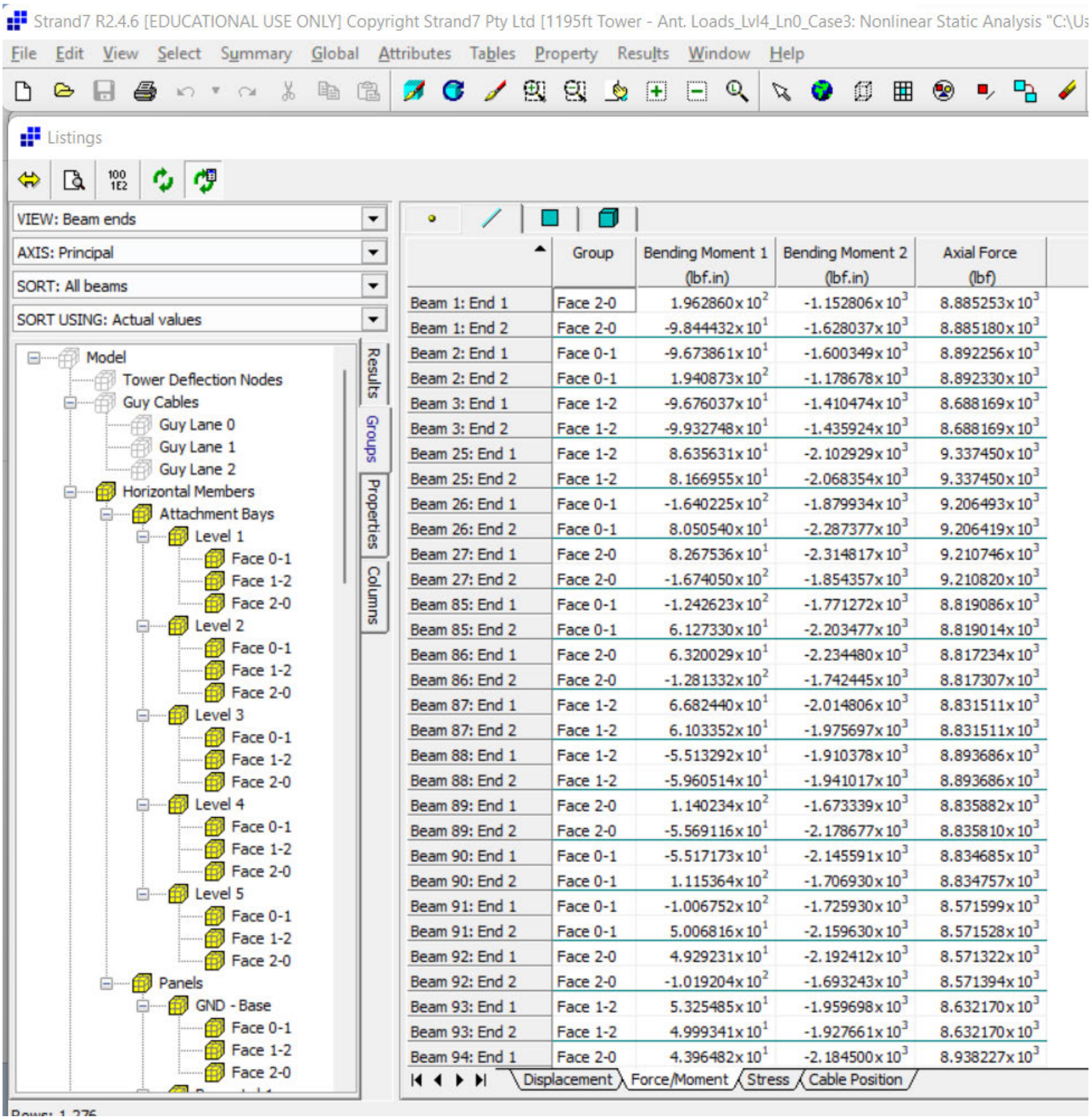


Figure 40 - Tower Horizontal Members, Stand 7 Grouping

Once the data is imported into another spreadsheet, the Faces associated with each Beam are used to sort the data. This allows each Face, or element of Face, to be assessed under each Load Case. The axial force, bending moments, axial stress, and fibre stresses on each Horizontal Member, under each Load Case is then plotted against Tower height.

Fibre stresses were the focus of the analysis, however the other parameters were extracted, analysed, and plotted as they contribute to fibre stresses and help explain behaviour. As each Load Case is applied to each Lane at each Level, a peak compressive and peak tensile stress within the Tower Horizontal Members is produced. These are represented by the minimum and maximum fibre stresses, which are used to populate Table 14.

This Table provides four (4) columns for each tower state, antenna down and antenna up. Column one (1) represents the Tower Horizontal Member stresses when the tower is in its ‘As Designed’ state, or when no load cases are being applied. Columns two (2) to four (4) represent Load Case 1, 2 & 3, respectively. As each Level had its respective Lanes subjected to Load Cases 1, 2 & 3, the peak fibre stresses in the Tower Horizontal Members were extracted and populates Table 14.

The numeric value indicates the peak fibre stress experienced, σ_{peak}, during each of the Load Cases. The Tower Horizontal Member material has a yield strength σ_{yield}, of 33000psi (227.5MPa). Within Table 14, a green box indicates the peak stress, σ_{peak}, measured was less than 25% of yield stress, σ_{yield}. Equivalently, a green box indicates $\sigma_{peak} < 0.25\,\sigma_{yield}$. Similarly, an amber box indicates $0.25\,\sigma_{yield} < \sigma_{peak} < 0.40\,\sigma_{yield}$ and a red box indicates $0.40\,\sigma_{yield} < \sigma_{peak} < \sigma_{yield}$.

In the ‘as designed’ columns, all the peak fibre stresses are the same as the tower is not being subjected to any Load Cases. In the Load Case 1 columns, each Level has the same peak fibre stresses across Lanes, as the Load Case de-tensions all 3 guy cables.

Table 14 - Tower Horizontal Member Stress (MPa)

TOWER HORIZONTAL MEMBER STRESS (MPa)		No Antenna								Antenna Installed							
		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)	
		Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)
Level 5	Lane 0	-18.809	82.401	-19.610	79.601	-18.917	77.664	-18.942	76.781	-23.186	85.553	-22.708	82.901	-23.494	79.828	-24.233	78.929
	Lane 1	-18.809	82.401	-19.610	79.601	-26.505	77.687	-26.254	76.803	-23.186	85.553	-22.708	82.901	-26.079	81.541	-25.887	80.655
	Lane 2	-18.809	82.401	-19.610	79.601	-25.745	77.739	-25.501	76.855	-23.186	85.553	-22.708	82.901	-25.303	81.645	-25.117	80.758
Level 4	Lane 0	-18.809	82.401	-18.807	81.089	-20.001	80.225	-20.019	79.924	-23.186	85.553	-23.238	84.217	-22.832	83.205	-22.831	82.899
	Lane 1	-18.809	82.401	-18.807	81.089	-26.924	80.253	-26.905	79.951	-23.186	85.553	-23.238	84.217	-26.983	83.464	-26.967	83.164
	Lane 2	-18.809	82.401	-18.807	81.089	-25.474	80.304	-25.586	80.003	-23.186	85.553	-23.238	84.217	-26.064	83.519	-26.182	83.219
Level 3	Lane 0	-18.809	82.401	-18.915	79.367	-18.925	78.912	-18.926	78.708	-23.186	85.553	-23.225	82.576	-23.184	82.151	-23.183	81.946
	Lane 1	-18.809	82.401	-18.915	79.367	-19.104	78.964	-19.075	78.759	-23.186	85.553	-23.225	82.576	-23.245	82.166	-23.245	81.960
	Lane 2	-18.809	82.401	-18.915	79.367	-19.270	78.900	-19.262	78.695	-23.186	85.553	-23.225	82.576	-23.274	82.102	-23.276	81.896
Level 2	Lane 0	-18.809	82.401	-18.796	81.057	-18.791	80.897	-18.790	80.828	-23.186	85.553	-23.208	84.220	-23.123	84.074	-23.217	84.004
	Lane 1	-18.809	82.401	-18.796	81.057	-18.863	80.999	-18.866	80.930	-23.186	85.553	-23.208	84.220	-23.211	84.159	-23.211	84.090
	Lane 2	-18.809	82.401	-18.796	81.057	-18.993	80.931	-18.995	80.862	-23.186	85.553	-23.208	84.220	-23.206	84.091	-23.206	84.023
Level 1	Lane 0	-18.809	82.401	-18.909	80.671	-18.917	80.630	-18.916	80.602	-23.186	85.553	-23.228	83.848	-23.230	83.807	-23.230	83.779
	Lane 1	-18.809	82.401	-18.909	80.671	-18.914	80.615	-18.914	80.588	-23.186	85.553	-23.228	83.848	-23.229	83.791	-23.229	83.764
	Lane 2	-18.809	82.401	-18.909	80.671	-18.919	80.660	-18.920	80.631	-23.186	85.553	-23.228	83.848	-23.229	83.837	-23.229	83.808

Legend

- Stress < 25% Yield Stress — Value indicates stress (MPa)
- 25% < Stress ≤ 40% Yield Stress — Value indicates stress (MPa)
- Stress > 40% Yield Stress — Value indicates stress (MPa)

$$1psi = 0.0068947573MPa$$

$$\sigma_{YieldPoint} = 33000psi = 227.5MPa$$

A factor of safety (FoS) is calculated as the ratio of yield strength, σ_{yield}, and applied, or peak stress, σ_{peak}. Equivalently, $FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$. Within Table 15, a green box indicates the Factor of Safety, FoS, was greater than ten (10). Equivalently, a green box indicates FoS > 10. Similarly, an amber box indicates 10 > FoS > 2.5 and a red box indicates FoS < 2.5.

Table 15 - Tower Horizontal Member Stress, Factor of Safety (FoS)

TOWER HORIZONTAL MEMBER STRESS (FoS)		No Antenna								Antenna Installed							
		As Designed		Case 1		Case 2		Case 3		As Designed		Case 1		Case 2		Case 3	
		Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)	Min Fibre Stress Comp. (MPa)	Max Fibre Stress Tensile (MPa)
Level 5	Lane 0	12.097	2.761	11.602	2.858	12.028	2.930	12.012	2.963	9.813	2.659	10.020	2.745	9.684	2.850	9.389	2.883
	Lane 1	12.097	2.761	11.602	2.858	8.584	2.929	8.667	2.962	9.813	2.659	10.020	2.745	8.725	2.790	8.789	2.821
	Lane 2	12.097	2.761	11.602	2.858	8.838	2.927	8.922	2.960	9.813	2.659	10.020	2.745	8.992	2.787	9.059	2.817
Level 4	Lane 0	12.097	2.761	12.098	2.806	11.376	2.836	11.366	2.847	9.813	2.659	9.791	2.702	9.965	2.735	9.966	2.745
	Lane 1	12.097	2.761	12.098	2.806	8.451	2.835	8.457	2.846	9.813	2.659	9.791	2.702	8.432	2.726	8.437	2.736
	Lane 2	12.097	2.761	12.098	2.806	8.932	2.833	8.893	2.844	9.813	2.659	9.791	2.702	8.729	2.724	8.690	2.734
Level 3	Lane 0	12.097	2.761	12.029	2.867	12.022	2.883	12.022	2.891	9.813	2.659	9.797	2.755	9.814	2.770	9.814	2.777
	Lane 1	12.097	2.761	12.029	2.867	11.910	2.881	11.928	2.889	9.813	2.659	9.797	2.755	9.788	2.769	9.788	2.776
	Lane 2	12.097	2.761	12.029	2.867	11.807	2.884	11.812	2.891	9.813	2.659	9.797	2.755	9.776	2.771	9.775	2.778
Level 2	Lane 0	12.097	2.761	12.105	2.807	12.108	2.813	12.109	2.815	9.813	2.659	9.804	2.702	9.840	2.706	9.800	2.709
	Lane 1	12.097	2.761	12.105	2.807	12.062	2.809	12.060	2.811	9.813	2.659	9.804	2.702	9.803	2.704	9.803	2.706
	Lane 2	12.097	2.761	12.105	2.807	11.980	2.811	11.978	2.814	9.813	2.659	9.804	2.702	9.805	2.706	9.805	2.708
Level 1	Lane 0	12.097	2.761	12.033	2.820	12.028	2.822	12.028	2.823	9.813	2.659	9.795	2.714	9.795	2.715	9.795	2.716
	Lane 1	12.097	2.761	12.033	2.820	12.029	2.822	12.029	2.823	9.813	2.659	9.795	2.714	9.795	2.715	9.795	2.716
	Lane 2	12.097	2.761	12.033	2.820	12.026	2.821	12.026	2.822	9.813	2.659	9.795	2.714	9.795	2.714	9.795	2.715

Legend

- FoS > 10 — Value equals FoS
- 2.5 < FoS ≤10 — Value equals FoS
- 0 < FoS ≤ 2.5 — Value equals FoS

$$Factor\ of\ Saftey = \frac{Material\ Strength}{Design\ Load}$$

TOWER HORIZONTAL MEMBER STRESSES – MINIMUM FIBRE STRESS (MAXIMUM COMPRESSIVE STRESS)

In both antenna down and up states, the Horizontal Members experience compressive stresses less than 40% of their yield strength. The compressive stresses do not change appreciably between Load Cases, however the peak in both states occurs on Level 4, Lane 1, Load Case 2. In this state, the guy cable at Level 4, Lane 1 is hanging down the Tower, shown in Figure 41.

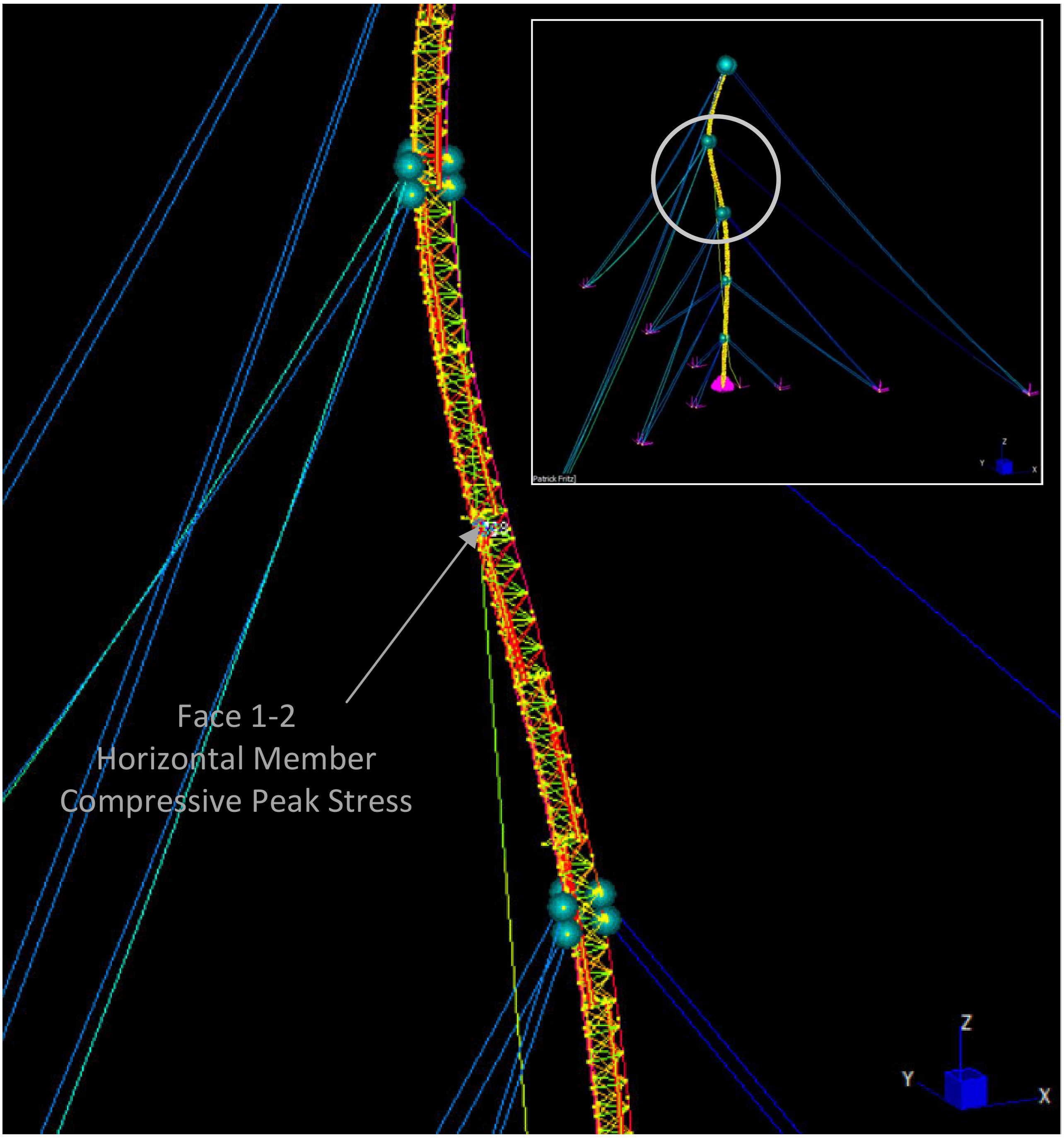


Figure 41 - Tower Horizontal Members, Antenna Down & Up – Peak Compressive Stress, Level 4, Lane 1, Case 2

The peak compressive stress is located directly between Level 3 & 4 on Face 1-2, as shown in Figure 42**Error! Reference source not found.**.

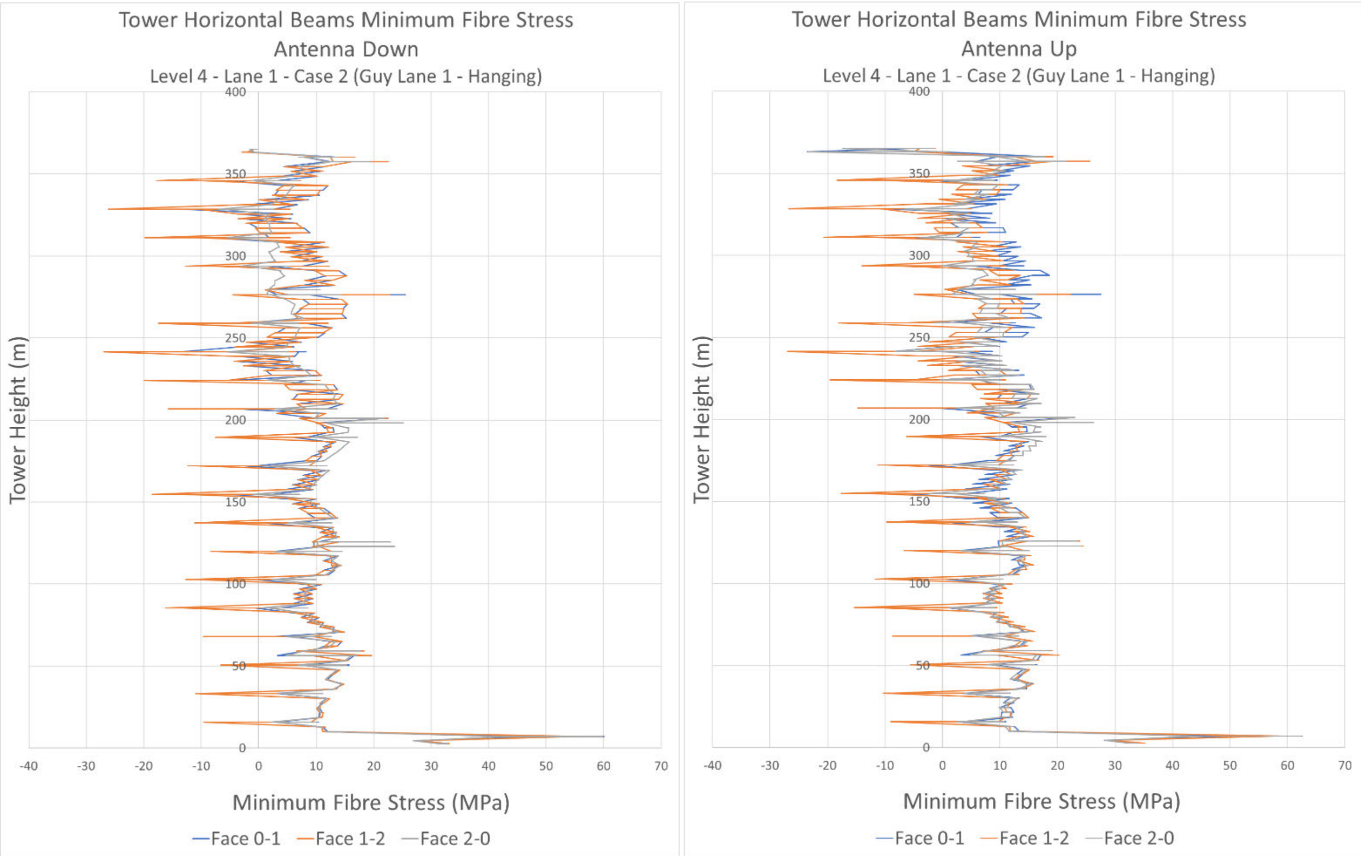


Figure 42 - Tower Horizontal Member Plot, Antenna Down & Up - Peak Compressive Stress, Level 4, Lane 1, Case 2

While the compressive stresses are well within their safety margin, the FoS is calculated,

$$FoS_{down} = \frac{\sigma_{yield}}{\sigma_{peak}} \qquad FoS_{up} = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS_{down} = \frac{227.5MPa}{26.9MPa} = 8.5 \qquad FoS_{up} = \frac{227.5MPa}{27.0MPa} = 8.4$$

TOWER HORIZONTAL MEMBER STRESSES – MAXIMUM FIBRE STRESS (MAXIMUM TENSILE STRESS)

In both antenna down and up states, the Horizontal Members at the base of to the Tower shown in Figure 43**Error! Reference source not found.** exhibit the greatest tensile stresses.

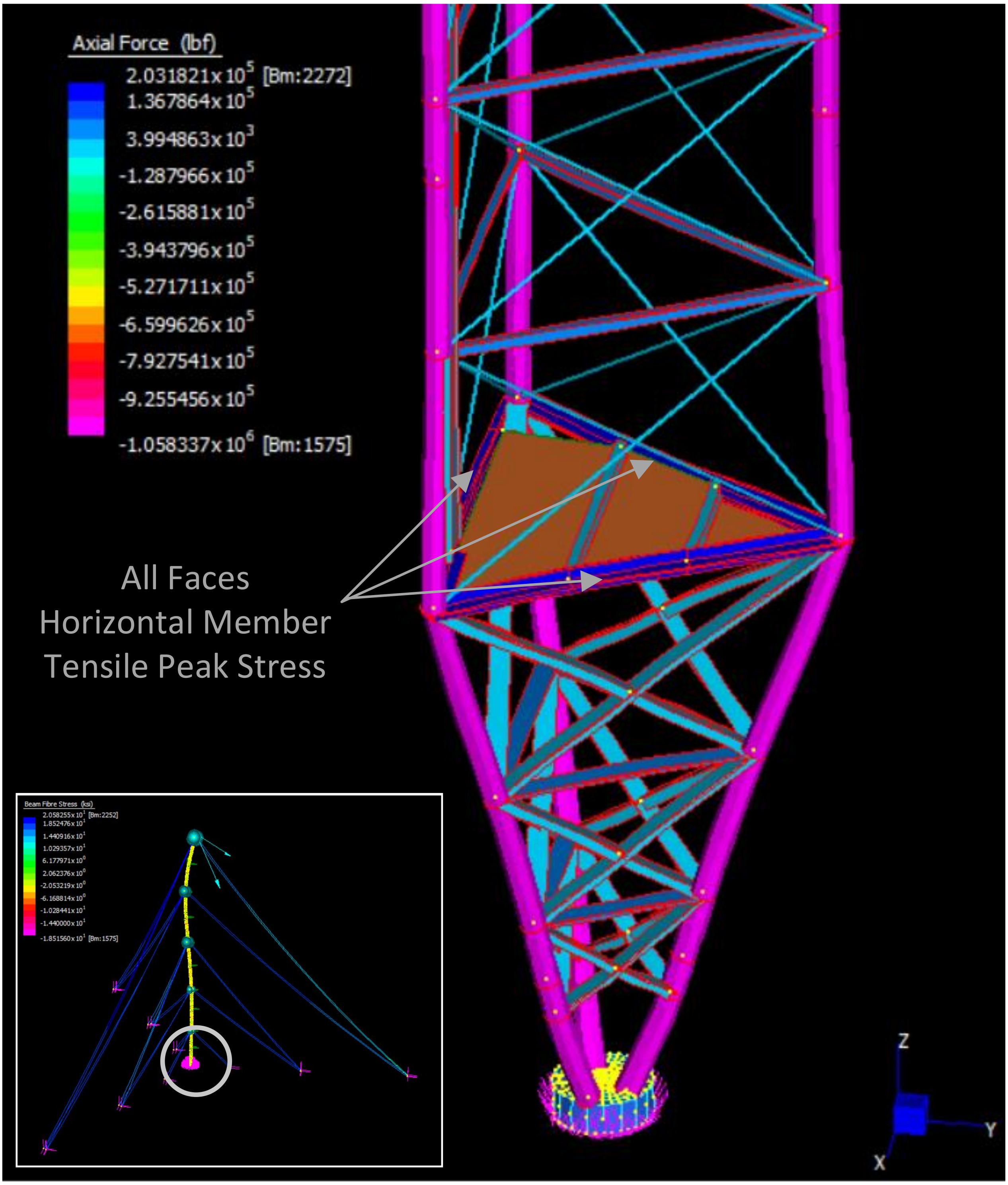


Figure 43 - Tower Horizontal Member, Antenna Down & Up - Peak Tensile Stress, No Load Case Applied

This increased tensile stress is a result of the Horizontal Member reacting against the Tower Legs change in direction. As the Tower Leg changes from a vertical direction to align with the Base Joint, the compressive forces that were vertically aligned now have a horizontal component. This horizontal component is reacted by the Horizontal Member at the joint, resulting in an increased tensile stress.

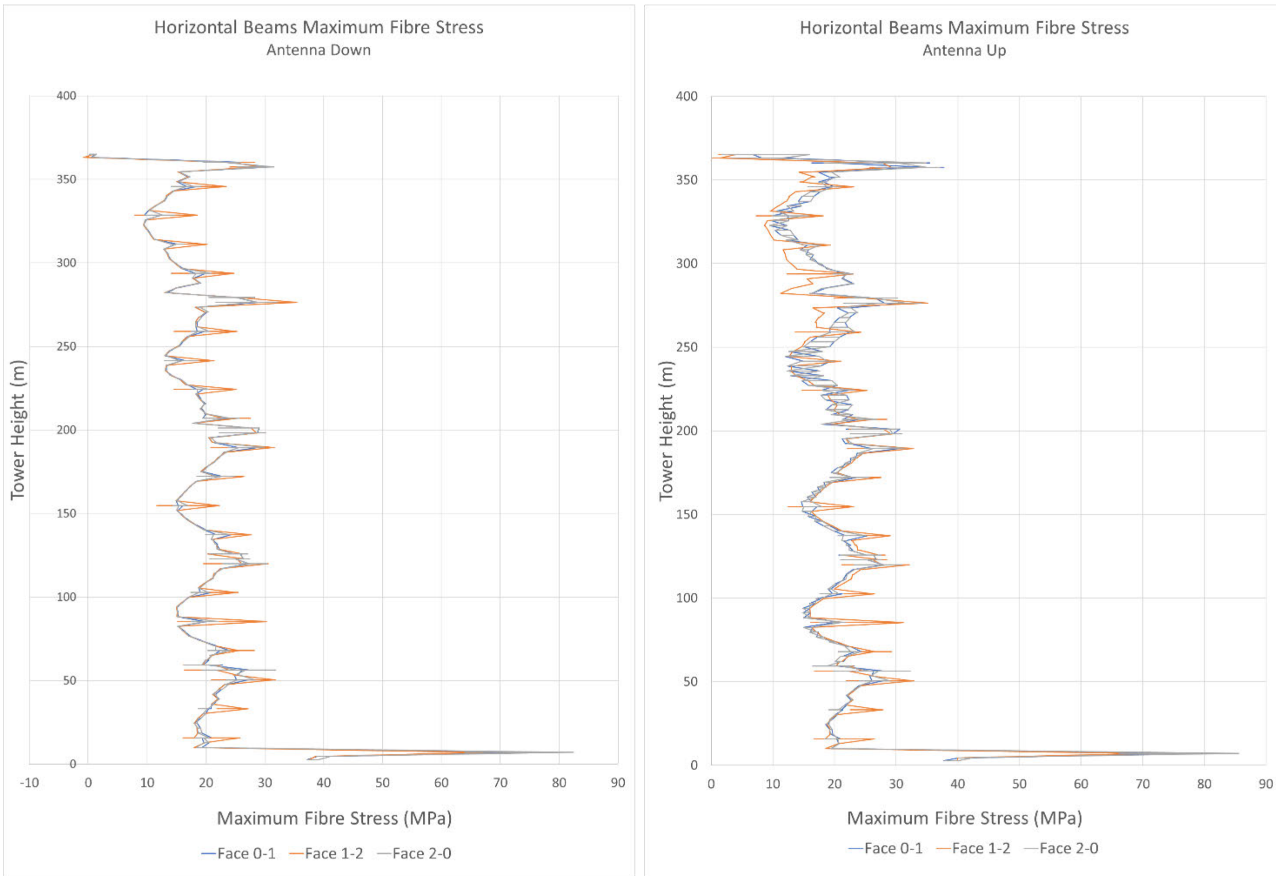


Figure 44 - Tower Horizontal Member Plot, Antenna Down & Up - Peak Tensile Stress, No Load Cases Applied

Error! Reference source not found. The peak tensile stresses at the base of the Tower are largely localised at the geometry change and may require mesh refinement to better model. Conservatively assuming the stress is representative, FoS is calculated as,

$$FoS_{down} = \frac{\sigma_{yield}}{\sigma_{peak}} \qquad FoS_{up} = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS_{down} = \frac{227.5MPa}{82.4MPa} = 2.8 \qquad FoS_{up} = \frac{227.5MPa}{85.6MPa} = 2.7$$

TOWER DIAGONAL TIE-ROD MEMBERS

The Tower Diagonal Tie Rod Member analysis measured axial force, minimum fibre stress and maximum fibre stress. The fibre stresses were used in the analysis, however as the Tie-Rods are truss elements, they only support axial forces and axial stress could have been used. When the peak fibre stresses are measured against the materials yield strength, it can most closely approximate a safety margin.

DIAGONAL TIE ROD DATA POST PROCESSING

The Diagonal Tie Rods were designated using Groups within Strand 7. Each beam is comprised of two nodes which make up its beam ends. When the model is run, each of these nodes is imparted with data, such as displacement, forces and stresses, which is extracted for analysis.

Figure 45 shows an extract from the force/moment tab in the Strand 7 result file, where the Groups tab is selected, then the necessary columns are selected to display the information that is to be extracted. Selecting the required Group eliminates all other model elements from the selectable window, allowing the required parameter to be extracted and imported into another spreadsheet for analysis.

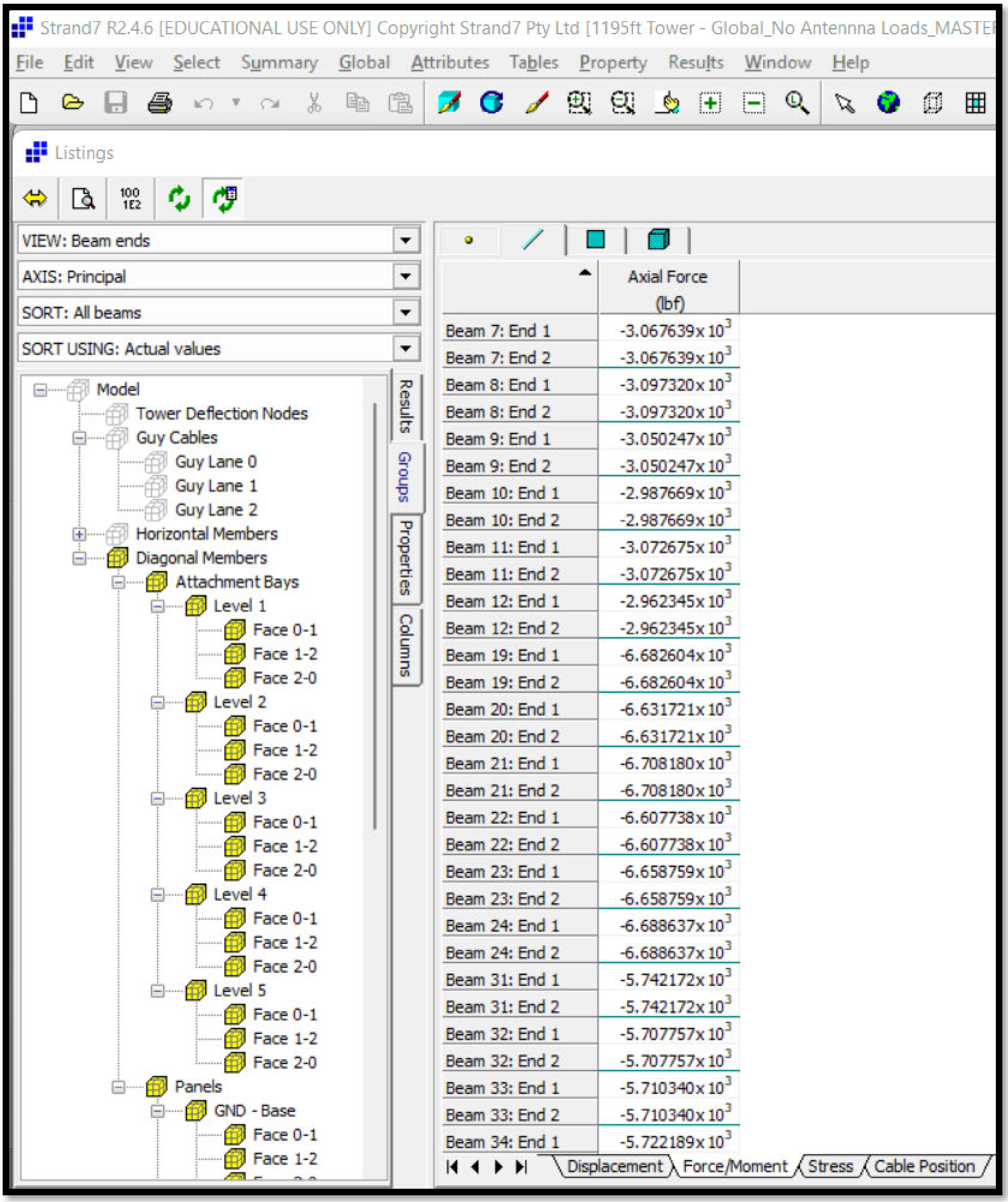


Figure 45 - Tower Diagonal Tie Rods, Strand 7 Grouping

Once the data is imported into another spreadsheet, the Faces associated with each Beam are used to sort the data. This allows each Face, or element of Face, to be assessed under each Load Case. The axial force and fibre stresses on each Tie Rod Member, under each Load Case is then plotted against Tower height.

As each Load Case is applied to each Lane at each Level, a peak compressive and peak tensile stresses within the Diagonal Tie Rods are produced. These are represented by the minimum and maximum fibre stresses, which are used to populate Table 16.

This Table provides four (4) columns for each tower state, antenna down and antenna up. Column one (1) represents the peak Diagonal Tie Rod fibre stress when the tower is in its ‘As Designed’ state, or when no load cases are being applied. Columns two (2) to four (4) represent Load Case 1, 2 & 3, respectively. As each Level had its respective Lanes subjected to Load Cases 1, 2 & 3, the peak fibre stresses in the Diagonal Tie Rods were extracted and populate Table 16.

The numeric value indicates the peak fibre stress experienced, σ_{peak}, during each of the Load Cases. The Diagonal Tie Rod material has a yield strength σ_{yield}, of 33000psi (227.5MPa). Within Table 17, a green box indicates the peak stress, σ_{peak}, measured was less than 25% of yield stress, σ_{yield}. Equivalently, a green box indicates $\sigma_{peak} < 0.25\,\sigma_{yield}$. Similarly, an amber box indicates $0.25\,\sigma_{yield} < \sigma_{peak} < 0.40\,\sigma_{yield}$ and a red box indicates $0.40\,\sigma_{yield} < \sigma_{peak} < \sigma_{yield}$.

In the As Designed columns, all the peak fibre stresses are the same as the tower is not being subjected to any Load Cases. In the Load Case 1 columns, each Level has the same peak fibre stresses across Lanes, as the Load Case de-tensions all 3 guy cables.

Table 16 - Tower Diagonal Tie Rod Stress (MPa)

TOWER DIAGONAL TIE-ROD STRESS (MPa)		No Antenna								Antenna Installed							
		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)	
		Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)
Level 5	Lane 0	-103.513	74.722	-100.641	72.304	-99.327	70.909	-98.238	70.112	-121.480	80.455	-118.945	78.216	-114.695	75.310	-113.538	74.492
	Lane 1	-103.513	74.722	-100.641	72.304	-99.452	70.928	-98.365	70.133	-121.480	80.455	-118.945	78.216	-118.331	77.395	-117.408	76.634
	Lane 2	-103.513	74.722	-100.641	72.304	-99.941	70.833	-98.854	70.039	-121.480	80.455	-118.945	78.216	-119.046	77.233	-117.721	76.385
Level 4	Lane 0	-103.513	74.722	-102.545	73.662	-103.472	73.246	-103.085	72.970	-121.480	80.455	-120.372	79.354	-121.044	78.789	-120.645	78.509
	Lane 1	-103.513	74.722	-102.545	73.662	-102.887	73.162	-102.499	72.888	-121.480	80.455	-120.372	79.354	-119.766	78.352	-119.401	78.086
	Lane 2	-103.513	74.722	-102.545	73.662	-102.992	73.229	-102.606	72.953	-121.480	80.455	-120.372	79.354	-118.827	78.958	-118.446	78.681
Level 3	Lane 0	-103.513	74.722	-104.123	72.824	-106.195	72.993	-105.953	72.810	-121.480	80.455	-122.355	78.660	-124.565	78.877	-124.318	78.692
	Lane 1	-103.513	74.722	-104.123	72.824	-105.590	72.894	-105.348	72.710	-121.480	80.455	-122.355	78.660	-122.624	77.946	-122.333	77.751
	Lane 2	-103.513	74.722	-104.123	72.824	-105.721	72.973	-105.480	72.790	-121.480	80.455	-122.355	78.660	-121.017	78.446	-120.782	78.269
Level 2	Lane 0	-103.513	74.722	-107.147	74.532	-107.902	74.837	-107.789	74.766	-121.480	80.455	-125.057	80.265	-124.893	80.215	-124.834	80.158
	Lane 1	-103.513	74.722	-107.147	74.532	-108.103	74.849	-108.015	74.779	-121.480	80.455	-125.057	80.265	-126.027	80.578	-125.932	80.506
	Lane 2	-103.513	74.722	-107.147	74.532	-108.495	74.748	-108.383	74.678	-121.480	80.455	-125.057	80.265	-126.363	80.032	-126.255	79.970
Level 1	Lane 0	-103.513	74.722	-126.740	78.315	-128.379	78.932	-128.405	78.927	-121.480	80.455	-145.521	84.229	-144.556	83.983	-144.461	83.945
	Lane 1	-103.513	74.722	-126.740	78.315	-128.545	78.666	-128.571	78.661	-121.480	80.455	-145.521	84.229	-146.274	84.854	-146.253	84.849
	Lane 2	-103.513	74.722	-126.740	78.315	-129.016	78.532	-129.042	78.527	-121.480	80.455	-145.521	84.229	-147.824	84.353	-147.850	84.325

A factor of safety (FoS) is calculated as the ratio of yield strength, σ_{yield}, and applied, or peak stress, σ_{peak}. Equivalently, $FoS = \frac{\sigma_{yield}}{\sigma_{peak}}$. Within Table 17, a green box indicates the Factor of Safety, FoS, was greater than ten (10). Equivalently, a green box indicates $FoS > 10$. Similarly, an amber box indicates $10 > FoS > 2.5$ and a red box indicates $FoS < 2.5$.

Table 17 - Tower Diagonal Tie Rod Stress, Factor of Safety (FoS)

TOWER DIAGONAL TIE-ROD STRESS (FoS)		No Antenna								Antenna Installed							
		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)		As Designed		Case 1 (3 x Detensioned)		Case 2 (1 x Hanging)		Case 3 (1 x Removed)	
		Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)	Min Fibre Stress Comp. (Mpa)	Max Fibre Stress Tensile (Mpa)
Level 5	Lane 0	2.198	3.045	2.261	3.147	2.291	3.209	2.316	3.245	1.873	2.828	1.913	2.909	1.984	3.021	2.004	3.054
	Lane 1	2.198	3.045	2.261	3.147	2.288	3.208	2.313	3.244	1.873	2.828	1.913	2.909	1.923	2.940	1.938	2.969
	Lane 2	2.198	3.045	2.261	3.147	2.277	3.212	2.302	3.249	1.873	2.828	1.913	2.909	1.911	2.946	1.933	2.979
Level 4	Lane 0	2.198	3.045	2.219	3.089	2.199	3.106	2.207	3.118	1.873	2.828	1.890	2.867	1.880	2.888	1.886	2.898
	Lane 1	2.198	3.045	2.219	3.089	2.211	3.110	2.220	3.122	1.873	2.828	1.890	2.867	1.900	2.904	1.906	2.914
	Lane 2	2.198	3.045	2.219	3.089	2.209	3.107	2.217	3.119	1.873	2.828	1.890	2.867	1.915	2.882	1.921	2.892
Level 3	Lane 0	2.198	3.045	2.185	3.124	2.143	3.117	2.147	3.125	1.873	2.828	1.860	2.893	1.827	2.885	1.830	2.891
	Lane 1	2.198	3.045	2.185	3.124	2.155	3.121	2.160	3.129	1.873	2.828	1.860	2.893	1.855	2.919	1.860	2.926
	Lane 2	2.198	3.045	2.185	3.124	2.152	3.118	2.157	3.126	1.873	2.828	1.860	2.893	1.880	2.900	1.884	2.907
Level 2	Lane 0	2.198	3.045	2.124	3.053	2.109	3.040	2.111	3.043	1.873	2.828	1.819	2.835	1.822	2.836	1.823	2.838
	Lane 1	2.198	3.045	2.124	3.053	2.105	3.040	2.106	3.043	1.873	2.828	1.819	2.835	1.805	2.824	1.807	2.826
	Lane 2	2.198	3.045	2.124	3.053	2.097	3.044	2.099	3.047	1.873	2.828	1.819	2.835	1.801	2.843	1.802	2.845
Level 1	Lane 0	2.198	3.045	1.795	2.905	1.772	2.883	1.772	2.883	1.873	2.828	1.564	2.701	1.574	2.709	1.575	2.710
	Lane 1	2.198	3.045	1.795	2.905	1.770	2.892	1.770	2.893	1.873	2.828	1.564	2.701	1.555	2.681	1.556	2.682
	Lane 2	2.198	3.045	1.795	2.905	1.764	2.897	1.763	2.897	1.873	2.828	1.564	2.701	1.539	2.697	1.539	2.698

Legend

- FoS > 10, Value equals FoS
- 2.5 < FoS ≤10, Value equals FoS
- 0 < FoS ≤ 2.5, Value equals FoS

$$Factor\ of\ Saftey = \frac{Material\ Strength}{Design\ Load}$$

TOWER DIAGONAL TIE ROD STRESSES SUMMARY

When the antenna is down, there are tensile stresses in the Tie Rods between 25% and 40% of yield strength. There are compressive stresses exceeding 40% of yield strength. The compressive stresses do not change appreciably when applying Load Cases between Levels 2 to 5 but increases around 20% when applying Load Cases at Level 1.

In all cases, the peak compressive and tensile stresses occur in the diagonal elements at the very bottom of the model, as shown in Figure 46. As the model is a global representation, this area may need model refinement to better understand.

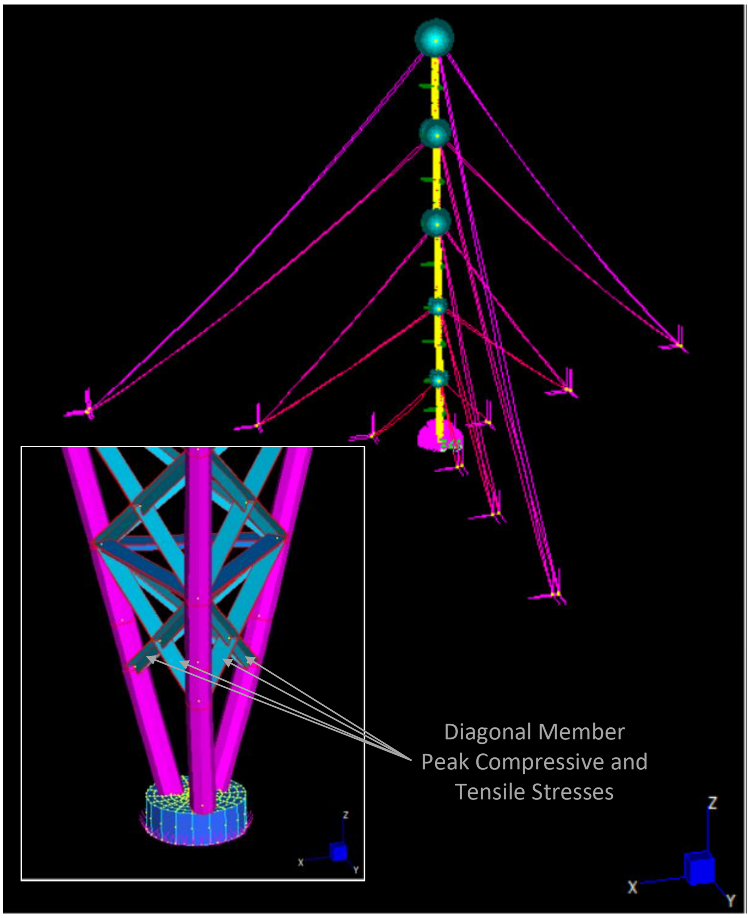


Figure 46 - Tower Diagonal Tie Rod, Antenna Down/Up, All Load Cases

Although model refinement may see the peak stresses in these areas reduce and redistribute, they are assumed to be a focal point for the stress and the figures are used to calculate the Factors of Safety. Figure 47 shows the stress distribution for the peak fibre stresses when the antenna is down. The distribution for antenna up is visually identical to the antenna down and is not shown. The FoS is calculated for both antenna down and up.

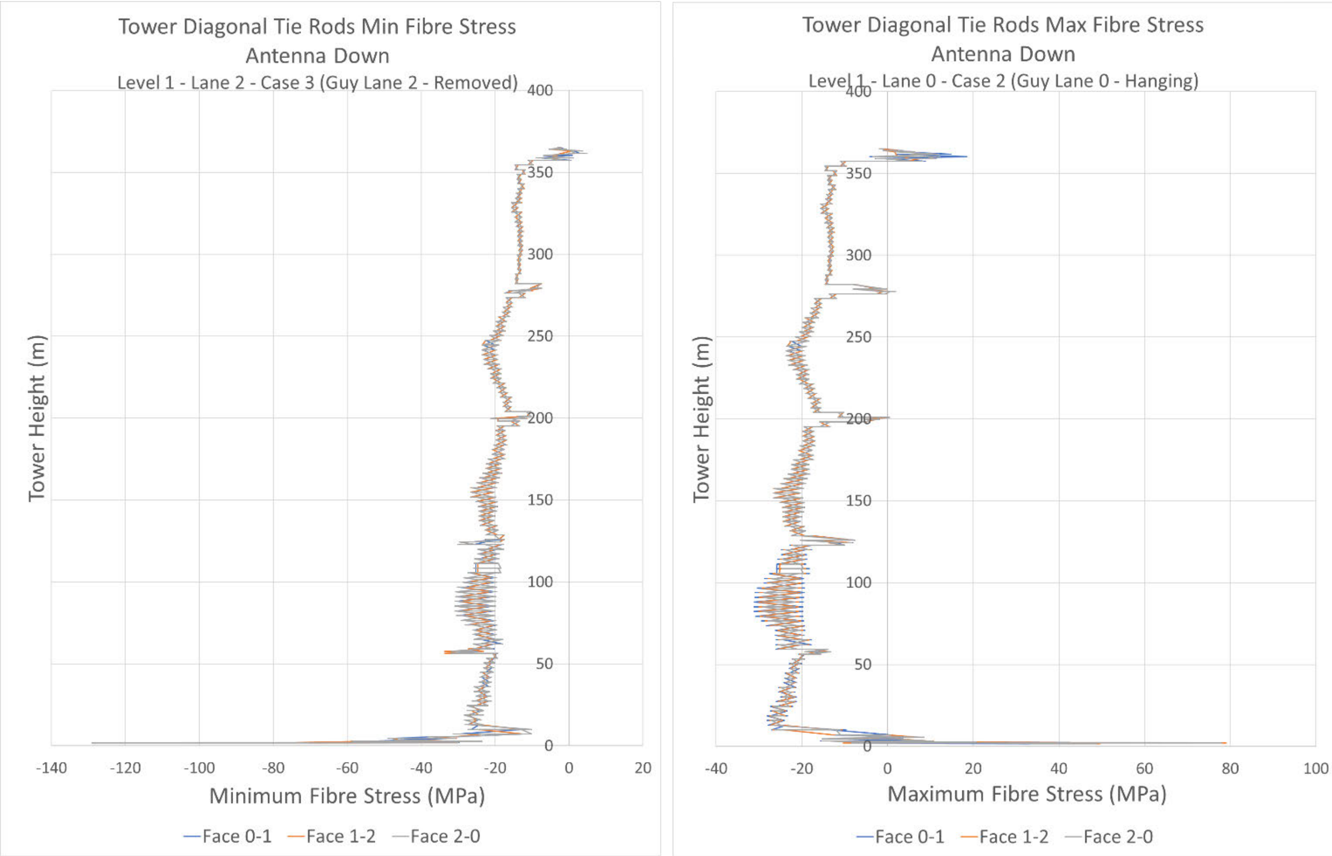


Figure 47 - Tower Diagonal Tie Rods, Antenna Down - Maximum Compressive and Tensile Stresses

The FoS is calculated for the antenna down,

$$FoS_{down,comp} = \frac{\sigma_{yield}}{\sigma_{peak}}$$
$$FoS_{down,comp} = \frac{227.5MPa}{129.0MPa} = 1.8$$

$$FoS_{down,tensile} = \frac{\sigma_{yield}}{\sigma_{peak}}$$
$$FoS_{down,tensile} = \frac{227.5MPa}{78.9MPa} = 2.9$$

The FoS is calculated for the antenna up,

$$FoS_{down,comp} = \frac{\sigma_{yield}}{\sigma_{peak}}$$
$$FoS_{down,comp} = \frac{227.5MPa}{147.9MPa} = 1.5$$

$$FoS_{down,tensile} = \frac{\sigma_{yield}}{\sigma_{peak}}$$
$$FoS_{down,tensile} = \frac{227.5MPa}{84.9MPa} = 2.7$$

While the stresses and safety margins given Table 16 and Table 17 are applicable to the peaks, if the peak is considered an outlier the following two Figures show the peak stresses in antenna down and up states.

Omitting the Tower Base peak in the antenna down state, the peak fibre stresses occur when applying Load Case 3 to Lane 0 at Level 5. The peak compressive stress occurs in the middle of Level 3 and 4 Attachment Bays. The peak tensile stress occurs at the Level 5 Attachment Bay, as show in Figure 48.

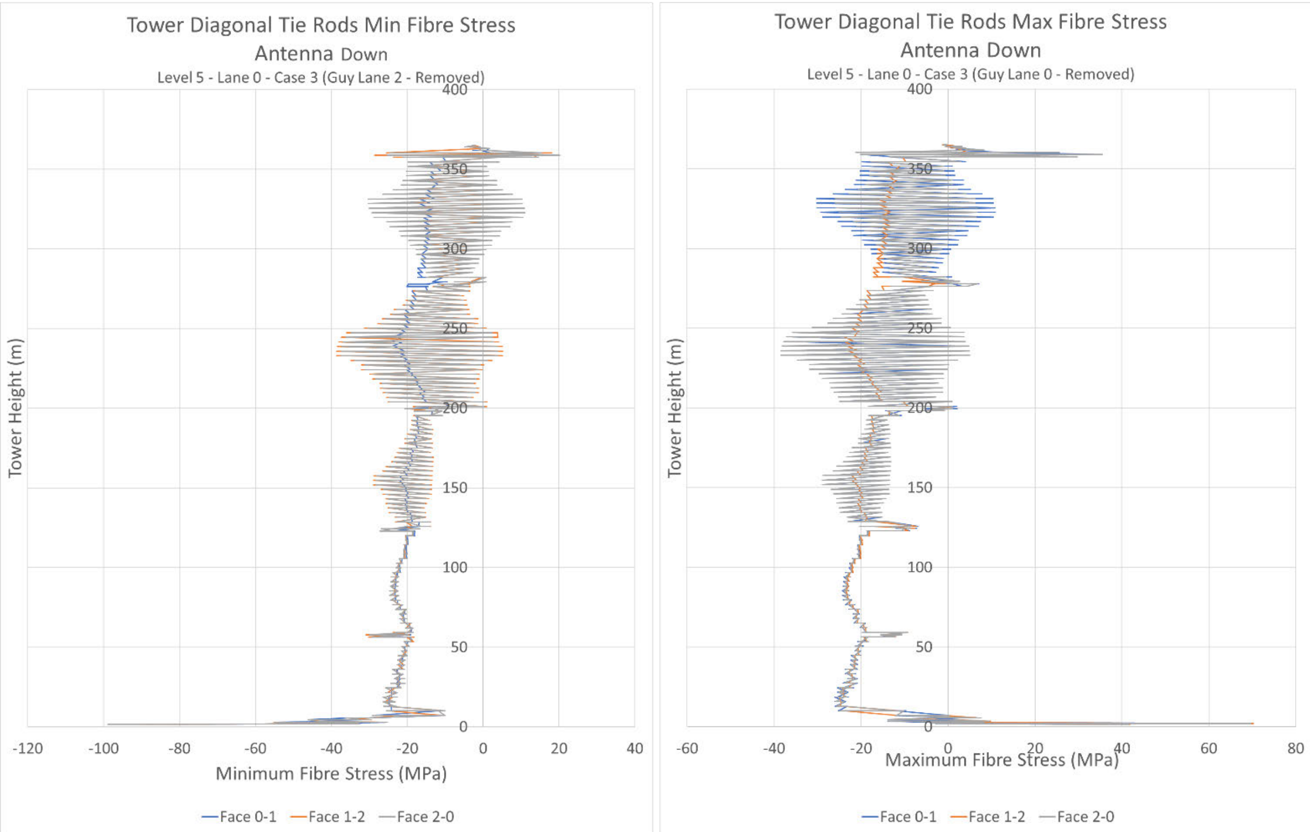


Figure 48 - Tower Diagonal Tie Rods, Antenna Down, Level 5, Lane 0, Case 3

The FoS is calculated for the antenna down,

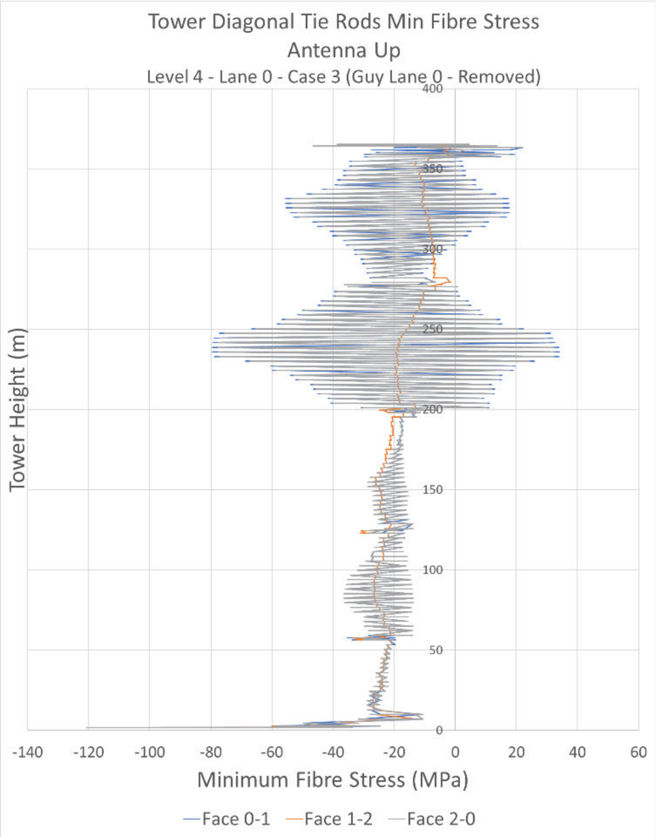
$$FoS_{down,comp} = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS_{down,comp} = \frac{227.5MPa}{40MPa} = 5.7$$

$$FoS_{down,tensile} = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS_{down,tensile} = \frac{227.5MPa}{35MPa} = 6.5$$

Omitting the Tower Base peak in the antenna up state, the peak fibre stresses occur when applying Load Case 3 to Lane 0 at Level 4. The peak compressive stress occurs in the middle of Level 3 and 4 Attachment Bays. The peak tensile stress occurs at the Level 5 Attachment Bay, as show in Figure 49.



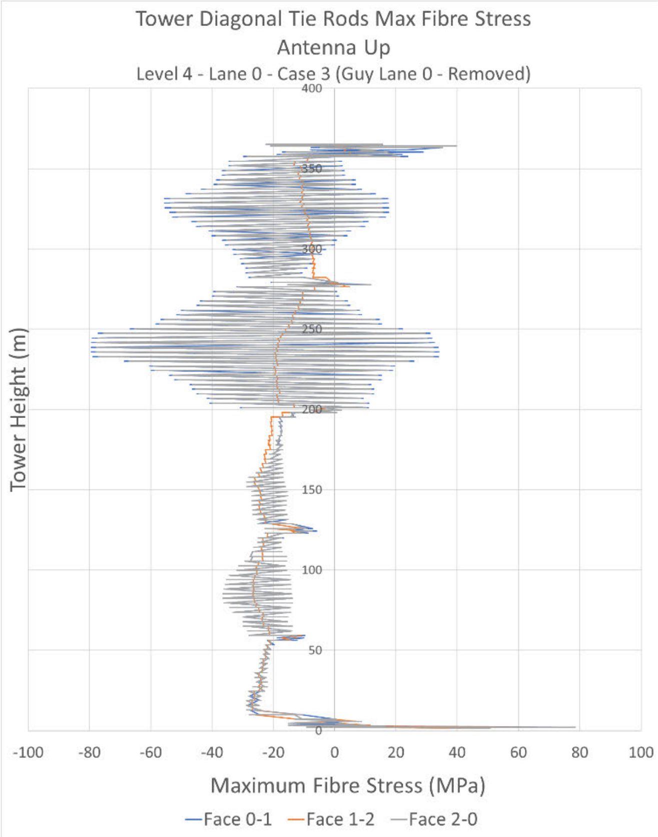


Figure 49- Tower Diagonal Tie Rods, Antenna Up, Level 4, Lane 0, Case 3

The FoS is calculated for the antenna up,

$$FoS_{down,comp} = \frac{\sigma_{yield}}{\sigma_{peak}} \qquad FoS_{down,tensile} = \frac{\sigma_{yield}}{\sigma_{peak}}$$

$$FoS_{down,comp} = \frac{227.5MPa}{80MPa} = 2.85 \qquad FoS_{down,tensile} = \frac{227.5MPa}{40MPa} = 5.7$$

CONSIDERATIONS

TOWER DISPLACMENTS

The antenna load was represented by a load vector at the halyard where the antenna attaches to the tower. This was deemed an acceptable representation, as the antenna load does act at a single point on the tower and the direction of that force will not change significantly during tower displacements. Affecting Level 5 guy cables while the antenna is up causes the greatest deflections, specifically Lane 0. If the antenna load is not being properly represented, it may be causing a misrepresentation of how the antenna loads contribute to tower deflections on guy cable removal. Once surveying data of the tower while undergoing guy replacement is attained, this concern will be able to be quantified and addressed, with the model updated accordingly.

TOWER LEGS

Peak compressive stress concentrations at the base of the Tower may require model refinement to better understand. Tensile loads experienced in Lanes 1 & 2 at Level 5 may require further analysis to ensure they are representative, and whether the local area requires model refinement to better assess.

Tensile stresses in tower structures can be dangerous as they are generally not designed to be reacted against. Specifically, each Leg member has splice plates welded to its ends such that they can be bolted together and form one leg assembly. The combination of compressive and tensile forces in a local weld area may require model refinement and further analysis.

TOWER HORIZONTAL MEMBERS

The Horizontal Members experiencing the high tensile stresses would benefit from model refinement at the geometry change. While the stresses are within a reasonable safety factor, future Load Cases will need to ensure this area is representative.

TOWER DIAGONAL TIE RODS

Given the low safety margins and stress locality of the peak stresses, further model refinement may justify pursuing. In general, the Diagonal Tie Rods could be better modelled so they can include some allowance for critical bending. The Project did not have time to consider the Euler Buckling Limits of the Tie Rods, or whether its limit was a factor in any of the Load Cases. The Tie-Rods in the model are truss elements and oppose in compression without considering their Euler Buckling Limit. If this limit were reached, the member would no longer support further loading and the forces would be redistributed within the surrounding structure. As this element is not factored into the model, it may need to be considered further.

CONCLUSION

OBSERVATIONS

The Harold E. Holt (HEH) naval base in Exmouth, Western Australia is one of Australia's major VLF communication stations. The maintenance and upkeep of the station is critical to Australia's sovereignty. This maintenance and upkeep includes the removal and replacement of guy wires. When the array is in its 'as maintained' configuration, the structure is stable and reliable. In this state it can endure extreme environmental conditions. The industry problem investigated in this project involved better understanding the uncertainty as to what stresses are being absorbed by the tower and whether these stresses are reaching critical values during routine maintenance (in other words, when guy wires are removed, or tension changes).

This project adopted a numerical analysis, via finite element methods, to develop a representative model of a typical tower structure. This enabled an exploration of what stressors are being imparted under various guy wire and antenna array configurations.

MODEL VALIDATION

Model validation was conducted by using catenary theory to develop a Cable Length Solver. The Solver used model data and iterated on cable lengths using catenary theory to achieve a theoretical length for an objective tension. Once the model could be run using a geometric non-linear solver and have the thirty (30) guy cable tensions converge within 5% of the objective tensions, the models were deemed to be sufficiently accurate for further analysis.

Once confidence in the Tower Models was attained by meeting the objective tension requirement, the application of Load Cases was undertaken. Each of the three (3) upper cables at the five (5) Tower Attachment Bays were subjected to Load Cases 1, 2 & 3. These Load Cases were applied to both tower models, one (1) model where the antenna is down, and one (1) model where the antenna is up, resulting in 72 load cases being analysed.

This was deemed a suitable way in which to model and validate this type of problem. The same methodology could be applied to other large guy supported towers, or other cable structures in general. Even with FEA software being able to better model cable elements, using catenary theory as described in this report would assist in model validation.

TOWER DISPLACEMENTS

Tower Displacement was first assessed, which measured the deflections against a set of tolerances. These tolerances were intended for an ‘as designed’ state, where no Load Cases are being applied, however the values were still used to provide some benchmarking. The modelling found removing guy cables from Level 5 produced the most significant deflections, both when the antenna is down and when it is up. When the antenna is up, Lanes 1 & 2 have slightly increased tensions when compared with Lane 0, to counteract the antenna forces. For this reason, when Lane 0 is affected at any Level, increased deflections can be observed.

The tower displays a ‘s’ profile when the antenna is up and affecting Level 4 at Lane 0 increases the bowing effect in the area. This appears to contribute to the stress behaviour noted in the Tower Legs, Horizontal Members and Diagonal Tie Rods.

TOWER LEGS

When the antenna is down, the Tower is symmetrically loaded, and the Leg stresses gradually increase and peak at the base. As Load Cases are applied, the tower becomes asymmetrically loaded and the compressive stresses relax in the leg being affected, as the other two (2) Lanes pull the tower towards them. As the peaks were located in the very base elements, model refinement in this area may assist in better understanding the stresses. The tensile stresses generated when the antenna is down did not warrant investigation.

When the antenna was up, the Load Cases appear to exacerbate the tower ‘s’ profile already in effect. Without any Load Cases being applied, the compressive stress in Lane 0 Leg is already generally greater than Lanes 1 & 2 due to the antenna loads. At the Level 4 Attachment Bay, where the apex in the ‘s’ profile is observed, the stress in Lane 0 is almost 100% greater than that of Lanes 1 & 2 at the same elevation, without any Load Cases being applied. The greatest compressive stress in the Tower Legs occurs when removing Lane 0 guy cable from Level 4. When this occurs, the apex of the towers ‘s’ profile at Level 4 is increased and the compressive stresses in Lane 0 Leg at Level 4 peak.

Tensile stresses were appreciable in the antenna up state. On removing Lanes 1 or 2 at Level 5, the tensile forces in the respective Legs, directly above the guy cable Attachment Bay, peak. The modelling also showed that immediately below the peak tensile stress, the Leg goes back into compression. This behaviour appears to be the result of the antenna loads acting in conjunction with guy cables at Level 5.

TOWER HORIZONTAL MEMBERS

In both antenna down and up states, the Horizontal Members experience compressive stresses less than 40% of their yield strength. The compressive stresses do not change appreciably and do not change appreciably between Load Cases.

The greatest tensile stress in the Horizontal Members occurs in members around the tower geometry change, where the vertical legs redirect towards the Base Joint. It appears that these Horizontal Members are reacting to the kick load that is imparted by the geometry change and while the stresses have an adequate Factor of Safety, refining the model in this area may assist in better understanding the stresses.

TOWER DIAGONAL TIE RODS

The peak compressive and tensile stresses occurred in the diagonal elements at the very base of the model. While these are diagonal members, they were modelled with beam, not truss elements. The modelling shows an extreme peak in both compressive and tensile stresses in these members and may require model refinement to better understand.

If these members were excluded from the data, the peak compressive and tensile stresses in the Tie Rods were found to occur between Levels 3 and 4 Attachment Bays. The Tie Rod stress peaks appeared to increase as the upper levels were affected, and generally increased as deflection increased. The modelling of the Diagonal Tie Rods is an area outlined in Future Scope of Work Section, as there is an intent to incorporate a buckling limit into their property structure.

LESSONS LEARNED

The lessons learned can be separated into the core components of the project - the theoretical aspects, and the practical aspects. The theoretical aspects related to catenary theory and understanding its derivation such that it could be applied to a unique, practical application. Prior to the project, no knowledge of the catenary was understood to any appreciable depth. Developing an understanding of its derivation and then application took considerable effort and time.

The practical aspects relate to operator use of Strand 7 and Excel. Strand 7 had never been utilised prior and developing a working knowledge of its functions was developed through the course of the project modelling. As such, there are aspects which would have been modelled in a different manner had it been done with more experience. The following factors would be considered if another larger scale modelling task was undertaken,

1. Be conscious of what the models intent is. Direct time into aspects that affect the models intent, not time into intimate detail that has no impact.

2. Be conscious of what output data the modeller wants to extract. What are the requirements of model, why is it being modelled and what data needs to be extracted to support the models intent?

3. How is the model going to enable and support that extraction? Understand exactly how that data will eventually be extracted in terms of process steps, and if slight changes to the modelling or element grouping could reduce the process steps.

4. Realistically scope the post analysis task and understand what needs to be extracted to meet the models requirements. Spend effort on refining the elements that need to be extracted, not extracting unnecessary information.

5. How can the model elements be created such that they are consistently identifiable when extracting resulting data?

In terms of practical aspects of Excel, imbedding functions using VBA code had not previously been conducted, so was an aspect which needed to be developed. The amount of data processing and manipulation to generate the deflection and stress plots also required heavy use of imbedded functions not previously utilised.

FUTURE SCOPE OF WORK

While meetings its original aims, this project has highlighted areas for further examination. The future scope of work could take several forms, some aspects worth considering include:

1. Model refinement in the areas of peak stress concentrations. Specifically, the bottom section of the tower entirely could be remodelled with a finer representation of the structure. This area had peak stresses for the Legs, the Horizontal Members and the Diagonal Tie Rods.

2. Validate the deflection using surveying data. Tower deflection data has recently been sourced as part of guy cable replacements, which will prove extremely beneficial in validating the model accuracy. Once a pool of this deflection data has been generated, it will be invaluable in validating current and future models.

3. Incorporate wind loading into the model. Replacing guy cables under static environmental conditions is current practice, so not including wind loading was a reasonable approach. Wind loading, however, is an important consideration which will eventually tie into a required analysis.

4. Model the antenna as an element rather than an applied load to determine any differences. The current way of modelling the antenna as a point force may be contributing the out of tolerance deflections, as noted in the Considerations Section, which impacts model accuracy. If the deflections are shown to be erroneous, remodelling the antenna as an independent structure may prove more accurate.

5. Develop Maintenance Recommendations. After the tower deflections can be validated with surveying data, there would be great value in manipulating the cable tensions in the model to see if tower deflections can be reduced during guy replacements, especially in the upper Levels.

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ANNEX A - PROJECT SPECIFICATION

ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

Project Specification

For: Mr. Patrick Graeme Fritz

Title: Design Analysis of Guy Wires of Communication Towers: Industry Based Project Proposed by Raytheon Australia

Major: Mechanical

Supervisors: A/Prof Jayantha Epaarachchi & Mr. Stephen Mitchell

Sponsor: Raytheon Australia

Confidentiality: The source data used to derive the model is not able to be included within the dissertation nor made available for marking purposes.

Enrollment: ENG4111 – EXT S1, 2022

ENG4112 – EXT S2, 2022

Project Aim: Generate a structural model of a large communication tower to allow the behavior to be studied under various guy wire and antenna configurations. This will inform decisions on the best way to manage the tower deflections and allow the calculation of the structural stability and strength margins when wires are de-tensioned.

Programme: Version 1, 16th March 2022

1. Source and install STRAND7 FEA software on an appropriately configured computer to generate the tower model.
2. Conduct a literature review on the derivation of catenary equations such that a validation tool can be created to assess cable tensions and tower reactions.
3. Using an appropriate computation software, generate a validation tool based on the literature review of catenary equations. It is expected that EXCEL or MATLAB will be suitable to compute the non-linear computations.

4. Generate some basic catenary models in the FEA software to get both accustomed with the software package and ensure the validation tool is producing accurate results.
5. Review original communication tower design to determine the best way in which to model the structure. Generate a separate spreadsheet to provide traceability to the individual element properties within the model.
6. Build a global model of the communication tower such that areas of stress concentration can be evaluated. If required, build localized models of any areas which require further evaluation.
7. Assess model accuracy under simple loadings and use validation tool to build confidence in results. Run more complex loading scenarios to understand stress concentrations, tower deflections and safety margins under various guy wire and antenna configurations.
8. Generate a report summarising results for several different guy wire and array panel configurations.

If time and resource permit:

9. Develop more detailed localized models around stress concentrations and safety margins.
10. Develop data pack for maintenance instruction implementation.

ANNEX B - RESOURCE PLAN

ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

Project Resources

While the dissertation is heavily focused on FEA analysis, there are some fundamental aspects which are required for successful completions. These can be delineated into four groups: hardware, software, datasets and knowledge base.

Hardware

- Currently, the operating system being personally utilised is a macOS. This operating system is not able to support STRAND7 FEA software in a reliable manner, as detailed in the software specification.
- It is possible that I may be able to utilise a workplace supplied device, however on initial investigation it does not seem likely due to both hardening and access restrictions.
- To alleviate this, an additional operating system will be required. A laptop with sufficient processing capabilities will be purchased. There are limited graphic requirements and as I will utilise an external monitor to increase the size of the model, a small laptop with sufficient processing capabilities will be sourced.
- Given the large amount of time that will be spent in front of the computer, the primary workstation will need to be assessed to ensure OH&S factors are mitigated.

Software

- STARND7 FEA software will be required to run the geometric non-linear solvers. This software is not readily available at the workplace due to licencing restrictions, nor easily sourced through the university. Student licences are available from STRAND7, and while they have reduced access, it is mostly related to support functions and not modelling options.
- A three month licence was sourced early in the project and once it was deemed suitable for the Project, a 12 moth subscription was requested and approved.
- To develop a validation tool for the Project, an iterative computational tool is required. MATLAB is able to perform this function, however due as the workplace supervisor did not have ready access to the software, EXCEL was utilised. The actual computations

should be easily managed with the EXCEL solvers and user defined functions, based on the catenary equation derivation.

Data Sets

- Access to the tower design drawings will be critical in developing the tower model. As there are security classifications, only specific and essential data which is relevant to the model will be accessed.
- None of the source data will be able to be utilised in the dissertation report, and a vetting will need to occur prior to submission.

Knowledge base

- As the STRAND7 software has not been utilised, there will be a learning curve to overcome such that the model can be effectively and accurately developed.
- Having access to the both the Project and workplace supervisor will be critical to ensure the work is able to progress in a timely fashion.
- Additional tutoring may also be required.

ANNEX C - RISK MANAGEMENT PLAN

Hazard No.	Project Hazard/Risk Description	Cause or Accident	Hazard Consequence (Accident)	Existing Controls	Existing Probability	Existing Severity	Existing HRI	Additional Controls	Treated Probability	Treated Severity	Treated HRI	Status	Notes
1	Working at desk for extended periods of time	Improper ergonomic setup	Musculoskeletal injury	Nil	OCCASIONAL	MINOR	LOW (18)	Source appropriate seating Wrist support mouse pad Correctly configured workstation Regular standing/stretching everry 15-20mins	REMOTE	MINOR	LOW (19)	Controlled	Will need to source appropriate seating Will need to provide workstation assessment
2	Display monitor too small to clearly view model	Eye strain	Headaches, migrains, mild visual degradation	Nil	OCCASIONAL	MINOR	LOW (18)	Suitably sized monitor Practice eye excercises, changing focal point, moving viual cues, near/far focal points every 15-20 mins Improve lighting in workstation area	REMOTE	MINOR	LOW (19)	Controlled	Will need to access an alternate monitor for the modelling
3	Inability to source and install appropriate software	Software licence limitations	Inability to complete Project	3 month student licences available from STRAND7. No access to Company licences.	CRITICAL	OCCASIONAL	SERIOUS (6)	Source extended 12 Month student liscence from STRAND7.	MAJOR	REMOTE	MEDIUM (14)	Aware	
4	Inability to source and install appropriate software	Computer has insufficient processing power to efficiently process model solvers	Unable to solve non-linear analysis	Existing MAC desktop - software does not run on MAC operating system	CRITICAL	FREQUENT	HIGH (3)	Source laptop with appropriate processing power to run software and use external display to increase screen size	REMOTE	MINOR	LOW (19)	Aware	
5	Inability to source approprate datasets to run models	Access restrictions due to security controls	Unable to get sufficient information to model tower	Current emplyee of Company, data restricted to level of security clearence	REMOTE	MAJOR	MEDIUM (14)	Workplace supervisor to only provide data necessary to model tower	IMPROBABLE	MINOR	LOW (20)	Controlled	Will need to ensure the dissertation paper is vetted by Company to ensure no unintended source data canbe extrapolated from model
6	Failure to be appropriately trained in software tools required for project	Unable to use software effectively	Poor model representation and invalid solutions	Weekly meetings with workplace supervisor to discuss software use and troubleshooting	MAJOR	OCCASIONAL	MEDIUM (11)	Seek additional tutoring	MAJOR	REMOTE	MEDIUM (14)	Aware	No source data is able to be used and tutoring will be specific to STRAND7 functions.
7	Failure to generate basic catenary models	Insufficient knowledge and understanding of the catenary derivation	Unable to generate validation tool Unable to troubleshoot model Unable to understand model outputs	Literature review of various ways in which catenary equations can be derived	MAJOR	OCCASIONAL	MEDIUM (11)	Source math specific tutoring to assist in understanding the various methods in which the equations can be derived	MAJOR	REMOTE	MEDIUM (14)	Aware	
8	Inability to complete the modelling and test accuracy in timely manner leading to project delays	Incomplete knowledge of software Incomplete knowledge of FEA fundamentals	Inability to complete Project	Weekly meetings with workplace supervisor to discuss software use and troubleshooting Monthly collaborative meetings with both project and workplace supervisor	CRITICAL	OCCASIONAL	SERIOUS (6)	Seek additional tutoring Maintain open dialogue with both project and workplace supervisors	MAJOR	REMOTE	MEDIUM (14)	Aware	
9	Breakdown in communications with supervisory team leading to project delays	Conflicting work schedules, loss of motivation, personality differences	Delay in Project outcomes, poor model representation	Weekly meetings with workplace supervisor to discuss software use and troubleshooting Monthly collaborative meetings with both project and workplace supervisor	MAJOR	REMOTE	MEDIUM (14)	Maintain open dialogue with both project and workplace supervisors and ensure issues are documented through the week to discuss at scheduled meetings	MAJOR	IMPROBABLE	MEDIUM (17)	Aware	

Figure 50 - Risk Management Plan

ANNEX D - PROJECT PLAN TIMELINE

Figure 51 details the project plan timeline.

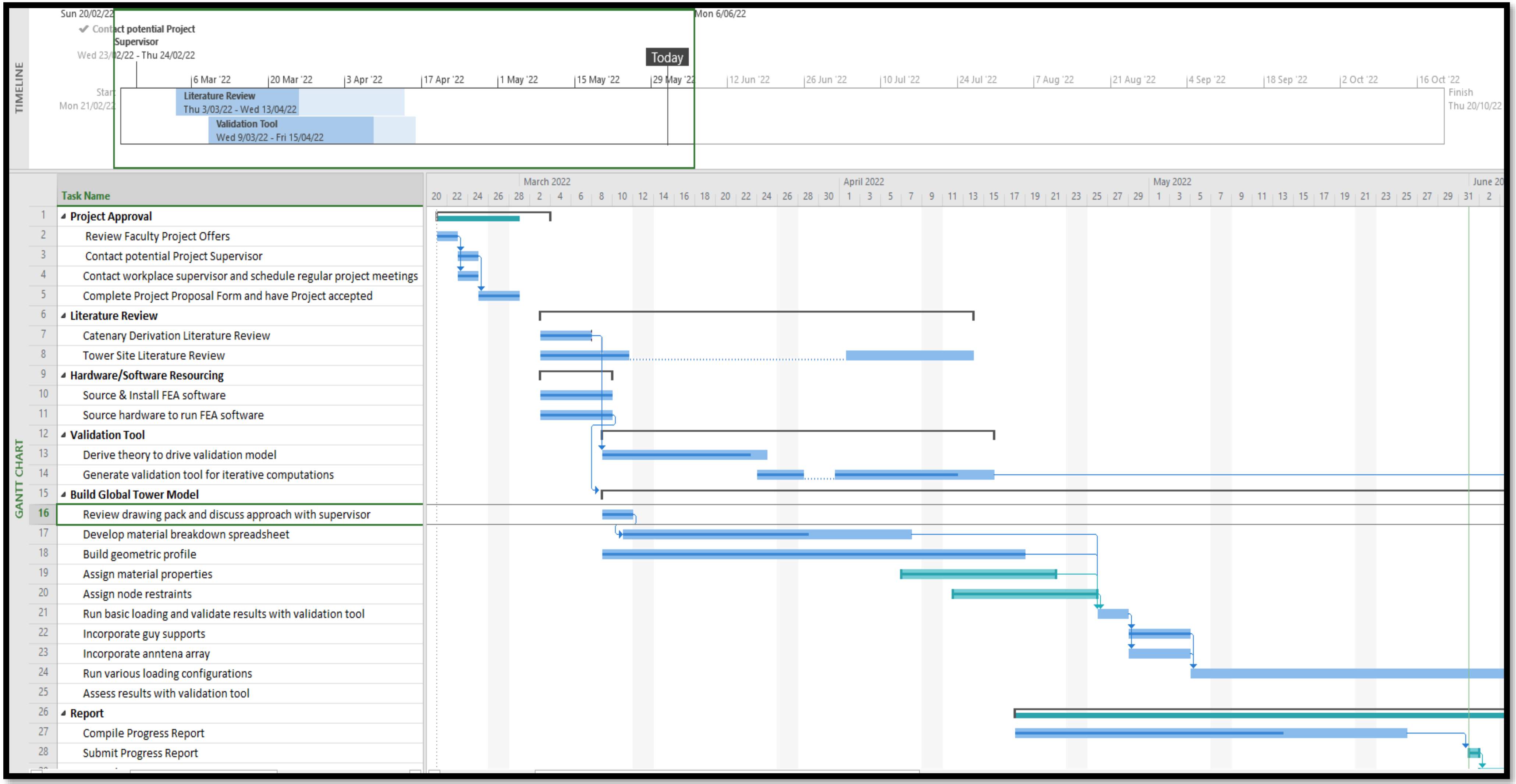

Figure 51 - Project Plan Timeline