

# Mitigating construction risk in the design and planning of high-voltage transmission lines

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## Abstract

**Title:** Mitigating construction risk in the design and planning of high-voltage transmission lines.

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**Keywords:** Construction methods, hazards, risk, quality, prescribed methods.

The Eskom transmission network in South Africa is rapidly expanding with the addition of new power stations such as Medupi, Kusile and multiple independent power producers. The changing grid code requirements to ensure stabilising of the grid in certain areas, and the simple need for expansion to new areas also require expanding the transmission network.

The constructions of these lines come with various risks to personnel, the quality of the end product and the environment that need to be managed from a project management, design engineering and construction point of view. The lines use a combination of structures, some of which are very old and were designed before new high capacity cranes and other similar construction equipment were available.

This study investigates the methods used to construct transmission lines and how the design of new methods with new technology can positively impact the end product. It focuses on the erection of galvanised lattice steel structures, although other processes such as foundations and stringing are mentioned.

The new method of erection of the cross-rope structure type with two cranes was tested on a construction site. The method of erection with the use of a spreader bar was tested at the Eskom structure test centre in Rosherville. Both tests were completed successfully. The method of erecting the self-supporting suspension structure in fewer lifts was tested on site but needs modifications to the structure to mitigate some construction risks. The erection of the guyed-V structure type with the hardware and insulators was tested on a construction site and was also completed successfully.

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## List of abbreviations

CAD	Computer aided design
CIGRE	International Council on Large Electric Systems
DC	Direct current
AC	Alternating current
EVKOM	Elektrisiteitsvoorsieningskommissie
ESCOM	Electricity Supply Commission
POLASA	Power Line Association of South Africa
VFP	Victoria Falls Power
UR	Unit risk
CR	Cumulative risk

## Nomenclature

$e$	Exposure / duration of time spent with hazard
$f$	Frequency of occurrence of exposure
$s$	Severity / outcome such as fatality etc.
L	Inductance
C	Shunt capacitance
R	Resistance
$I_R$	Current on receiving end
$I_S$	Current on sending end
$P_L$	Steady state stability power limit
$V_S$	Voltage over sending end
$V_R$	Voltage over receiving end
Km	Kilometer
kV	Kilovolt
m	Meter
\$	Dollar

## **Chapter 1. Introduction**

### **1.1. The history of Eskom**

Eskom was established in 1923 as ESCOM (Electricity supply commission) or EVKOM (Elektrisiteitsvoorsieningskommissie). The two acronyms were combined in 1986 into Eskom by which the company is still known today.

It was preceded by the Victoria Falls Power Company (VFP) and Transvaal Power Company (formed in 1906) which proposed generating power at the Victoria Falls and supplying the Witwatersrand. VFP took over Rand Central Electric Works and the General Electric Power Company in 1907 with power stations in Brakpan and Driehoek. VFP was the first company to offer to supply electricity to the general public [1].

The first transmission lines were built before the First World War to interconnect the VFP power stations. They consisted of 42 kV overhead lines from Brakpan via Hercules, Simmerpan, Rosherville and Robinson (Johannesburg) to Bantjies, and two double circuit 80 kV lines to connect Vereeniging power station to Robinson (Johannesburg) [1].

Eskom's transmission network (275 kV & 400 kV) consisted of 2775 km in 1967 [1]. Today the network consists of nearly 40 000 km of overhead lines (275 kV, 400 kV and 765 kV and 533 kV DC) which can be seen in Figure 1, as well as proposed future transmission lines.

Eskom is currently the largest power producer in Africa and operates a number of coal fired power stations, as well as a nuclear power plant and generates 95% of the electricity used in South Africa [2].

The demand for power in South Africa is more than the capacity and therefore Eskom needs to make use of load shedding to balance the capacity and demand. This is done by interrupting the supply to certain areas for a specified time while all other areas' power demand is met, and then changing the disruption to a different area according to a planned schedule [3]. Further to the new grid code requirements and the need to integrate new substations, independent power producers and power stations into the network, it creates a need for 7610 km of transmission lines to be built between 2013 and 2017 [4].

## 1.2. The generation of electricity

Figure 1 shows the South African transmission line grid with the major power stations and possible future expansions.

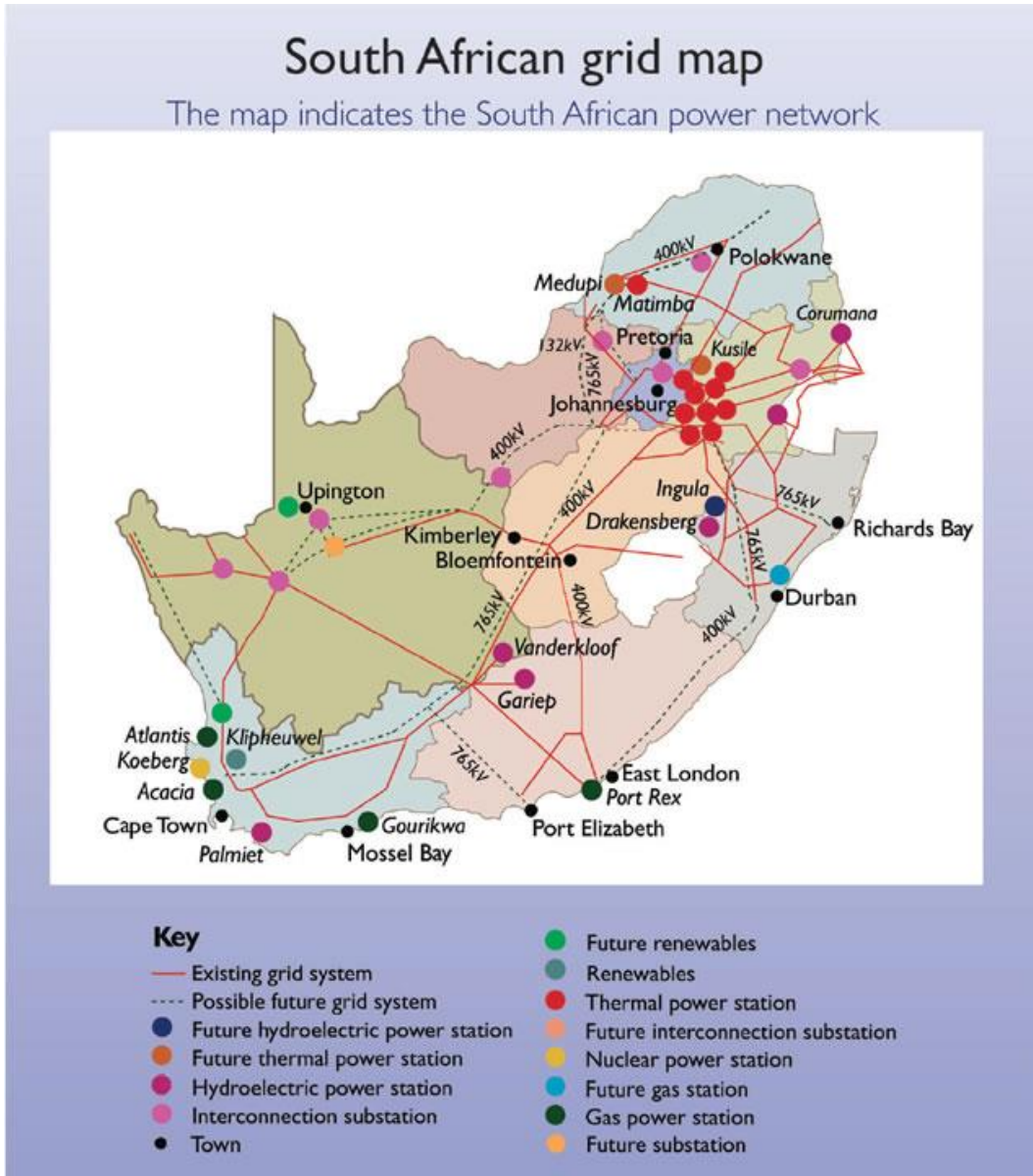


Figure 1: South African grid map

## 1.3. Electric-power transmission lines

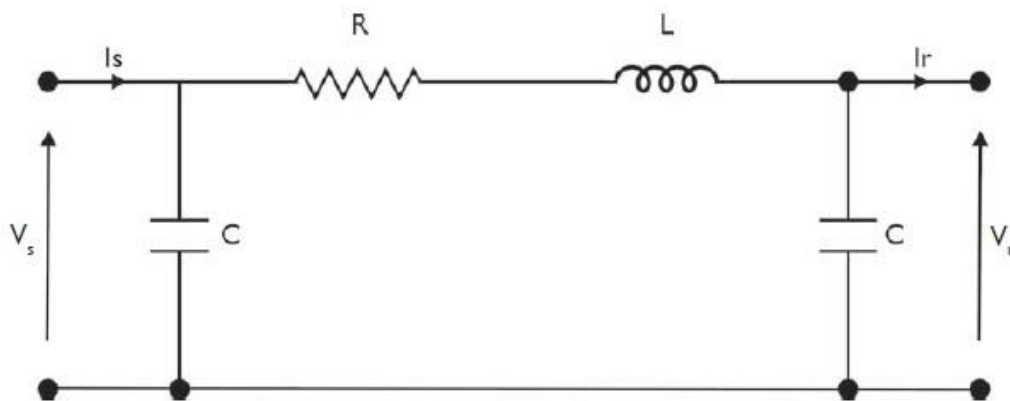
An electric-power transmission line is an overhead conductor or bundled conductors supported by structures (usually lattice steel or tubular steel or steel monopole structures) used to transfer

large amounts of power between two points such as a power station and a substation or even between two substations [5], [6].

The first three phase line was a 179 km line built in Germany in 1891 and since then has become an integral part of all countries' infrastructure. Electricity has become an integral part of everyone's daily life and a requirement for all industries to grow.

To understand how a power line works and why it consists of the components it has, one first has to look at some basic electric concepts.

Figure 2 shows a simplified nominal Pi circuit (single phase representation) which assumes that balanced conditions for a three phase line pertains and the series resistance and inductance, as well as the shunt capacitance can be calculated from this [5].  $V_R$  is the load end and  $V_S$  is the sending end [6].



**Figure 2 : Circuit representing an overhead power line**

The maximum power that a line can transmit is given by Equation 1:

**Equation 1: Power limit of a transmission line**

$$P_L = \frac{V_S V_R}{X}$$

$X$  is the series reactance and is normally much larger than the series resistance.  $P_L$  is known as the steady-state stability.

The equation tells us that the power that can be transmitted is proportional to the product of the sending- and receiving-end voltages [6] and since these are usually similar, the power limit is proportional to the square of the operating voltage. This is why a higher voltage line is used to

transmit more power. If the operating voltage of a line is doubled, the increase in the power transfer is close to fourfold [5].

The increase in voltage requires more insulation and wider servitudes but building a bigger line with a higher voltage is normally cheaper than building a lot of smaller lines in parallel.

The power that can be transmitted is inversely proportional to the series resistance, and hence the length of the line. The geometry of the conductor bundles, the phase separation and the length of the line dictates the resistance [5].

It can therefore be seen that to design and construct a transmission line structure it is important to understand the electrical influences that is imparted on the structures such as the insulation requirements, electrical clearances, bundle size, phase spacing etc. The power transfer that a transmission line is designed for dictates what voltage of line will be used and what conductor will be used, as well as in what spacing, which in turn dictates why a transmission line and structure looks the way it does.

## **1.4. Main features of transmission lines**

### **1.4.1. Composition**

Transmission lines consist of only four main components; foundations, supports (wooden poles, lattice steel structures, bolts and guy supports and fittings), as well as insulators (insulators, hardware and fittings), conductors and earth wires [7].

### **1.4.2. Foundations**

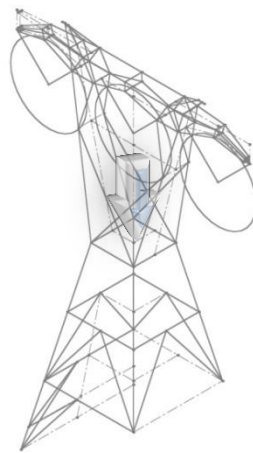
Foundations are designed by a civil engineer and depend on the type of structure (suspension, strain, guyed etc.), the allowable soils, and the types of foundations allowed for (drilled piles, cast pad and pier, rock anchors etc.) [8].

### **1.4.3. Lattice steel structures**

After the foundations are installed and allowed to cure, the galvanised lattice structures [9] are assembled in sections in a planned layout around the foundations. The different sections are then lifted to their positions and joined by climbers to form the final structure [8]. At the bend points of the line, the tension in the conductor requires a very heavy and strong tower to combat the forces applied transversely to the line direction, while at very regular points along the line suspension structures are required to restrict the sag of the line (keep the conductor off the ground).

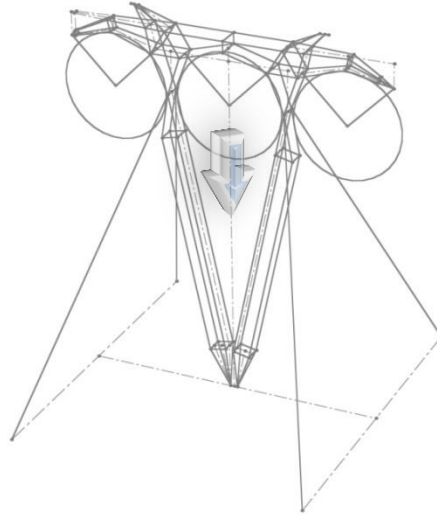
Both the angle-strain and suspension structures can be guyed structures or self-supporting structures depending on the site restrictions, type of conductor, size of line deviation, etc.

The following illustration of a self-supporting suspension structure [Figure 3] shows the four legs of the structure, giving it a very small footprint, as well as the possibility of being used on inclined terrain with leg extensions. It also illustrates the three “V” shapes which indicate the position of the insulator and hardware assemblies holding the conductors in place, and the circles show the electrical clearance required around the conductor bundle (phase-to-ground clearance requirement).



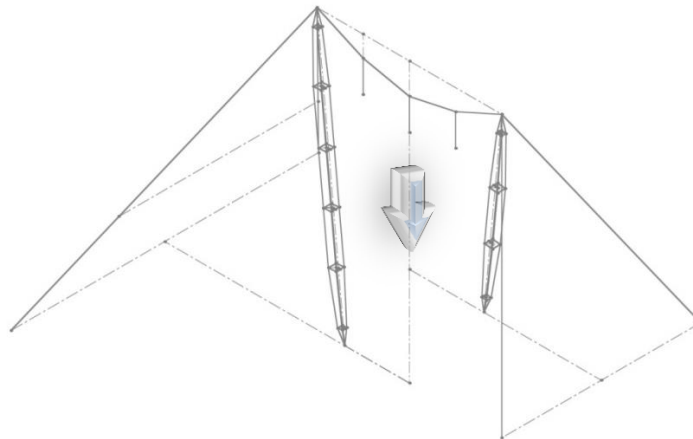
**Figure 3: Self-supporting suspension structure**

The guyed-V suspension structure [Figure 4] has a beam similar to that of the self-supporting suspension structure but it is supported simply by two masts held upright with guy ropes. It can be seen that this is therefore an improvement on the self-supporting structure as it uses less steel. It can however, only be used on flat terrain (slopes of less than 15 degrees). It is erected as a single unit and dressed similarly to the self-supporting structure.



**Figure 4: Guyed-V suspension structure**

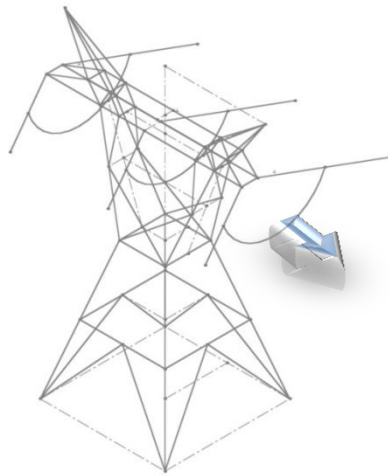
The guyed cross-rope suspension structure in the figure below [Figure 5] shows two masts supported by four guy wires with a service rope in between. The three hardware suspension assemblies hang from a service rope suspended between the masts. The mast length can be changed according to the slope of the ground and the length of the guy wires changed accordingly which makes this a forgiving structure while still being light weight and therefore a further improvement on the guyed-V structure.



**Figure 5 : Guyed cross-rope suspension structure**

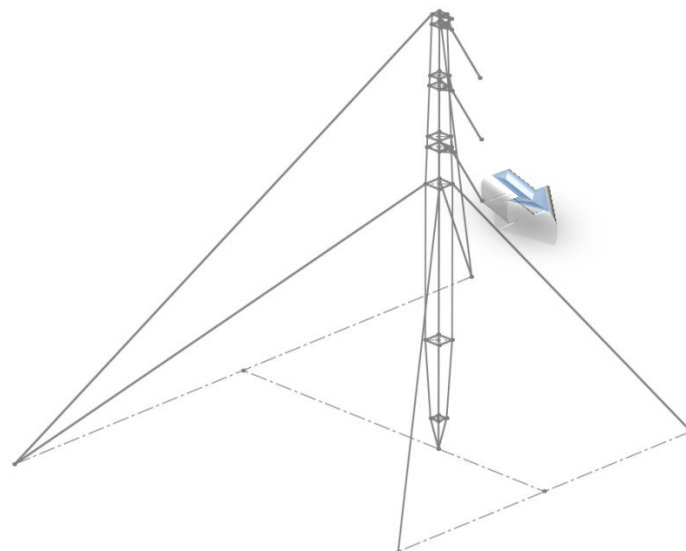
The self-supporting strain structure shown in the figure below [Figure 6] is used at points where the line makes an angle. The figure shows horizontal lines attached to the beam of the structure, which illustrates the attachment of the conductors and insulator assemblies which create a horizontal force on the beam. The circular bows show the jumpers connecting the conductors on

both sides. The arrow shows the direction of the resultant transverse force on the structure caused by the tension in the conductor.



**Figure 6 : Self-supporting strain structure**

A guyed strain structure is designed to accommodate a very specific load in a specific direction and can therefore only be used at specific angles (and not in a line for instance). The single-mast guyed strain structure (Figure 7) is designed to be used where a line makes a bend of roughly  $30^\circ$  and uses a light conductor. It is a single mast with four guy wires on one side which will be kept in tension by the force of the conductor acting on the opposite side and the mast is therefore in compression and keeping the conductors off the ground.



**Figure 7: Guyed single-mast strain structure**

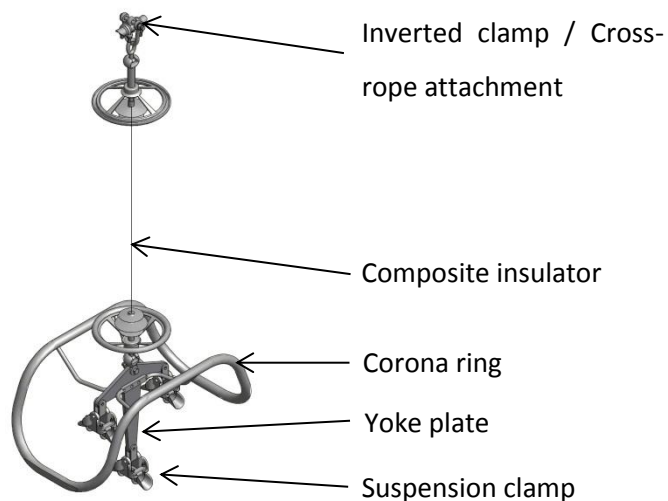
Other structures are available but are not used frequently as they can only be used in very specific conditions, such as small deviation angles and flat profiles, or are only required in very difficult terrain or for the purpose of a phase transposition.

#### 1.4.4. Insulators and hardware assemblies

The structures are then “dressed” by lifting and attaching hardware assemblies consisting of various shackles, clevis- and tongue fittings and insulators (composite or glass) to the various attachment points on the structures depending on the structure type and design. Running blocks are attached to the bottom of this through which the conductors can freely run during the stringing process.

The suspension assembly [Figure 8] consists of an inverted suspension clamp (for attaching to a cross-rope at the top) or a shackle for attaching to a self-supporting structure, an insulator which separates this from the live end which has a yoke plate which spaces the conductor bundle as designed.

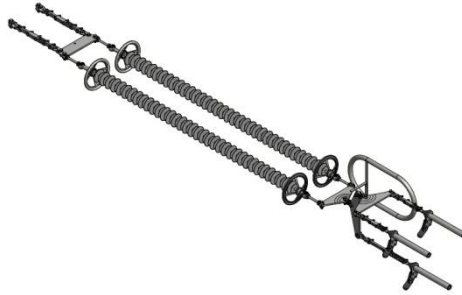
It holds the suspension clamps for clamping in of the conductor and it also holds a large corona ring. The load capacity of the components is much lower than the strain assembly as it only has to hold the weight of the conductors.



**Figure 8: Suspension assembly for three conductors**

The normal strain assembly [Figure 9] has a dead and a live end. The dead end has shackles to attach to the tower and a spacing yoke plate to space the insulators apart, as well as adjustable links to allow for the angle of the incoming conductors. It then has insulators to separate the live

end from the dead end. It further comprises of a yoke plate to space the insulators similarly as to the dead end which also spaces the conductor bundle as designed and the conductor attachment is completed with crimped fittings. It also holds a corona ring.



**Figure 9: Strain assembly for three conductors**

#### **1.4.5. Ground wires and conductors**

After allowing a time of 3 – 4 weeks (depending on MPa rating achieved in cube tests) for the foundations to cure [10], the conductors are strung into place by first pulling a pilot cable through the running blocks that have been “dressed” onto the structures. A conductor station is then set up with conductor drums with 2000m to 3000m lengths on drums fed through a bull-wheel tensioner and onto a running board attached to the pilot cable. The pilot cable is then pulled by a hydraulic tensioner on the other end of the stringing section which pulls the conductor, under tension (and off the ground), through all the running blocks until it reaches the puller station.

When this process is complete, the conductor is sagged to ensure the correct tension in the conductor by checking the conductor temperature (with a thermometer) and checking the required sag provided by the design engineer (or profiler) on a sag-and-tension chart for the corresponding temperature and sag; and measuring the sag with a theodolite. The conductor is then taken out of the running blocks and clamped into the towers’ hardware. Suspension towers have either “I” or “V” assemblies which describes the shape made by the hanging insulators. Strain structures have strain assemblies where the tension in the conductors places the insulators in a permanent horizontal position to which the conductors are attached with a crimped dead-end fitting.

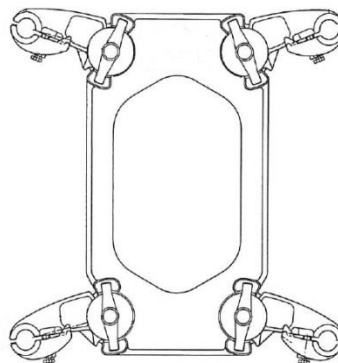
***Vibration dampers, spacer dampers and spacers***

Following the regulating of the conductors, the tension in the conductors make them prone to damage by Aeolian vibration which is a wind induced fatigue damage. Wind with speeds between 3 – 10 km/h causes the conductor to vibrate with amplitude of 1 – 2 times the conductor diameter. This causes fatigue damage to the aluminium strands of the conductor [Figure 10].



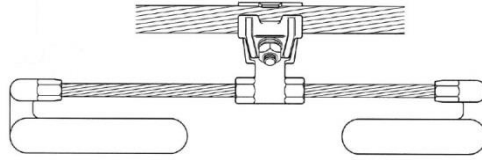
**Figure 10: Fatigue damage to aluminium conductor strands**

Spacer dampers [Figure 11] are installed at strategic points throughout a span to maintain the sub-conductor spacing, as well as to dampen the vibration. It consists of an aluminium body, rubber dampers and aluminium clamps which clamp to the conductors and space the bundle throughout the span.



**Figure 11: Spacer damper**

A vibration damper is used to minimise the vibration on single conductors or earth wires. [Figure 12].



**Figure 12: Vibration damper**

The vibration damper has a clamp to attach to the conductor and a steel wire to hold two weights to dampen the vibration. The attachment to the wire is offset from the middle to cater for a larger range of vibration frequencies.

### **1.5. The life of a transmission line**

Over the lifespan of a transmission line it will be exposed to all the elements which place great strain on the structure and will cause it to lose strength over time as the steel corrodes (stubs, rebar, structural steel, conductor steel core, hardware, etc) [9].

The structures therefore need to be designed to accommodate the additional loading of strong wind on the structure steel and conductors, as well as thick ice that builds up around the conductors increasing the weight [11] while it is ageing. Although these specifications take additional loading on structures during stringing activities into account, it does not allow for deviation from the design when looking at other details such as if joints on a structure are assembled incorrectly but cannot be properly inspected by a supervisor as he cannot climb the structure.

### **1.6. Design, construction and the role of the designer**

According to J. Wang and M. Roush risk is defined as, “a measure of the probability of occurrence of an incident and the severity of an adverse consequence that results from an exposure to a hazard” [12].

Quantifying risk is an important aspect of construction for the purpose of allocation resources [13]. If we allocate more resources to a part of the construction which has more risk, whether it be for a change of the design or for increased temporary safety measures to help mitigate risk during construction, we can reduce the risk to predetermined levels.

In the design of a transmission line, it is crucial to recognise at an early stage that there is a very narrow relationship between the design and construction. In general terms, the design of a transmission line is a description of parameters which will ultimately lead to satisfaction of the user's requirements, normally with a design specification [14] as the main part of the output, which, as Mark Kalin puts it, "was sufficient for the construction of Noah's Ark". Design for construction/constructability however, requires to a further degree that the designer looks at the physical activities, resources and equipment required to make the design a reality.

Each structure of a transmission line will be subjected to site specific conditions and hazards which will influence its construction. These include environmental constraints, labour practices etc. [15] Some environmental constraints even continue to travel and are seen at each site, such as poor labour practices where untrained labourers make mistakes during assembly or erection of structures and see it as "unimportant" or "not having a big influence" on the end product [16]. Some of these can be eliminated with good quality control and supervision on site but not all these practices can be eliminated and some of these will be looked at in more detail in Chapter 2.

An engineer's design can ultimately never take all hazards into account as it will be subject to changing site specific conditions which could change during the lifespan of the structure. A transmission line structure, for example, may also collapse 40 years after construction because of an unforeseen increase in the load that it was designed for. To design for such changes is very difficult however, it remains the responsibility of the engineer to design for unforeseen hazards with foresight and an intimate knowledge of the construction of his design, as well as the conditions that it will be used in [12] [17]. Planning with foresight, by doing a site inspection of the conditions in which a design will be built, is necessary for the designer to achieve a quality product, constructed to schedule with as little as possible damage to the environment [18].

According to the construction regulations [19], the responsibility of the designer is to:

- Inform the contractor of any known hazards / risks.
- Inform the contractor of the loading which the structure is designed to withstand.
- Give the contractor the method and sequence of construction.
- Carry out sufficient inspections during construction.

From these requirements the role of the designer before, during and with completion of construction (commissioning) is set out more clearly. The detailed extract of the construction regulations is given in Appendix A.

While the transmission line designer can design to all codes and practices, if the design is not built according to specification it will not conform to these design standards. The design engineer should therefore at an early stage in a project life cycle conduct a site inspection to familiarise himself with site specific conditions which will have an impact on his design, as well as the practical construction thereof. Along with this he must consider the equipment required for construction, and how the method of construction might impact on his design [20].

A practical example of this is for instance to have a design requirement to build a transmission line over mountainous terrain. When conducting a site specific investigation the designer might learn that there is no way to access structure locations by any other means than by foot or by helicopter. If the designer then designs the line but uses structural members in the structures which weigh more than 3.5 tons (weight limit of helicopters currently available in South Africa), the material will not be able to be flown to the structure locations and the design will not be practically feasible. The designer must therefore have an up-to-date knowledge of the equipment, materials, site specific hazards etc. which will impact the practical application of making his design a reality.

There are a few aspects in the practical application of a designer's design which, if overlooked, could have a major impact on the strength of his design and on the safety of the people doing the construction or even the odds of an accident happening during construction. These include, but are not limited to; incorrect bolts used and assembly thereof, incorrect assembly of structures, incorrect installation of guy anchors, use of incorrect tools during construction, incorrect sequencing of events and methods etc.

### **1.7. Need for study / new construction methods**

It is clear that the method of construction of transmission lines have an impact on the quality of the end product, the risk to the construction personnel and the environment, as well as the cost of construction, and that proper planning and investigation of site conditions can minimise these impacts [18].

The construction of foundations is however, a lot less of a risky operation as seen in previous years. It has proven test procedures that ensures its conformance to design, it is in the ground and can safely be inspected, and will therefore not form part of this study. Similarly, the process and tools used to string conductors (if the conductor is tension strung which is a requirement in South Africa) has not changed for many years and therefore the risk involved in this cannot be

greatly reduced because the process cannot be changed. This study will therefore focus only on the process of construction of transmission line structures in South Africa, although it will mention these other processes as it forms part of the transmission line construction process.

Over the years of transmission line structure development, the risk involved in structures have caused designers to develop structures that are supposed to be lighter, stronger and at the same time easier to construct, and have less impact on the environment such as the guyed cross-rope suspension structure. During this time, construction equipment has also evolved and cranes which are now more mobile are able to lift heavier loads. The method of construction has not evolved together with the structures and machines but has become stagnant a long time ago as will be shown in Chapter 2.

During a discussion with POLASA (Power Line Association of South Africa) [4] at an Eskom technology steering committee meeting, it was agreed that there is a need for standardisation of the methods of line construction with the benefits of:

- Detailed risk assessment of every method and mitigation measures during construction.
- Accurate documenting of methods with reasons for changes and change registers. The methods can then be documented on a central database to ensure access for all interested parties to the information.
- Setting up of a training syllabus with a training facility once the methods have been standardised and shown to be effective on site.

At the CIGRE international symposium held in Cape Town in October 2015 on “Development of Electricity Infrastructure in Sub-Saharan Africa”, Session 9, Paper 96 – “Standardized construction methods for overhead transmission lines – C.J. Henderson” was presented. Feedback from this was that partnerships should be created where information on construction methods can be shared freely and where future methods of construction can be discussed.

## 1.8. Objectives

The objectives of the study are to find the method of construction of transmission line structures that delivers the best quality end product, is the safest to build and impacts least on the environment and thereafter, facilitate efficient communication of this with the ultimate end user (contractor, subcontractor etc.) [14].

Questions that need to be looked at are:

- Is it possible to minimise the hazards and risks of accidents, as well as ensure compliance to design by specifying appropriate construction methods?
- How should the construction methods be prescribed?
- How do site conditions influence construction (and the prescribed methods)?
- What hazards will be minimised? (Hazards to the quality of the end product, personnel etc)
- What fundamental design aspects can be affected during construction and how is it affected?
- How will the prescribed methods be checked if it delivers a better product (conforms better to design, less risk, less impact on environment etc)?

To do this it is necessary to:

- Investigate the construction methods of structures that are currently used (through a comprehensive literature for abroad cases and site visit records for local practices) and have been used in the past, what has changed and how this impacts on factors such as safety, quality and the environment.
- Quantify risk of accident during construction through examples.
- Properly define what hazards affect transmission structure design, with the focus on structures and show how the design is affected with measurable quantities.
- Identify possible new methods of construction that will reduce risk during construction and hazards to the design as defined. Investigate new tools and techniques used locally and internationally.
- Test the methods in the field.

## Chapter 2. Construction methods and hazards

### 2.1. Introduction

At a very early stage in infrastructure development, in the 1940's, there were considerably less tools available to the designer. He did not have powerful computers with cad modelling applications, and powerful and mobile off-road cranes did not exist. However, the designer had to design a structure that was physically constructible with the tools that were available [21]. He had to test this structure to check its conformance and capability. He had to then survey the land by hand and profile his structure (also by hand) into the line. During all this time he was forced to have an intimate knowledge of the structure and the terrain it will be used in.

Years down the line in 1978, transmission lines in Russia were constructed with the use of bulldozers, diggers and cranes [22], but without the design of lattice transmission line structures, themselves changing a lot (still remained self-supporting structures). The construction process has adopted some of the new tools that are available and changed the methods and processes to construct transmission lines slightly, but the designer has not looked at how this will affect his design.

From the late 1930's up to now, changes in technology such as LiDAR scanning of servitudes, highly mobile off-road cranes, PLS Cadd modelling, etc. have only added to ease of design and the safe construction of transmission lines without impacting or changing the design of structures. If the design of a structure was changed to allow for the mobile crane, one would expect to see structures assembled in specific modules of specific weights depending on their attachment height which would fit comfortably into a loading chart of a crane. Instead what happened was that the construction was originally done by lifting members or small groups of members into position with a Derek crane, and this was adapted by contractors. As time went by, the size and capacity of the mobile crane increased due to the size and groups of members getting larger.

These changes in the construction method, without the changes to the design, have created a risk that the ultimate end product will not conform to the design specifications.

As technology progresses in future, the construction of lines so too must change and adapt to ensure that it is done as close as possible to the required specification, as well as doing it as safely as possible.

The main goal from an engineering perspective is to minimise hazards to the successful implementation of a design. If an engineer would for instance design a bridge but the hazards against its design were not minimised, it would put all users of that bridge at risk.

Secondly, there might be hazards to the construction personnel which are “less of a problem” as it is only temporary and can be mitigated by applying temporary measures during construction such as scaffolding or similar temporary bracing, using special tools instead of putting workers at risk, using climbing gear etc [23]. Since the implementation of the guyed cross-rope suspension structure, there have been eleven fatalities during the structure erection and dressing processes recorded in Eskom, and three fatalities during the clamping in of the conductors. These hazards should be highlighted to the contractor so that he can apply temporary measures to mitigate these hazards. Temporary injury prevention techniques have shown to be very effective although some are quite costly [13]. These hazards combined with the record of fatalities has brought the design of the guyed cross-rope suspension structure under scrutiny and put the future use of the structure in jeopardy.

Thirdly, there might be other hazards which are site specific such as environmental hazards, labour practices, weather related hazards which could all influence the construction, as well as the design. If the designer knew that the structure had to be built in a highly corrosive area, they would design it to have thicker galvanising, or if it had to be built in an area where it was subject to member theft, it would be designed with special anti-theft measures built in.

## **2.2. Understanding risk**

### **2.2.1. Risk perception**

Are certain structures more dangerous to use than others? It is certainly perceived as such by many. Is it justified though? Are there negative incidences happening more often than we would expect, by chance, which should make us single out a specific structure for special attention [24]? Could this be because of some critical fundamental design flaw, or maybe because of a flawed method of construction?

The cross-rope suspension structure is definitely perceived as dangerous and it might be because there certainly have been more incidents involving cross-rope structures than any other structure. The reason for this is purely because of the fact that there are more suspension structures than strain structures.

Richard Dawkins explained this by explaining the concept of Murphy's law which states that "if something can go wrong, it will." This would mean that if an incident would happen involving a cross-rope structure, someone might perceive this as being the fault of the design of the cross-rope purely because of their bias in their likelihood of noticing annoyance. The fact remains that incidents happen all the time and on all types of structures, we just notice them more often when they are an annoyance [24] and this will happen more often when the structure is used more often.

Perhaps a simpler way of explaining this would be; if you put up a cross-rope structure, the more strongly you do not want to see an incident, the more likely you are to notice it if it happens.

We however, know that the cross-rope structure is not more prone to incidents happening on it than any other structure and further to this that the design is not faulted. We know this because the structure was designed and modelled in a CAD environment and then tested to confirm its design compliance. We also know that thousands of these structures have successfully and safely been erected and are working perfectly and performing as designed.

This being said, something similar to Murphy's law is true and worth investigating although it is a concept which is much easier explained on living creatures, and that is the concept of natural selection as described by Charles Darwin. Darwin explained natural selection as a mechanism of evolution by which a creature that evolves to avoid predators better than other individuals of the same species is more likely to survive. A rabbit that runs faster than others will less likely be caught. Similarly, a fox running faster than other foxes will less likely starve.

An animal which is constantly alert as if Murphy's law was true would therefore have a better chance at survival [24].

Although a structure of a transmission line is not a living evolving creature in itself, we as its designers are constantly trying to improve on its design and therefore it is in a sense evolving. We can clearly see this by looking at the different types of structures that have existed and which have been used over the years, and also the ones which "die" off because they are too old to be used or have proved to be too dangerous because of incidents happening during their construction. The main hazards to the design as identified (bolts, steel plates in shears etc.) have been minimised over the years through new designs without this even being the main objective behind the design simply due to the fact that the more modern structures are designed to use less steel to reduce cost.

In doing so, we also reduced the number of processes to erect a structure from about ten to thirteen lifts for a self-supporting suspension structure (many years ago it was the only suspension structure available), to two for a guyed cross-rope suspension structure (currently the most widely used suspension structure) which can be reduced even further to one lift with the use of two cranes or a spreader bar.

### 2.2.2. Risk quantification

Research has shown that risk is a function of a frequency of incidents, severity of injury and exposure duration [25] [26] [27] as shown in Equation 2.

#### Equation 2: Relationship between the components of unit risk

$$UR = f \times s \times e$$

UR is unit risk measured in \$,  $f$  is frequency measured in injuries per year,  $s$  is severity measured in \$ per injury [12].

#### Equation 3: Cumulative risk

$$CR = \sum UR = \sum f \times s \times e$$

Where CR is cumulative risk measured in \$ per year and  $e$  is exposure duration measured in work hours (w h).

Three measurable quantities are present in the above equation:

- Frequency ( $f$ ) is the occurrence of making contact with a hazard per usage.
- Severity ( $s$ ) is the outcome such as fatalities, injuries, lost time etc. in dollars.
- Exposure ( $e$ ) is the duration of time spent with the hazard in work hours.

If an assumption is made that a straight line of 80 km in length needs to be built (typical expectancy for a trusted contractor), and that 80% of the structures used will be guyed cross-rope suspension structures with spans of 400m (purely for the purpose of comparing two or three different methods of construction for the same structure), then 160 structures need to be erected for the line.

**Table 1: Example of quantifying risk for structure erection**

What goes wrong?	How likely?	Exposure?	Severity / Consequence?
Lifting tackle fails	0.0001 times per use	320 times per year	2 fatalities (\$100 000)
Crane breaks	0.003 times per use	320 times per year	Loss of time (\$10 000)
Weather delays	0.015 times per construction event	160 times per year	Loss of time (\$1000)
Winch causes collapse of hardware during dressing	0.001 times per use	160 times per year	2 fatalities (\$100 000)
Temporary stay collapses	0.0001 times per use	160 times per year	1 fatality (\$50 000)
Bolts not tightened causes part of structure to collapse	0.0025 times per event	320 times per year	1 serious injury (\$20 000)
Worker falls from structure	0.001 times per climb	1280 times per year	1 fatality (\$100 000)
Tools fall on worker from structure	0.01 times per climb	1280 times per year	1 injury (\$10 000)

If a cross-rope structure requires one temporary backstay during erection, and two lifts to complete, then:

**Equation 4: Risk as a result of erecting a guyed cross-rope suspension structure with the current method**

$$\begin{aligned}
 UR &= (0.0001 \times 320 \times 100,000) + (0.003 \times 320 \times 10,000) + (0.015 \times 160 \times 1000) \\
 &\quad + (0.001 \times 160 \times 100,000) + (0.0001 \times 160 \times 50,000) \\
 &\quad + (0.0025 \times 320 \times 20,000) + (0.001 \times 1280 \times 100,000) \\
 &\quad + (0.01 \times 1280 \times 10,000) \\
 &= \$304,000.00 \text{ per year}
 \end{aligned}$$

It can therefore be seen that the unit risk (projected) is \$304,000.00 per year. If one were to change the method of erection of a cross-rope structure to use only one lift and to cut out the entire dressing procedure, by for instance using a spreader bar, the exposure to the hazard will reduce for lifting tackle failures, crane breakages, winch failures, temporary stay collapses, workers falling from the structure and tools falling from the structure.

Table 1 will change and then look as follows:

**Table 2: Revised example of quantifying risk for structure erection**

What goes wrong?	How likely?	Exposure?	Severity / Consequence?
Lifting tackle fails	0.0001 times per use	160 times per year	2 fatalities (\$100 000)
Crane breaks	0.003 times per use	160 times per year	Loss of time (\$10 000)
Weather delays	0.015 times per construction event	160 times per year	Loss of time (\$1000)
Winch causes collapse of hardware during dressing	0.001 times per use	0 times per year	2 fatalities (\$100 000)
Temporary stay collapses	0.0001 times per use	0 times per year	1 fatality (\$50 000)
Bolts not tightened causes part of structure to collapse	0.0025 times per event	160 times per year	1 serious injury (\$20 000)
Worker falls from structure	0.001 times per climb	640 times per year	1 fatality (\$100 000)
Tools fall on worker from structure	0.01 times per climb	640 times per year	1 injury (\$10 000)

The risk is then calculated similarly as in Equation 4.

**Equation 5: Risk as a result of erecting a guyed cross-rope suspension structure with one crane and a spreader beam**

$$\begin{aligned}
 UR = & (0.0001 \times 160 \times 100,000) + (0.003 \times 160 \times 10,000) + (0.015 \times 160 \times 1000) \\
 & + (0.001 \times 0 \times 100,000) + (0.0001 \times 0 \times 50,000) \\
 & + (0.0025 \times 160 \times 20,000) + (0.001 \times 640 \times 100,000) \\
 & + (0.01 \times 640 \times 10,000)
 \end{aligned}$$

= \$144,800.00 per year

It can therefore be seen that the risk has been reduced by 52.36% by only using a spreader bar to lift the cross-rope structure with the hardware assemblies as a single lift. If further to this, other methods are developed to erect self-supporting structures or erect the structure with the hardware assemblies attached, it will further reduce the risk of the construction of transmission line structures.

There are however, still 'unforeseen' events for which no amount of engineering can help.

### **2.3. What is an accident?**

An accident is an unplanned and unforeseen event with a negative outcome and kills an estimated 2.3 million people every year [28]. The rate of occupational fatalities in the construction sector in some countries is 4 to 5 times that in the manufacturing sector. The reason for this being that the workforce is unskilled and sub-contracted workers from outside urban areas with a low education level are employed. The work environment changes frequently and they receive little training [29].

These factors (such as a changing environment) make training difficult. The fact that to erect structures is a labour intensive job but requires relatively uneducated staff, further increases the danger of accidents on site. If the methods of construction are not clearly specified, changes to the method will be made by each contractor and will create a further changing environment, increasing the risk of accidents.

### **2.4. Hazards in construction**

#### **2.4.1. Defining a hazard**

A hazard is everything that impacts negatively on a design. Although it appears straightforward, there are quite a few hazards on site which can impact on various aspects of a design's feasibility. To investigate some of these further one has to differentiate between the different types of hazards; hazards to the design, hazards to the construction personnel, and other hazards such as hazards to the environment etc. as well as when the construction is taking place.

In this chapter the discussion surrounds three main categories of hazards:

- Hazards to the design,
- Hazards to the construction personnel, and
- Hazards to the environment.

### **2.4.2. Hazards to the design**

A transmission line structure consists of only a few elements: bolts, lattice steel and in some cases guy wires; or in the case of monopole structures: bolts, cold-bended steel and welds and in some cases guy wires. A hazard to the common lattice steel structure will therefore only be found in the bolts (such as a bolt that has a manufacturing defect in it or more likely a bolt that is used incorrectly and therefore will not perform as it was intended by the designer), or a steel defect, or wrong assembly of a structure joint.

Hazards in the lattice steel will also be steel that is supplied with a manufacturing defect (defect in the forming at the steel mills before being supplied to the transmission structure manufacturer) in it and therefore does not conform to the designer's specification. Defects in the transmission structure manufacturing such as punched or drilled holes that are taper, skew flanges, link plates with holes drilled incorrectly causing overturning moments in joints etc. will also be a hazard.

Another hazard is a defect in guy wires. Up to 80% of structures used on 400 kV and 765 kV lines use guy wires and service ropes which form a critical part of the strength of the structure. The incorrect use of guy wires can lead to damage of the guy wire or overloading of the structure.

Another hazard includes handling of materials causing damage, such as wrong handling of composite insulators which could jeopardise its strength.

### **2.4.3. Hazards to the construction personnel**

Mechanical hazards to the construction personnel include failure of lifting tackle causing falling of heavy loads, wrongful interpretation of the lifting charts of a crane causing overloading of a crane, or incompetent signalling causing clashing of a lift with a stationary part of a structure. Loose members of a structural piece which is being lifted cause partial collapse of that piece which is extremely hazardous.

Special tools that have caused great concern and are used frequently on site are come-along clamps. These clamps use a sliding friction grip action to force a loose body onto a fixed body to grip conductors or guy anchors. Slippage of these clamps have caused great concern and have caused deaths during construction. More on these tools can be seen in Appendix D: Stringing.

Electrical hazards include infringement of the load into other electrical lines during lifting of a structure (people are unable to accurately judge clearance distances of a suspended load to power lines) [30] and shocking of a construction worker due to electrical induction onto a piece

of a structure (insulated from the ground by assembly on wooden blocks). Electrostatic induction on conductors or electromagnetic induction on conductors being strung parallel to existing lines can cause very dangerous conditions for workers stringing the conductors or clamping in the conductors.

Other hazards include working at heights, falling tools, moving vehicles/loads/parts on site and hazardous site conditions or environmental constraints such as limited working space etc.

#### **2.4.4. Hazards to the environment**

Environmental impact is of special concern as the whole servitude needs a certain width of clear space to allow for not only construction, but safe operation of the transmission line. A specified width is therefore cleared, throughout the servitude, of all trees and bushes, and an area at each structure position is also cleared for assembly and erection.

To limit the impact on the environment, search and rescue operations are done to save endangered plant species. Some areas are classified as having only endangered plant species and have to be avoided completely during construction.

Other hazards to the environment do, however, stay connected with every construction operation and these have to be mitigated on site by allocating resources especially for this. These include human waste, chemical and oil spills, garbage, damage to water resources with access roads, etc.

## **2.5. Structural risks**

### **2.5.1. Overloading during erection**

Overloading of a structure during erection is something that has seldom happened. The main cause for fear is that the structure (especially in the case of self-supporting structures) is assembled in various pieces such as a K-frame, beam etc. all of which have members at extremities that are not fixed. The K-frame for instance has members on all four corners that will eventually be attached to gusset plates on the beam and main body of the structure. This makes the extremities of the members able to move further to allow for ease of assembly (and making up of tolerances to allow holes in plates to match) when the part is suspended from the crane.

During erection of the structure however, when the assembly is picked up, the extremities of these loosely attached members (especially at the bottom of the assembly) are the last pieces to leave the ground. If the centre of mass of the assembly is not directly below the crane beam

attachment point, the whole assembly will swing slightly as it leaves the ground, creating the possibility of some of these loose protruding members to snag on the ground and get damaged.

Currently the hazard is controlled to some extent by guide ropes attached to the assemblies which are used to stabilise the swinging action by hand (with multiple manual labourers).

Slight movements of up to a metre are still an expected occurrence and can cause slight bends in long protruding members and thereby permanently damage the structure.

### **2.5.2. Overloading because of overtightening of guy wires**

Installation of a guy wire to a specific tension requires that the guy wire be gripped with a come-along clamp, and pulled with a lever hoist and a dynamometer to an anchor point on the side of the foundation link plate. The setup can be seen in Figure 13.



**Figure 13: Guy wire during installation with a lever hoist and load cell**

The guy wire is then tightened to the correct tension with the help of the dynamometer. The issue is then to carry the tension over onto the link plate by attaching the free end of the guy wire and tightening it with the bolts on the U-bolt.

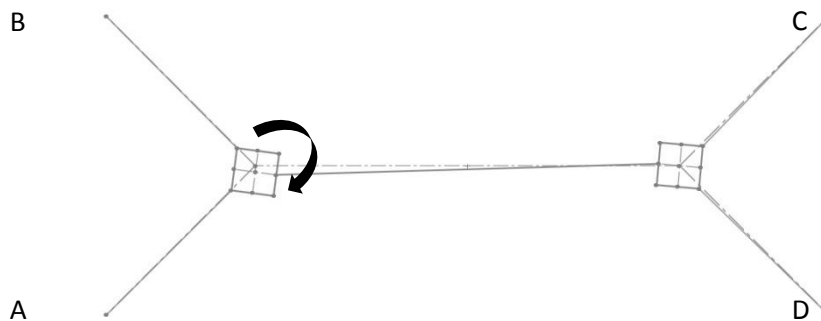
One problem is that the tension is not carried over correctly from the dynamometer to the stub. Firstly, the guy wire is tightened until the dynamometer reads 10% of the ultimate tensile strength. As the bolts are tightened, the reading on the dynamometer will drop. If the bolts are tightened until the reading on the dynamometer reads 0 kN, the tension in the guy wire will be double that specified. If however, the bolts are tightened until the reading on the dynamometer only starts to drop, the differing tensions between the guy wire and the lever hoist makes it difficult to get the correct final tension in the guy wire.

Tests therefore had to be done to check the various methods and it revealed that the best method is to tension the guy wire to a tension of 50% of the final desired tension and then tightening the nuts on the U-bolt until the dynamometer reading gets to 0 kN.

A second problem that has been encountered on site is that if the lengths of the guy wires are incorrect, or if the adjustable guy wire is over tightened, the structure will be misaligned. This happens not as expected with the centre leaning more towards the over taut guy wire, but rather the mast closest to the adjustable guy anchor will rotate out of alignment.

In Figure 14, guy A is adjustable and is over taut during erection of the structure. This causes the left mast to move slightly and rotate to allow for a shorter (straighter) distance to the top of the right mast.

The masts (modelled in PLS Cadd) were modelled with the load on one guy wire increased significantly more than the others for simulation. The masts however, stayed plumb and the tension in all four masts simply evened out the applied load. This raised many questions but it was ultimately accepted that there is a slight difference between the PLS model and physical model.



**Figure 14: Rotation of mast due to over tightening of adjustable guy anchor**

Overtightening can occur because:

- Incorrect method of carrying over the load from the dynamometer to the foundation link plate as described above.
- The elongation of the guy wire is very limited. Site workers however, expect the elongation to be considerably longer than it is. (This is clearly visible when they install the fixed plate in the adjustable U-bolt much further than it would ultimately fit and then have to move it while final alignment of the structure and loading of the U-bolt occurs.)

- The lengths of the fixed-length guys are calculated incorrectly.
- The surveyor makes a mistake with either the setting of the link or with the measurement of the guy length.

The simplest way of avoiding this is to have a clear method of tightening of guy wires which is addressed as described previously. Secondly, to have a clear indication of the impact of the incorrect guy length (due to miscalculation, faults in checking of the stub etc.) on the tension of the guy wires and the alignment of the structure and could include a mathematical example showing the elongation of the guy wire.

To calculate the length of the guy wire, there are three ways which it will yield different lengths:

- A straight line
- A catenary
- An elastic catenary

An example of a comparison study between these three methods can be seen in Appendix E: Guy wire example calculations.

From this one can deduct that the method for installation of the guy wire should be clearly stated. It would be very easy for the contractor to over tighten the guy wires and cause a rotation of the masts when just turning the nuts on the U-bolt by two or three turns (5,25mm) for mistakenly ensuring it is tight while thinking that the elongation and tension is a linear relationship.

### **2.5.3. Overloading during stringing (backstaying)**

During stringing and regulating, the conductor is mostly attached to an angle-strain structure on one side which creates great overturning moments on the structure. The contractor therefore is required to backstay the structure onto buried anchors or precast concrete blocks.

The backstay should be tensioned to counter the force applied by the conductor tension on the opposite side of the structure which exceeds the loads the structure was designed and tested for.

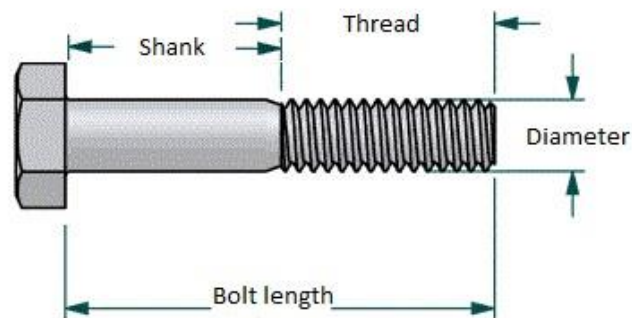
The backstay therefore has to be installed to a specific tension which should be installed exactly as a guy wire (see section 2.5.2) [11].

#### 2.5.4. Bolts and nuts

The part mostly used during transmission line construction is the normal grade 6.8 hexagonal bolt [Figure 15] and nut. As stated previously, the cumulative risk is the sum of the product of the frequency of occurrence, the severity and the exposure or time spent with the hazard.

The more parts are used, the greater the chances that a failure will occur and therefore it requires a more in-detail look.

Bolts used to assemble lattice steel structures can be divided into a few sections namely the head, the unthreaded shank and the thread [31].



**Figure 15 : Bolt details**

The main problems associated with bolts are:

- Single vs. double shear
- Difference in the shear across the thread vs. shear across the shank
- Corrosion of bolts

These aspects are discussed in more detail in Appendix B: Bolts and nuts, but it is clear that the part has the potential to pose a risk to the completion of a structure that conforms to the mechanical design requirements, as well as the safety of the personnel doing the construction.

### **2.5.5. Steel plates/member bends, flanges, defects**

#### ***Defects in the steel angles and plates***

A major hazard affecting transmission line structures is damage to members / plates during manufacturing of the steel. Carbon steel can sometimes show cracking because of different quantities of elements in the alloy combined with heating before bending. If the cracks are highly visible as seen in Figure 57, the member can be rejected. The cracks can sometimes be microscopic and still have a negative effect on the strength of the end product and can be unseen during inspection, especially if covered by a galvanised coating.

Another hazard affecting a design is damage to the steel members during manufacturing of the tower. This can take one of many forms but some of the most common include:

- Cracking and tearing at holes due to fixing of holes with welding prior to punching or due to damaged punches.
- Delamination in the ends of the steel members during galvanising.

These can be seen in Appendix C: Defects due to manufacturing.

#### ***Incorrect assembly sequence of structure***

The incorrect assembly sequence of the cross-rope suspension structure is a common mistake which can lead to a severe lack of strength of the design. This can be seen in Appendix C: Defects due to manufacturing.

## **2.6. Tower erection method and sequence**

### **2.6.1. Tools – cranes**

There are two main types of cranes used commonly; a mobile crane such as a truck-mounted crane, rough terrain crane, crawler cranes and aerial cranes (helicopters); and fixed cranes such as tower cranes, gantry cranes, jib cranes etc.

Cranes were first powered by humans or animals pulling ropes through a pulley system or turning a wheel giving it similar operation to that of a modern winch. With the rise of the industrial revolution in the 1800's, the use of humans or animals was replaced by mechanical power such as steam engines. Sir William Armstrong designed the first hydraulic water-powered crane in 1838 [32].

The first mobile hydraulic crane developed by Liebherr was done in 1968 and was called the AK40 and could lift a maximum of six tons [33]. Similar companies such as Coles produced hydraulic off-road cranes by 1966 with a nineteen ton lifting capacity [34].

Today we mostly use mobile all-terrain hydraulic mast cranes to construct transmission lines as they are freely available. Mobile cranes with a capacity of 1200 tons and a reach of 188m exist. In very difficult terrain, however, construction resorts to more expensive methods such as using helicopters and Derricks (also known as jib cranes).

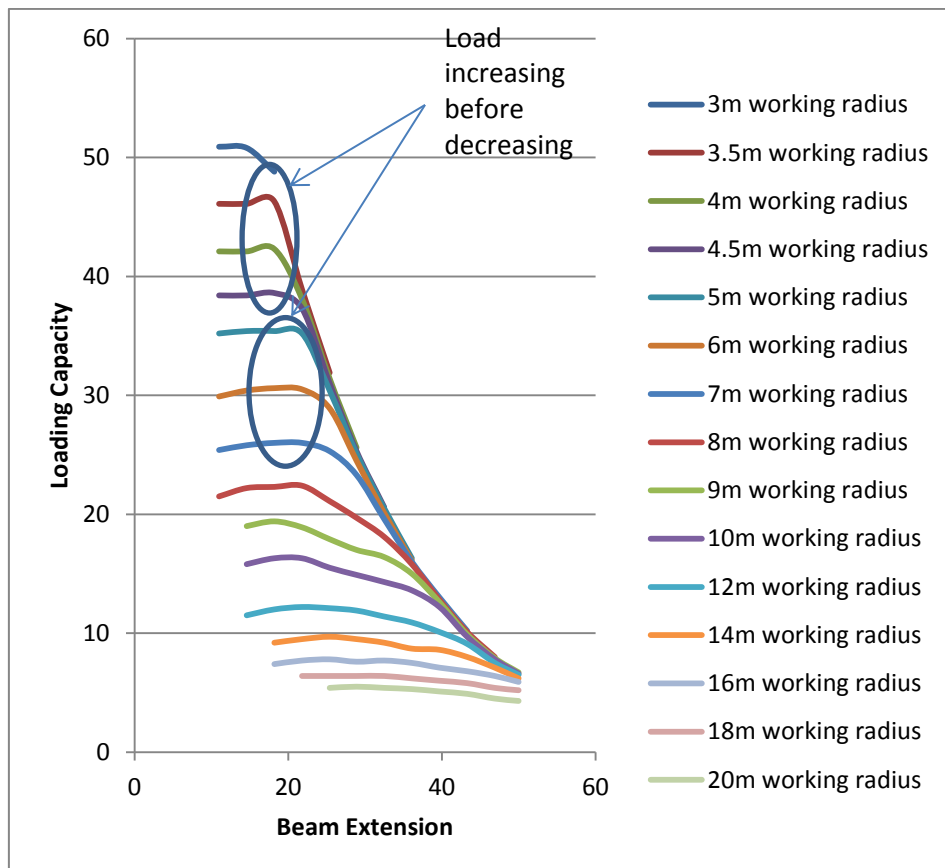
A modern crane is however, not free of risk as described earlier, it is dependent on operator skill, rigging practice, environmental conditions and planning etc. The use of a crane has an element of risk that can be quantified and the use thereof needs to be minimised [35].

Figure 16 below also illustrates how loading charts of cranes can easily be misinterpreted. The first line shows the expected drop in the crane capacity at a given operating radius with the extension of the beam. At 3.0m working radius it is 50 900 kg for an 11m beam extension and 48 800 kg for an 18.2m beam extension. If one were to expect the same tendency for all lifts, one might easily pick up a heavy load and shorten the beam slightly.

If one looks at a working radius of 16m the crane capacity is 7400 kg for a beam extension of 18.2m and it increases to 7800 kg for a beam extension of 25.4m. This is because a shorter beam would cause the beam to be used at a lower angle and increase the shear forces experienced as a result. If the beam was extended further, the angle with the ground would increase and the shear forces experienced would decrease. Figure 16 is based on the data from Table 3 and is for a Liebherr crane [36].

**Table 3: Crane lifting capacities**

		Mast extension (m)											
		11	14.6	18.2	21.8	25.4	28.9	32.5	36.1	39.7	43.3	46.9	50
Working radius (m)	3	50.9	50.8	48.8									
	3.5	46.1	46.1	46.3	38.9	31.9							
	4	42.1	42.1	42.3	38.1	31.4	25.6						
	4.5	38.4	38.4	38.6	37.3	31	25.3	20.6					
	5	35.2	35.4	35.4	35.2	30.4	25.1	20.5	16.3				
	6	29.9	30.4	30.6	30.5	28.9	24.5	20.1	16.1				
	7	25.4	25.8	26	26	25.3	23.3	19.6	16	13	10.2		
	8	21.5	22.2	22.3	22.4	21.1	19.7	18.1	15.8	12.8	10.1	8	
	9		19	19.4	18.9	17.9	17	16.4	15	12.6	9.9	7.9	6.7
	10		15.8	16.3	16.3	15.5	14.9	14.3	13.6	12.2	9.7	7.8	6.6
Working radius (m)	12		11.5	12	12.2	12.1	11.9	11.4	10.9	10.1	9.1	7.5	6.5
	14			9.2	9.5	9.7	9.5	9.2	8.7	8.6	8	7.1	6.2
	16			7.4	7.7	7.8	7.6	7.7	7.5	7.1	6.8	6.4	5.9
	18				6.4	6.4	6.4	6.4	6.2	6	5.8	5.4	5.2
	20					5.4	5.5	5.4	5.3	5.1	4.9	4.5	4.3



**Figure 16 : Example crane lifting charts**

This shows that something as simple as interpreting the crane lifting charts incorrectly can cause a loss of 5% in lifting capacity which could damage a crane.

### 2.6.2. Past methodology of structure erection

In the past, technology such as telescopic boom mobile cranes were not available and structures had to be built by lifting member by member into place using a Derek crane as seen below (Figure 18, Figure 19) [21], [37].



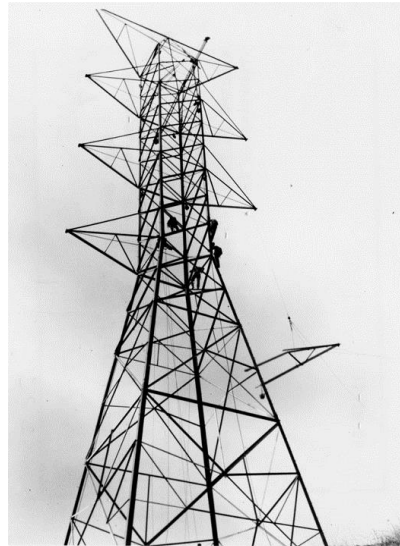
**Figure 17: Construction of a self-supporting structure with a Derek crane - Hoover Dam construction (1931-1936)**

This is also referred to as building the structure “by elevation” whereby the structure is built from the bottom up by lifting individual members or lightweight pre-assembled pieces into place. Hoisting is done with winches or manually (by hand) [18].



**Figure 18 : Construction of a self-supporting structure with a Derek crane**

It was a time-consuming process and therefore a costly one. Joints could not be inspected while sections of the structure were on the ground and therefore the structural integrity could not be assured (as seen in the previously stated section: Hazards) unless an inspector climbed each structure and checked all critical joints.



**Figure 19 : Construction of a self-supporting structure using a Derek crane**

Over the years construction technology has greatly increased and we now have access to batching plants, mobile diggers, specialised highly mobile cranes with capacities of more than 200 tons, bulldozers, etc. With the increased access to these new technologies, the methods of construction have changed over time and currently vary greatly from contractor to contractor.

## **2.7. Stringing**

### **2.7.1. The stringing process**

The stringing process, although seen as quite dangerous, is very difficult to change. The process is described in a little more detail in Appendix D: Stringing.

The process specified is most commonly used for tension stringing, which means to pull the conductor under tension through pullers, tensioners and over roller blocks/running blocks, to ensure that the conductor is not dragged over the ground and get damaged. The process has been used since the beginning of transmission line construction and has changed very little although the equipment has become more complex and technically advanced which has made the control of the process better and safer. It also ensures a better quality product.

### 2.7.2. Electrocution during stringing

During the stringing and regulating process, the conductor is tensioned through plastic or rubber coated bull wheels, and pulled over running blocks also covered to protect the surface of the conductor against damage and hanging from insulators. This however, causes a problem if the conductor is strung parallel to an existing energised transmission line as a result of induced voltage or current.

The risk can be avoided by applying safety earths in two ways, namely a set of running earths on either side of the stringing sites and a master earth further away which can act as a fall back as seen in Figure 20. The main aim of this is to create a preferred path for induced voltage and current. Internationally, line contractors are required to apply safety earth principles as laid down in IEC and ITEE standards.



**Figure 20: Running earths applied on tensioner**

The process becomes especially dangerous when the line runs parallel to an existing energised line and then turns away from the line. The current induced in the line is still present but the visual indication thereof is no longer visible. When the jumpers at a strain tower are installed or during transfer of conductors onto strain or suspension hardware, the worker could form part of the circuit of least resistance and get injured or killed as a result.

### 2.7.3. Clamping in of conductors and climbing of structures

Investigation into international practices shows clearly that cherry pickers and bucket trucks are used when working at heights to clamp in conductors or to assemble structures. However, this is not the case in South Africa.

After erection of the guyed cross-rope structure for instance, a worker has to hook onto the spacer rope with his double lanyard and manoeuvre to the hardware attachment point. He can

then attach a pulley from which a ladder can be lifted and hooked onto the spacer rope, before he can descend over the insulator and hardware to the running block. It is a timeous and dangerous process and simple mistakes can lead to falling from height and result in death.

The main risk comes in if a worker has done the same job for years and has never had to rely on the double lanyard during a near miss. He then does not use it as instructed when he is not being properly supervised. The same risk applies to other jobs such as regulating conductors and installation of special in-line strain assemblies.

During certain jobs carried out locally, the use of a cherry picker was used rather than climbing in precarious positions as shown in Figure 21. It showed great benefits to savings in time and increase in safety [38].



**Figure 21: Local use of a cherry picker to install custom assemblies**

Incidents during the clamping-in operation have led to fatalities and serious injuries in the past which could have been avoided with the use of equipment such as a cherry picker or bucket truck.

## **2.8. Current structure erection methodology**

### **2.8.1. Overview of the structure erection process**

After the erection by elevation went out of practice, due to the availability of mobile cranes, the method of construction changed to a method where large sections of structures (or modules) are assembled on the ground and these sections are then lifted piece by piece into position in order to complete the structure. Since this method was started, the capacities of cranes have changed, the reach of cranes have changed but the method has stayed the same. The method works and

has therefore continued to be used even though it has never been accurately studied or documented from an engineering perspective even with the availability of new tools.

In interviews with senior foreman on site, who have been using this method for many years, they simply answer that they have been taught this method by those who used it before them and they therefore continue to use it.

The use of these methods to erect structures, which have been inherited from past generations, even show the continuing use of bad and dangerous practices that were used when these methods were developed and has trickled down to current construction sites. One of these which still occur on many sites is the attachment of lifting tackle to the bottom members of a structure beam. This is bad practice because it is underneath the centre of gravity of the object being lifted and goes against acceptable rigging procedure [39]. The reason for this therefore has to be clear and documented, however, while studying the subject the only reasoning for this coming from sites is that it allows for the use of a crane with a shorter reach.

Many years ago, with old technology, it might have been the only way to erect the tall structures. It was therefore the safest method given to contractors which still allows for the feasibility of construction. It was also the method taught to generations thereafter. When staff were questioned about this on site, the general was “that’s the way we’ve always done it”.

The justification of poor rigging practice is unacceptable, as it adds substantially to the risk of erecting transmission line structures. It is not justified because of inability to have the right equipment. However even with the right equipment, the same bad practice has continued. While this might be seen by some as bad practice on the part of contractors, the description of the method that should be used to erect structures should come from the designer of the structure as he should know best and should think about safe constructability of his design, to conform to the requirements as previously stated.

To specify a safer way to erect structures, while looking at new construction technology and with the ultimate goal of having a structure that more closely conforms to design specifications, the engineer has to consider the following factors:

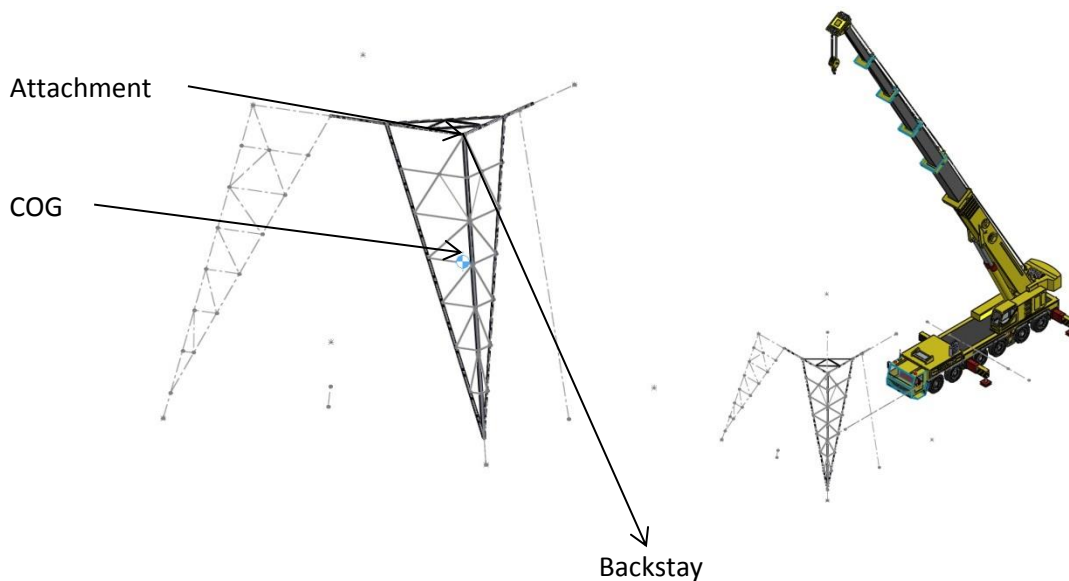
- What mechanical hazards that happen regularly on site have the greatest impact on the design. For example, overloading because of incorrect assembly of bolts, bending of loosely attached members during lifts, etc.
- The technology that is currently freely available in terms of construction equipment.

- Minimising the hazards with proper quality control integrated into the new methods.

### 2.8.2. Self-supporting suspension structures

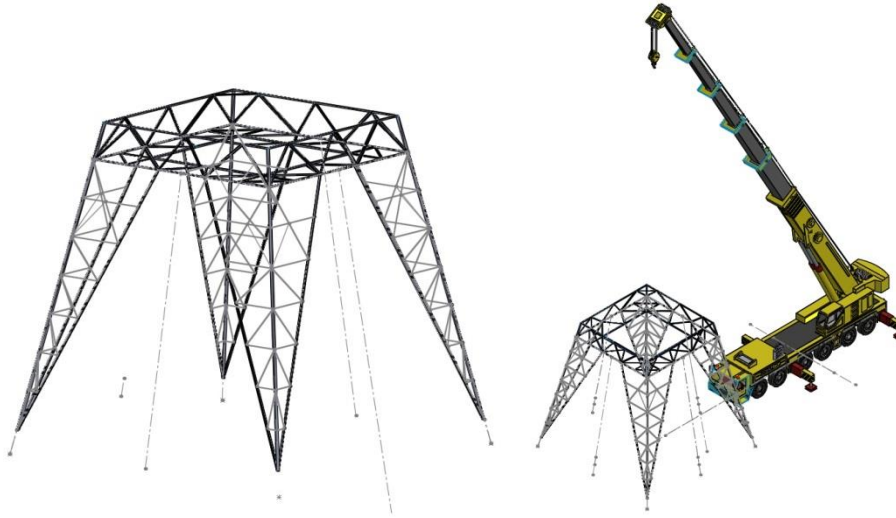
There are two main self-supporting structures. Firstly an angle-strain structure which is only used on bend points and therefore has to endure much larger loads (conductor tension causing transverse loads, wind loading, conductor weight etc.) and weigh more. Secondly there are self-supporting suspension structures which are only used in line with the conductors and only have to hold the weight of the conductors and counter transverse winds and therefore weigh much less.

During assembling of these self-supporting suspension structures, the weight of the structure is seldom the factor dictating the size of the crane used, but rather the height which requires a very long boom. The sections being lifted are quite light and therefore the sequence that is most commonly used is depicted below step-by-step with the hazards indicated.



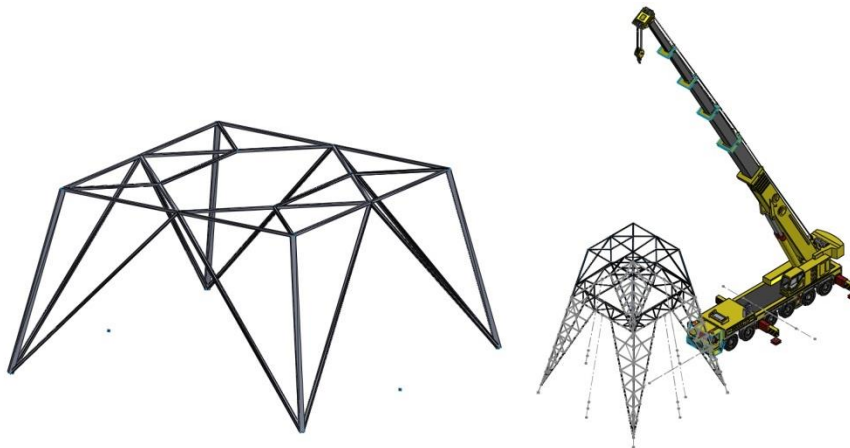
**Figure 22: Erection of legs - process 1 to 4**

Firstly, the crane (in most cases a smaller truck-mounted crane) is used to erect the legs of the structure which are back stayed temporarily onto a concrete block until the legs are interconnected at the top. This setup can be seen in Figure 22.



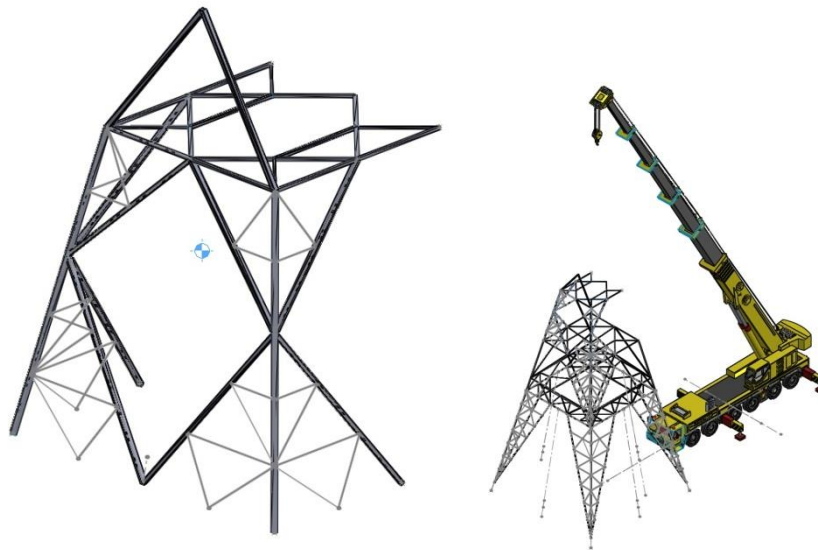
**Figure 23: Legs are joined at the base of the body extension in lifting process 5 and 6**

Secondly, the legs are joined together at the base of the body as seen in Figure 23. These lifts are very light in weight although the members are only loosely attached to each other which make them more flexible. This is done to allow for mobility which helps with ease of attachment to the legs which are still slightly unstable and held upright with backstays. Once these sections are tightened, the legs are stable and the temporary backstays can be removed. The lifting of the body can then continue (Figure 24, Figure 25).



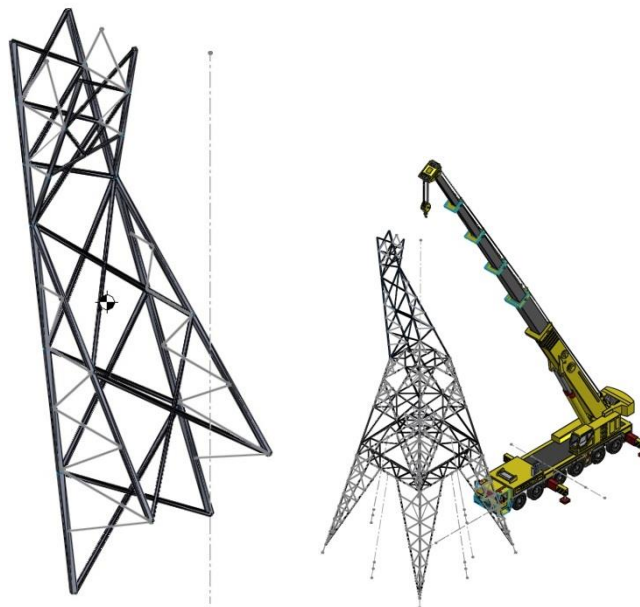
**Figure 24: Lifting of the body extension (if needed) in process 7 and 8**

The main body is then lifted into place on top of the body extension in two pieces as shown in Figure 25.



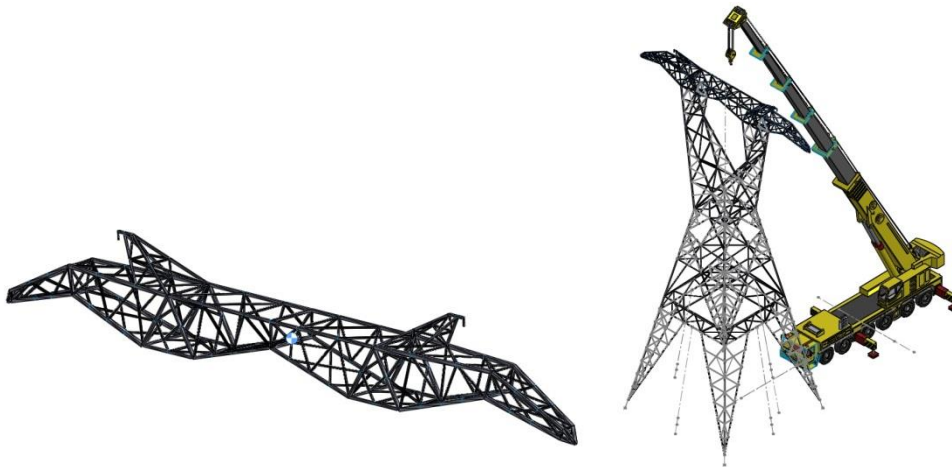
**Figure 25: Lifting of the main body to which the K-frames attach in process 9 and 10**

The K-frames (shown below) are lifted into place attaching to the main body (Figure 26).



**Figure 26: Lifting of the K-frames in process 11 and 12**

Lastly, the main beam which is the heaviest part of the structure is lifted as one piece and this lift requires the longest reach of the crane (Figure 27).



**Figure 27: Lifting of the main beam in process 13**

The above processes show the erection procedure illustrated for a self-supporting strain structure with a body extension. It is also illustrated as the worst case currently seen on site in terms of the number of lifts. Some contractors however, assemble half of the body extension attached to half of the main body and therefore reduce the total number of lifts to eleven.

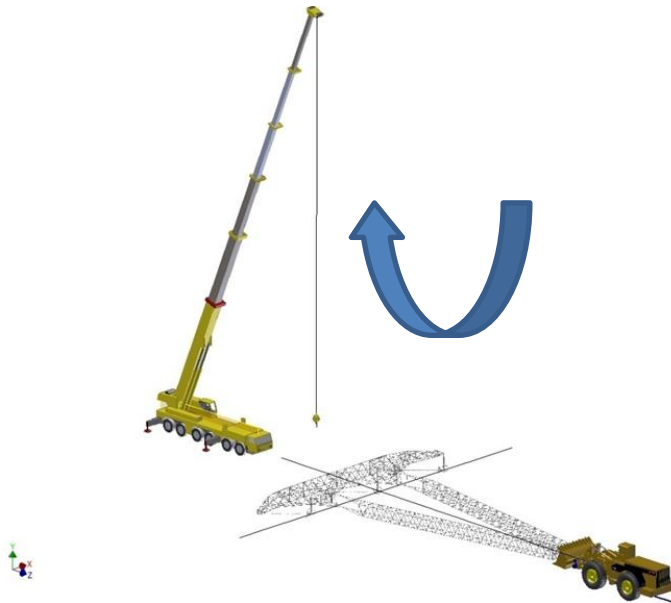
It can also be seen that it is a process of lifts which is very difficult to explain, even with illustrations. There is no clear definition for the parts that make up the structure. There is little clarity on what sections of parts should be assembled loosely, and which sections can have bolts tight to allow for stable lifts which still assemble easily. There is also no indication where lifting tackle should be attached.

There is a clear understanding on site between workers what a “beam” or “K-frame” is, but there is no documented definition in any of the research done illustrating this, and fixing this as an across-the-board term that can then be used by all contractors and designers.

Structures such as the guyed-V and cross-rope are an improvement in this regard as the whole structure is assembled and lifted as a single piece with all bolts tightened and the whole structure fixed onto the stubs and guy wires tightened in one step.

### 2.8.3. Guyed-V suspension structures

The guyed-V structure is assembled as a single piece lying in line with the line direction. The bottoms of the two masts are then either placed in a custom built trolley or tied together onto the bucket of a bulldozer. A crane is positioned close to the centre foundation so that it can lift the beam portion of the structure straight upward while the bulldozer pushes the bottom of the masts forward towards the centre foundation as shown in Figure 28.

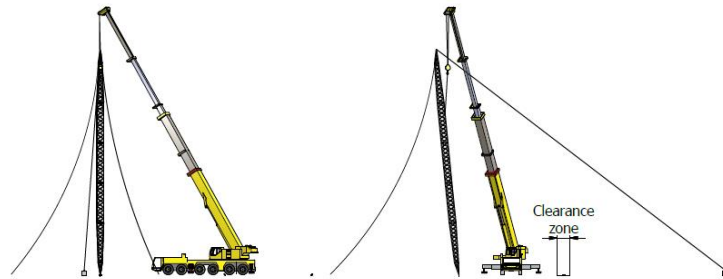


**Figure 28: Lifting of a guyed-V structure in one process**

Once the structure hangs above the centre foundation it is loosened from the trolley/bulldozer and lowered onto the foundation and the guy wires tightened. The whole structure being lifted in one lift makes for less room for mistakes and makes this structure less of a hazard to erect.

### 2.8.4. Guyed cross-rope suspension structures

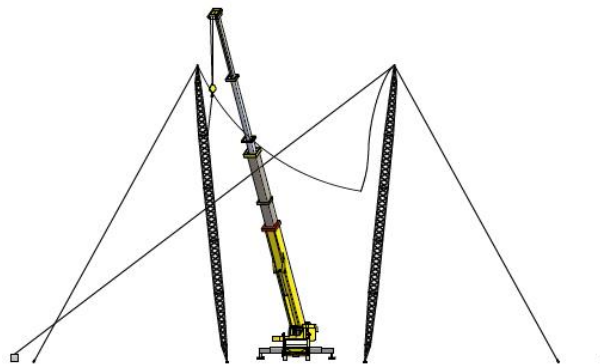
To erect the guyed cross-rope structure the currently used method starts by picking up the first mast (Figure 29) and securing it to the pin on the foundation. The guy wires can then be pulled and connected to the stubs on the outer foundations, as well as the temporary stay wire which can be connected to a temporary anchor point opposite the guy foundation anchors. Only once the mast is fixed on all three/four points can a climber ascend the tower and disconnect the crane slings.



**Figure 29: Lifting of the first cross-rope beam - process 1**

The service rope should be attached to the second mast together with a nylon rope so that a climber can climb the first structure which is stable with the three/four attachments to secure the service rope while the second mast is supported by the crane.

The second mast is then picked up and secured to the pin on the foundation. A climber can ascend the first mast with the nylon rope attached to the service rope on the second mast and pull it across to attach it to the first mast (while the crane is holding it slightly straighter upwards it will be easier to attach). Once the crane lowers it further and the mast leans backwards, the guy wires can be attached. Once the guy wires are attached a climber can ascend the mast and disconnect the crane slings as shown below in Figure 30.



**Figure 30: Lifting of the second cross-rope beam - process 2**

The method requires temporary backstaying of the first mast (Figure 29), as well as attachment of the guy wires while the mast is not yet in its correct position. This immediately leaves a gap where the guy wires can be of incorrect length and it will not be noticed until the second mast is picked up and secured and the plumb surveying of the structure starts. It also means that a

worker has to climb the structure while it is only stayed with a temporary backstay to disconnect the crane hook.

For guyed cross-rope structures three of the four guy wires are usually of a fixed length which is surveyed and specially made before the structure erection starts. The service rope is marked with a piece of tape in the middle so that the structure can be easily plumb surveyed.

## **2.9. Summary**

The crane has evolved over the last 170 years to be able to lift amazing weights, travel off-road, and have plenty of built-in safety measures in place but they are still not used as designed to their capacity, and accidents still happen.

High capacity cranes are used simply because of their longer reach but they are used to lift loads well below their designed load limits.

Cranes remain a hazard on site that needs to be managed. A crane upset occurs in about every 10 000 hours of use [40]. According to the US OSHA Bureau of Labour Statistics' Census of Fatal Occupational Injuries, 79 fatalities relating to cranes, Derrek's, hoists and hoisting accessories were recorded in 1993. In 1992, 400 crane incidents were reviewed and identified 354 fatalities over a five year period (71 per year) showing one death per thousand workers over a working lifetime of 45 years. Their analysis also identified the major causes of the incidents to be: contact with energised power lines (45% of cases), under-the-hook lifting device failure, upset cranes, dropped loads, boom collapse, crushing by the counter weight, outrigger use, and falls and rigging failures [41], [42].

Why is it then that a more detailed investigation is not done so that the design of transmission line structures can be changed to be able to ease the lifting operation while increasing the size of the load (while staying below the crane capacity), and in doing so reducing the number of lifts and the overall time of operation? If certain construction methods are specified, lifts can be reduced and the risks of crane use minimised.

Similarly, if international practices show the use of equipment such as cherry pickers or bucket trucks for certain jobs, and we can clearly conclude from past incidents that the use of such equipment would have prevented serious injury or death, why are such methods not specified?

## **Chapter 3. New methodologies to mitigate construction risk**

### **3.1. Introduction**

The following methods mentioned in this chapter, were developed in combination with contractors to reduce the risk of construction by minimising the time of crane use or amounts of lifts.

It starts by defining the structure layouts to ensure that there is a common understanding between contractors and engineers about the structure layout and modules. It then describes the structure erection methods in detail using these definitions for the self-supporting structure, the guyed-V suspension structure and two methods for the guyed cross-rope suspension structure.

### **3.2. Labelling convention and definition of tower sections**

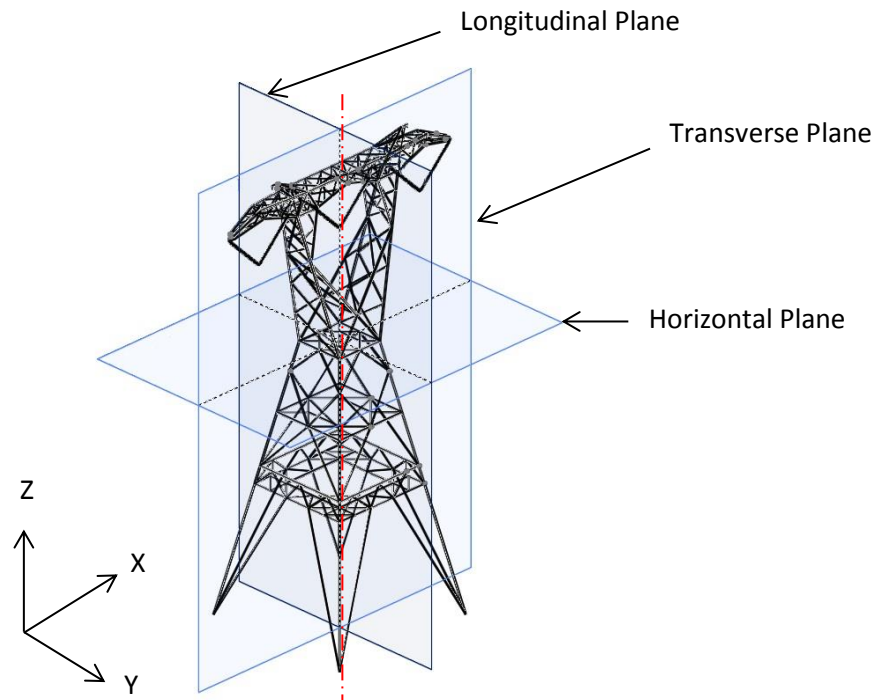
#### **3.2.1. The need for structure definition**

As seen during this report in sections describing different parts of structures, it is seen that there is a resemblance to that of human anatomy in some sense with descriptions of “legs”, a “waist” etc. which can also be seen with the resemblance of a self-supporting structure to the outline of a human. This reference and its use have not changed a lot since the design of the self-supporting structure and are used every day in offices and on sites.

The definition of these sections has however, stayed uncaptured and not properly defined and has created an industry bereft of proper descriptions of the outlines of structures during all stages from design to construction. Contractors who are asked to give a safe work procedure describing attachment points to sections of structures, and weights of these sections, have had to make use of drawings (many times not to scale or size) or pictures to show site practices. Engineers who have to describe the methods of construction to contractors have to make use of 3D illustrations etc. Although the modelling of structures and equipment is a good practice for visualisation and offers many other benefits, it still is a difficult and time-consuming process which can only be done with expensive computer programs (and therefore by few people).

Before starting to describe the proposed future methods of structure erection, the different types of structures, as well as the different parts of these structures, should be defined so that there is an across-the-board understanding of the different parts of each structure and where the critical joints occur.

To define a labelling convention requires clear illustrations like the following of the planes and axes used in structural definition [7]:



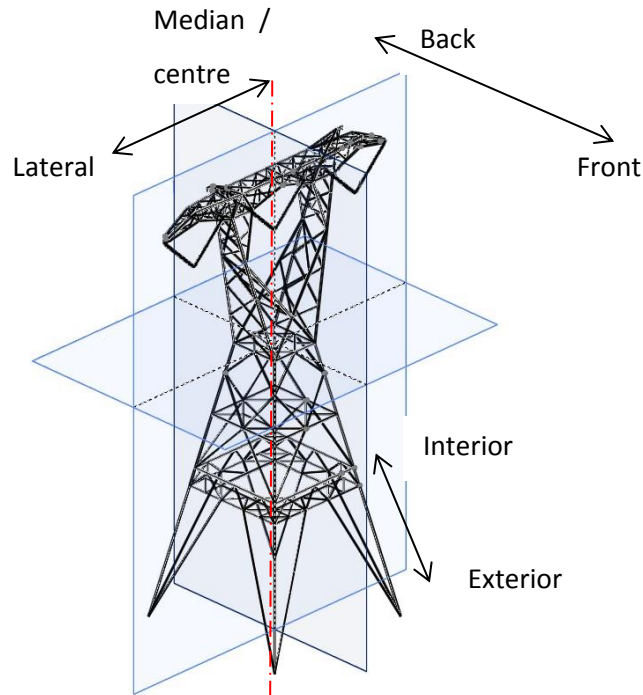
**Figure 31: Planes in structures**

**Table 4: Description of terms used to describe structural parts.**

Longitudinal plane	Y-Z Plane	Creates a left and right hand side
Transverse plane	X-Z Plane	Creates a back and front side
Horizontal plane / Transverse plane	X-Y plane	Creates a top and bottom side
Median / Centre axis	Z-axis	Centroid of structure
Longitudinal force	Y-axis	Force parallel to y-axis
Transverse force	X-axis	Force parallel to x-axis
Vertical force	Z-axis	Force parallel to Z-axis

The terms exterior and interior are used to describe the extremity from the centre of mass of the structure, the term exterior being the furthest point and interior the nearest.

Median / centre refers to the middle (Z-axis) and lateral refers to the sides. There will therefore be a medial phase and a left and right lateral phase.



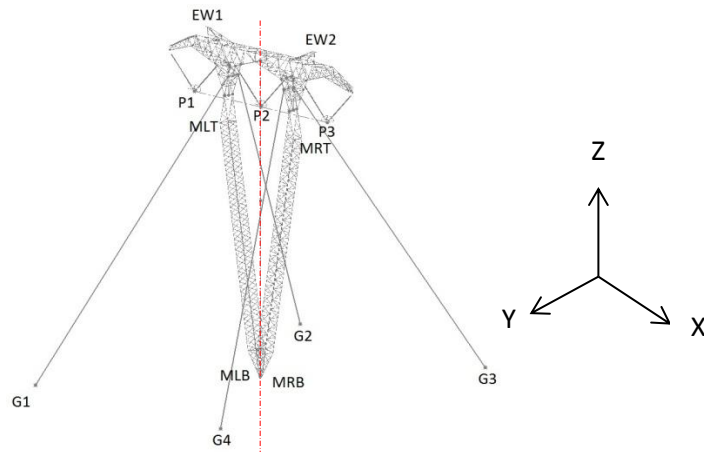
**Figure 32: Directional references of a structure**

Points referred to as the median / centre, back or front, and other directional references can be seen in Figure 32.

If it is assumed that certain points are the same independent of which structure it is, the labelling convention is further simplified. For instance one could number the attachment points of the phases P1, P2 and P3, starting from left lateral phase to the right, and the earth wire could be called EW1 and EW2 from left lateral earth wire to right for all suspension structures.

Similarly, the guy wire attachment points to the link plates will be called G1, G2 etc. in a clockwise direction as seen in Figure 34 and the structure legs called L1, L2 etc. in a clockwise direction starting with the front left leg as being L1.

### 3.2.2. Guyed-V structure definition



**Figure 33: Labelling convention for guyed-V suspension structure**

The guyed-V suspension structure can be seen in Figure 33 and consists of eleven main points.

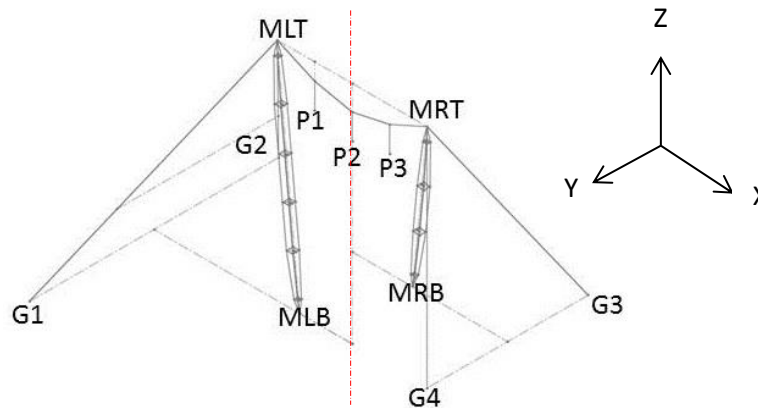
**Table 5: Labelling definition for a guyed-V suspension structure**

G1-G4	Guy wire attachment to foundations
P1-P3	Three phases
MLB	Mast left bottom
MLT / EW1	Mast left top / Earth wire 1
MRB	Mast right bottom
MRT / EW2	Mast right top / Earth wire 2

The advantage of the structure is a definite weight saving over the self-supporting structure. It however, has a larger footprint requirement for the guy wires. The beam at the top makes the structure more stable to lift but also creates a place for birds to nest. It therefore has some construction benefits but costs more and has worse line performance than that of the guyed cross-rope suspension structure.

### 3.2.3. Guyed cross-rope suspension structure definition

The next type of structure defined is the guyed cross-rope suspension structure.



**Figure 34: Labelling convention for guyed cross-rope suspension structure**

The guyed cross-rope suspension structure can be seen in Figure 34 and consists of eleven main points.

**Table 6: Labelling definition for guyed cross-rope suspension structure**

G1-G4	Guy wire attachment to foundations
P1-P3	Three phases
MLB	Mast left bottom
MLT / EW1	Mast left top / Earth wire 1
MRB	Mast right bottom
MRT / EW2	Mast right top / Earth wire 2

The advantage of the structure is the clear weight saving and that the masts are completed and all bolts tightened on the ground before the structure is picked up and there are therefore no loose joints or members with extremities that are not tightened to gusset plates etc. Everything can therefore be inspected on the ground prior to erection of the structure. The disadvantage being that until all four guy wires are tightened, the structure needs temporary stays or supports to remain stable.

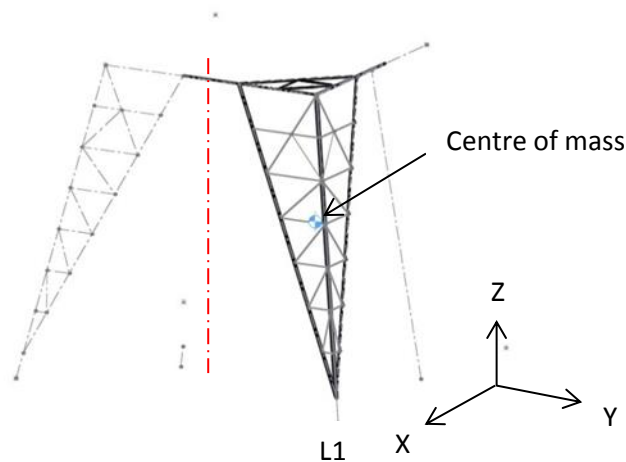
### 3.2.4. Self-supporting suspension structure definition

#### *Problems relating to self-supporting suspension structure definition*

The self-supporting suspension structure is the oldest type of structure still currently in use together with the self-supporting strain structure. From the pictures seen of the construction of the first overhead power lines (Figure 17, Figure 18), little has changed in their design. The definition of these structures is more complex than that of the guyed cross-rope suspension structure as it contains more joints and parts and modules. The following section describes some of these modules in more detail.

#### *Self-supporting suspension legs*

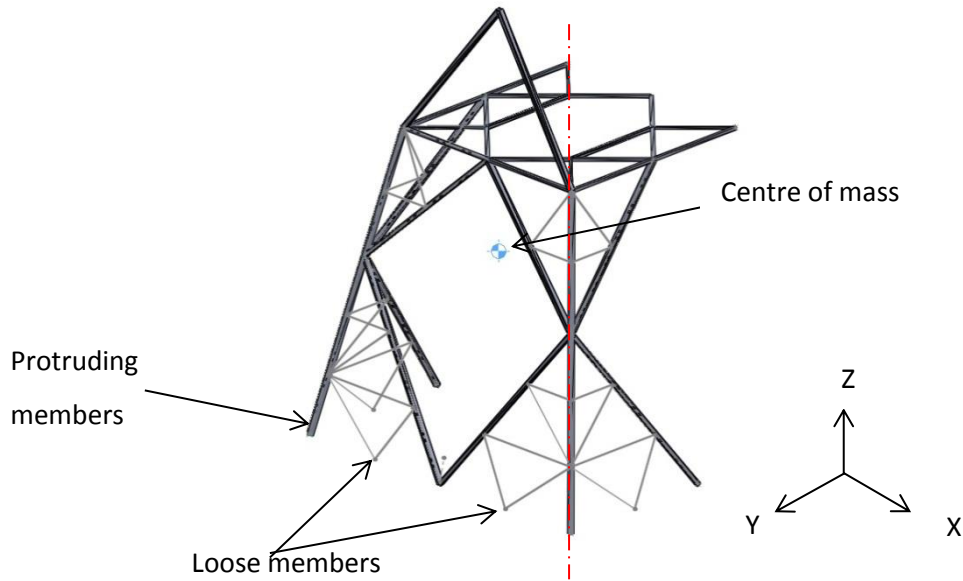
The legs form the basis of the structure and connect to the foundation stubs. It can be seen in Figure 35 that the leg has to be temporarily stayed because it only rests on a single point (L1) until all four legs are in position and can be interconnected. If the leg is lifted into position a worker has to then climb a module which is only temporarily supported to disconnect the crane, which adds to the risk of the installation of the leg. The risk can be avoided by using tools such as a cherry picker or a bucket truck to disconnect the crane instead of climbing the module.



**Figure 35: Self-supporting suspension leg**

#### *Self-supporting suspension body*

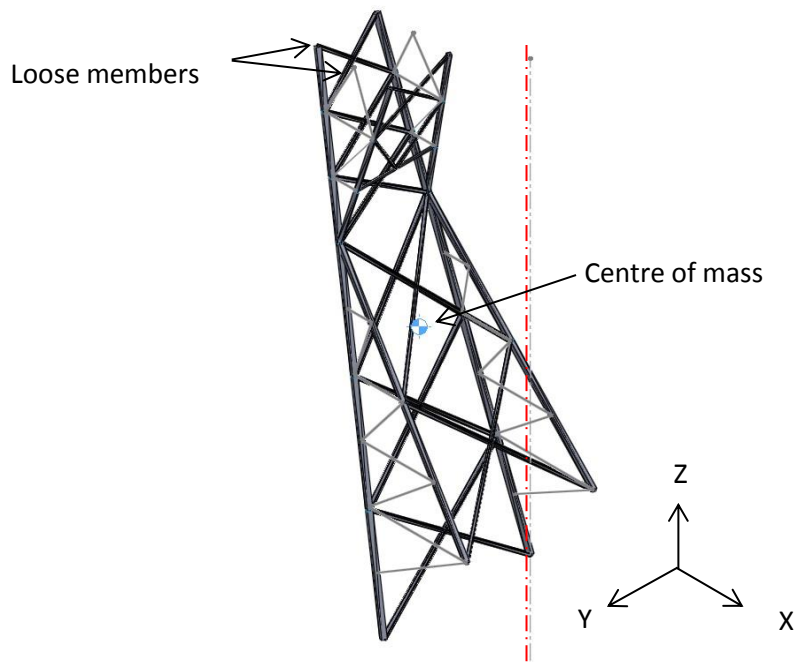
The body of the structure (Figure 36) forms the connection between the legs and the K-frame. It is usually split into two sections and when it is lifted into place it also requires a backstay to stabilise the top section and to be able to adjust the angle of the section for fitment when the second half of the module is lifted into place. The bottom has plenty of loose members and members that protrude to join onto plates that frequently get snagged and damaged.



**Figure 36: Self-supporting suspension body**

***Self-supporting suspension K-frame***

The K-frames (Figure 37) joins the beam and the body of the structure. It is also assembled as two modules and lifted into place as such. The modules are assembled to have loose joints and members where they have to join to the body and beam of the structure and also have a few loose members which are tied with wire to the main members before the lift.

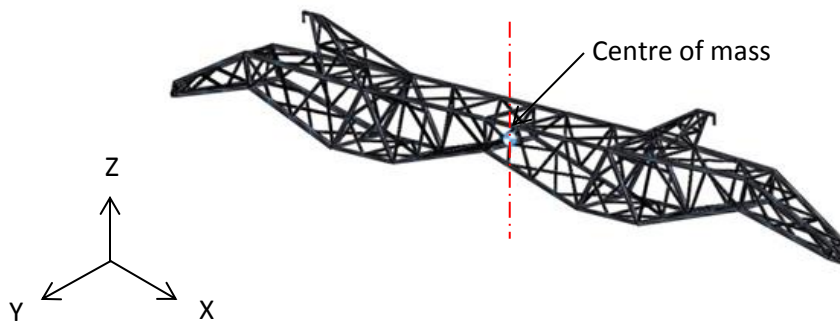


**Figure 37: Self-supporting suspension K-frame**

### ***Self-supporting suspension beam***

The beam (Figure 38) is the final module of the structure to be lifted into place although sometimes the cross arms or earth peaks are lifted separately.

The beam is the only module to have all members and joints tightened before being lifted into place. It is also the heaviest module. Lifting the heaviest module for attachment to the highest point means the beam dictates the size of crane required, although the height of the lift most of the time determines the crane size rather than the weight of the lift.



**Figure 38: Self-supporting suspension beam**

### **3.3. General safety precautions**

Only winches will be allowed to secure the safety and construction ropes when erecting the structures and hoisting of hardware and other equipment. No vehicle may pull or lift any equipment or structure member by any means other than with a vehicle mounted winch. The pulling/lifting or tightening of stay ropes by driving the vehicle onto which the cable is mounted is strictly prohibited. All winches should comply with regulations set forth for lifting machines in the driven machinery regulations [43]. The reach and capacity of the crane must be incorporated into the contractor's safe work procedure.

During assembly and erection, members will not be bent or overstressed to force them into place.

The field assembly and erection methods chosen will be influenced by variables such as line and tower design, line route, terrain, climatic and seasonal weather conditions, the impact of any environmental restrictions, line route access, schedule requirements and the availability of critical resources in both manpower and equipment. Deviation of the method statement is permitted if the contractor submits a concession request with a complete method statement detailing the erection method.

Towers will be assembled in strict accordance with the approved design drawings. No tower will be erected with a known shortage of members, without consultation with the line engineer capable of assessing the risk of the shortage.

Guyed-V and guyed cross-rope structures will be completely erected with all members in place, all bolts installed and tightened, punched and painted, and the entire structure inspected in accordance with inspection and test plan forms, to confirm conformance with the design drawings prior to the erection and the installation of conductors and ground wires.

It is recommended that when assembling the self-supporting structures, as many bolts as possible will be fitted finger tight and with all connecting faces touching to assemble the module (K-frame, body, etc.). Only bolts which present difficulties in the assembly will be left over for the revision team to complete. A minimum of 50% of bolts have to be installed in any member at the edge of a module to allow for movement to attach to another module, 100% of all other bolts have to be tightened.

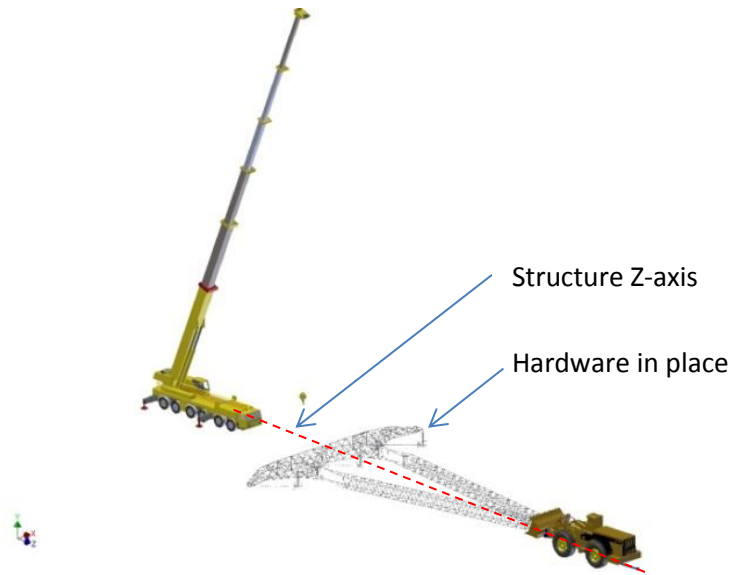
When erecting structures in the vicinity of energised lines, care will be taken to ground these un-energised structures before any worker comes in contact with them and spotters placed in line with the closest phase of the nearby line to check proximity during a lift.

### **3.4. New method to erect guyed-V suspension structure**

The new proposed method for the lifting of the guyed-V structure is exactly as it used to be except for lifting it with its hardware and stringing equipment attached which removes the dressing process. This can be seen in Figure 39.

The structure is to be assembled with its main Z-axis along the longitudinal direction of the line so that the crane can be positioned accordingly, above the beam and in the longitudinal direction of the line. The structure should have a clear lifting path from its assembled position to its final position.

The bottom of the two masts of the tower (MBL & MBR) has to be tied together and supported by either the loading bucket of a tractor-loader-backhoe, or a custom made trolley to allow for ease of longitudinal movement towards the foundation stubs without damage to the corrosion protection of MBL & MBR.



**Figure 39: 3D Modelled erection of a geyed-V suspension structure with the hardware, insulators and running blocks attached**

The guy wires should be tightened so that the structure is stable and permanently fixed before anybody ascends the structure to disconnect the crane. The removal of the dressing process adds to the reduction of risk and ensures the proper inspection of all hardware and hardware attachment on the ground before erection of the structure.

### **3.5. New method to erect geyed cross-rope suspension structures**

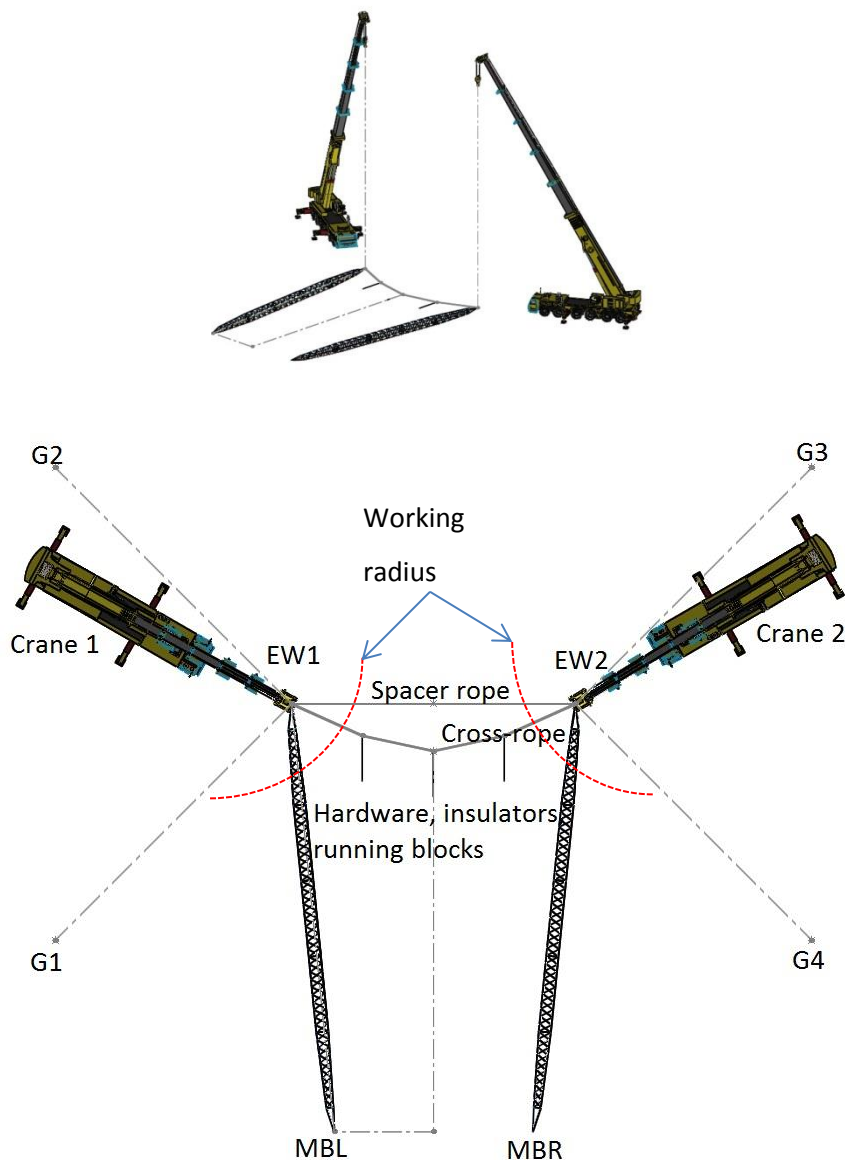
#### **3.5.1. Two-crane method**

The first proposed method to eliminate anyone having to climb a cross-rope structure while it is being supported by temporary backstays etc. is to lift both masts at the same time using two cranes.

At first glance this option seems to be more complex (having two cranes means double the amount of communication required and double the amount of moving pieces at any given time) and more costly because it requires two cranes. While testing it, it has however, emerged to be a very forgiving method mainly because it is not a single rigid body being lifted but two separate bodies merely connected with a rope. The assemblies are so light in comparison to the masts that they have very little effect on the process at all. And while this method clearly requires no one to climb the structure while it is temporarily stayed to disconnect the crane, it also has the added benefit that the attachment of the cross-rope and hardware assemblies can be inspected on ground level before the lift commences.

The contractor must properly plan the lift (as seen in Figure 40) to ensure:

- Both masts are assembled as per the appropriate approved drawing, the correct distance from the centre line of the servitude in a longitudinal direction with EW1 and EW2 at the crane end and MBL and MBR at the other end.
- The cranes should be positioned, in a stable setup, at the appropriate distance from the foundation stub to allow a clear lifting path of the mast to its final position while not interfering with the path between EW1 and G2.



**Figure 40: Lifting procedure for erection of cross-rope suspension structure with two cranes**

After MBL and MBR are positioned on the stubs, the cranes can hold EW1 and EW2 in position so that G2 – G4 can be pulled and attached to the foundation stubs (nonadjustable) and G1 can be pulled and tightened with a load cell (adjustable) to 10% of the UTS before someone climbs the masts to release the cranes.

### **3.5.2. One crane and spreader beam method**

The second proposed method to eliminate anyone having to climb a cross-rope structure while it is being supported by temporary backstays etc. is to lift both masts at the same time using one crane and a spreader beam as shown in Figure 41.

Having one crane means less communication required and less moving pieces at any given time, as well as half the amount of lifts and it is less costly because it requires one crane. While testing it, it has shown to be a method requiring accurate slings and well-maintained equipment. It also requires a crane with a tall reach because the angle from EW1 and EW2 to the crane hook requires a crane +/- 8m taller than the mast. It however, lifts both bodies as one in one motion, spreading the load evenly. The assemblies are also light in comparison to the masts and they have very little effect on the process at all. And while this method clearly requires no one to climb the structure while it is temporarily stayed to disconnect the crane, it also has the added benefit that the attachment of the cross-rope and hardware assemblies can be inspected on ground level before the lift commences.

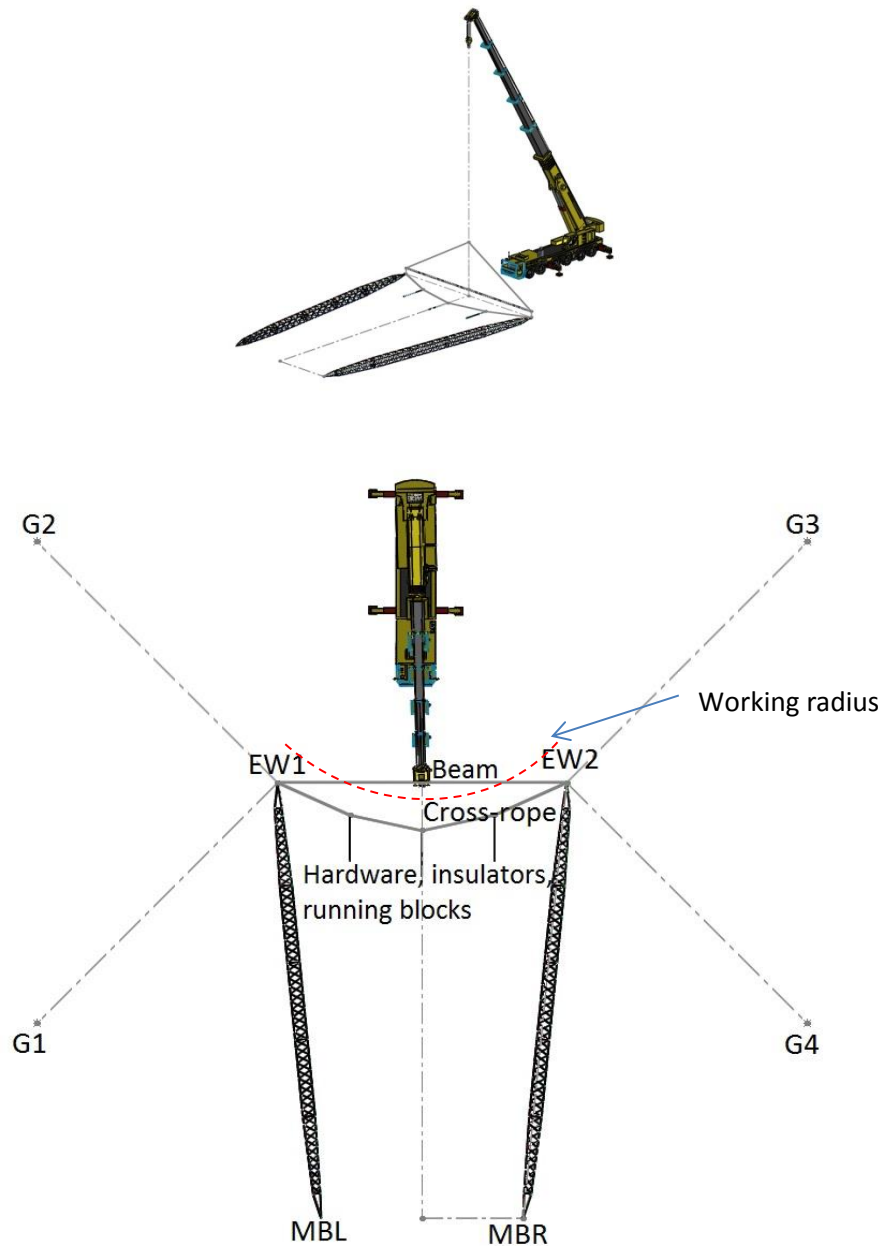
The contractor must properly plan the lift to ensure:

- Both masts are assembled as per the appropriate approved drawing, the correct distance from the centre line of the servitude in a longitudinal direction with EW1 and EW2 at the crane end and MBL and MBR at the other end.
- The slings at the end of the beam are only 1m long and dictate the tolerance of the distance from the servitude centre line.

The crane can be positioned, in a stable setup longitudinally along the centre line of the servitude, at the appropriate distance from the foundation stubs to allow a clear lifting path of the masts to their final position.

The beam is defined as “lifting tackle” in the driven machinery regulations [43] and should be inspected every three months by a registered lifting machinery inspector. The beam required is 28m long and therefore requires a break in the middle and needs to be disassembled after each structure erection and reassembled at the next structure site as it is too long to transport.

The beam is however, not a “lifting machine” and therefore does not need to be inspected and tested by an inspector each time it is reassembled.

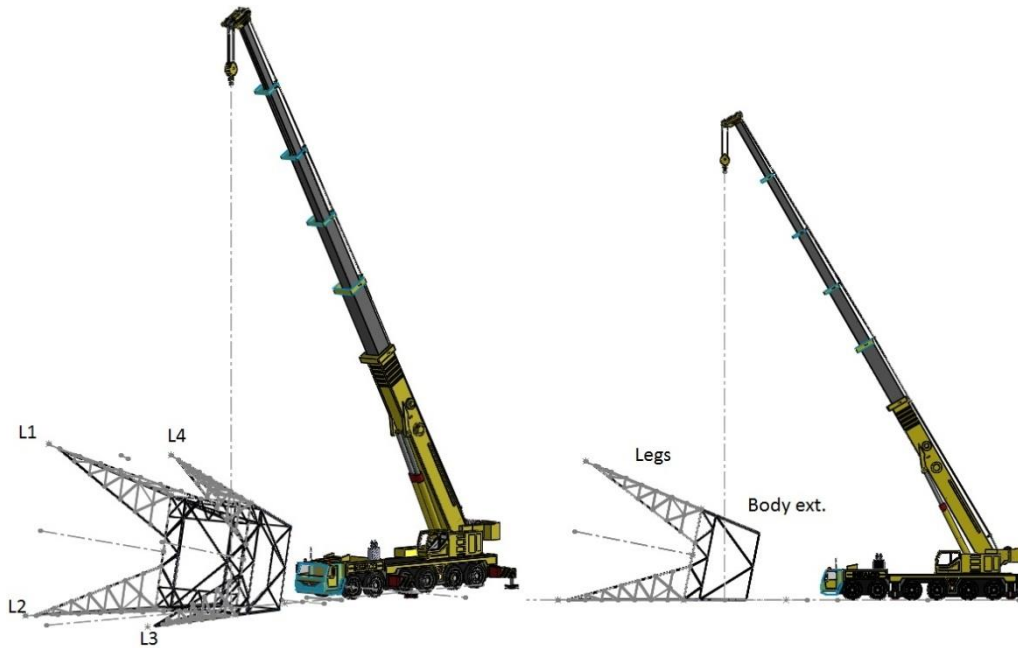


**Figure 41: Lifting procedure overview of erection of cross-rope suspension structure with a spreader beam and one crane**

After MBL and MBR are positioned on the stubs, the cranes can hold EW1 and EW2 in position so that G2 – G4 can be pulled and attached to the foundation stubs (nonadjustable) and G1 can be pulled and tightened with a load cell (adjustable) to 10% of the UTS before someone climbs the masts to release the cranes.

### 3.6. New method to erect self-supporting suspension structure

The proposed method to minimise the amount of lifts needed to erect the self-supporting suspension structure, as well as to eliminate the dressing process, is to lift the legs and the body extension as a single piece as shown in Figure 42.



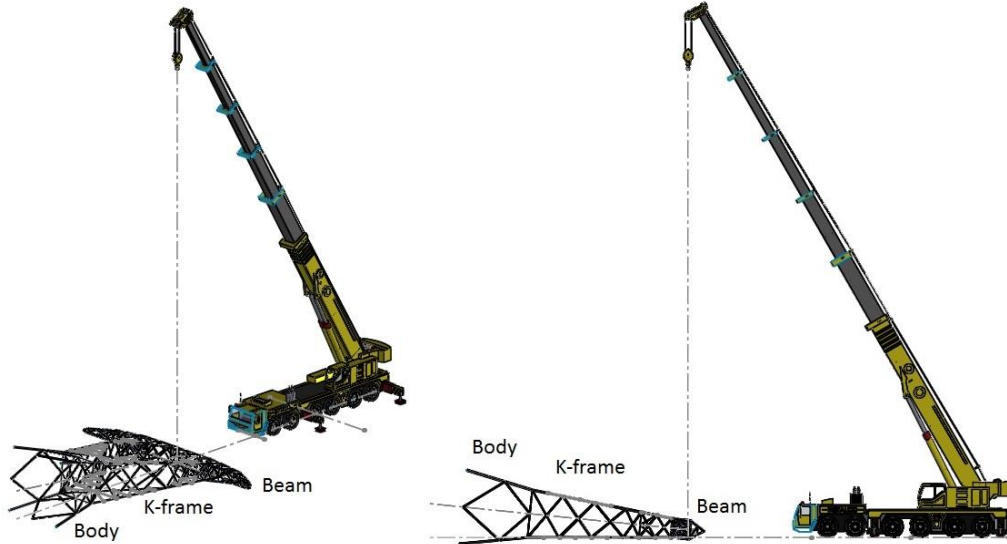
**Figure 42: Erection of self-supporting suspension structure legs and body extension in one lift**

Thereafter the body, K-frames and beam can be lifted in a single piece as shown in Figure 43.

The contractor must properly plan the lift to ensure:

- The modules are assembled as per the appropriate approved drawing and connected according to the drawings.
- The first section (legs and body extension) should be the correct distance from the final attachment points of L1 - L4 on the stubs of the foundations, as well as close enough to the crane to allow for the weight of the section to fit into the loading chart. It should also leave enough room for the second section (body, K-frames and beam) to be assembled and also be close enough to stay in the reach of the final attachment point and the crane in the loading chart.

- Adequate spreader beams are used to allow for spreading of the lifting load, as well as temporary bracing, keeping the deviation of members pressing onto the ground under the self-weight of the section, to a minimum.



**Figure 43: Erection of self-supporting suspension structure body, K-frames and beam in one lift**

The layout of the two sections, their weight, their assembled location in relation to the position of the foundation stubs and the crane are all very important aspects of the lift that needs proper detailed planning.

After erection the contractor must ensure that:

- Installation of all bolts is completed ensuring correct orientation of nuts to the outside / downward.
- All bolts are punched and painted.
- Fix all minor galvanising damage that may have occurred during the structure erection process with a method approved by the Galvanizer's Association of South Africa.

### 3.7. Summary

The proposed new methods all reduce the number of lifts required to erect the structure. It further ensures that more of the critical joints are assembled on the ground and that more of the structure members are permanently fastened on the ground for inspection before the structure is erected.

## Chapter 4. Implementing the new methodologies

### 4.1. Introduction

From the practices discussed in Section 2.8 on the current methods used to erect structures, it is clear that the current hazards to the design, as well as the safety of the personnel are not adequately mitigated. There is need for new processes/methods to address these hazards or avoid them all together. The methods described below are to be avoided as far as possible:

- Assembling of the structure’s critical joints at height with difficult work conditions, difficult inspection to conformance of design and unstable structure during the assembly.
- Having climbers on the structure while it is in a temporary state of weakness due to the incomplete assembly.
- Attaching of hardware (critical points of attachment of conductors and insulators), service ropes and cross-ropes in the air where it cannot be thoroughly inspected.
- Lifting and attaching of stringing equipment and guide ropes to attach to earth wire attachment points and hardware.

### 4.2. Guyed-V suspension structure lift

In the Western Cape on a 765 kV line, a contractor agreed to help test the feasibility of erection of a 703B guyed-V structure with the hardware, insulators and running blocks attached.

The main concern by the contractor was the additional weight of the hardware, insulator and running blocks. A rough rigging study was done with the weights in Table 7:

**Table 7: Weights of additions to lifting process as estimated by contractor**

Weight of running block ( kg)	800 x 3
Weight of assembly ( kg)	120 x 3
Weight of dolly ( kg)	650
Weight of hook block ( kg)	850 (1 sheave, 3 lines, 31.2t capacity)
Weight of lifting beam & tackle ( kg)	1000
Total ( kg)	5260

\*The weights are the estimates of the contractor and are rounded up for simplification to use and calculated on site and have an additional safety margin.

A more accurate study would weigh the lifting beam and dolly for a closer approximation and would create a more positive and assured mind set on site. If glass disc insulators are to be used instead of composite insulators, 660 kg x 3 should be added to the total weight as seen in Table 8.

**Table 8: Weights of 765 kV guyed-V structure with additional weights**

Attachment height (m)	Structure weight (kg)	Additional weight (kg)	Weight on crane (kg)
30	13372	5260	18632
31.5	13711	5260	18971
33	13967	5260	19227
34.5	14224	5260	19484
36	14480	5260	19740
37.5	14737	5260	19997
39	14994	5260	20254

The maximum weight lifted would still be within the capacity of the lifting tackle and beam of the contractor (tested at 36.2 tons), as well as the capacity of the crane.

Figure 44 shows the successful lifting of the 703B on site with all the insulators, hardware and running blocks attached. The detailed running block with running earths can be seen in Figure 46. The rope over the running block will be used to feed the pilot cable over the running block from ground level, which in turn will be used to pull the running board with all the conductors under tension through the running block.

It can clearly be seen that all the details of these components and the way they attach to the structure can now be inspected on the ground before the lifting of the structure commences. This will greatly improve quality insurance and safety assurance.

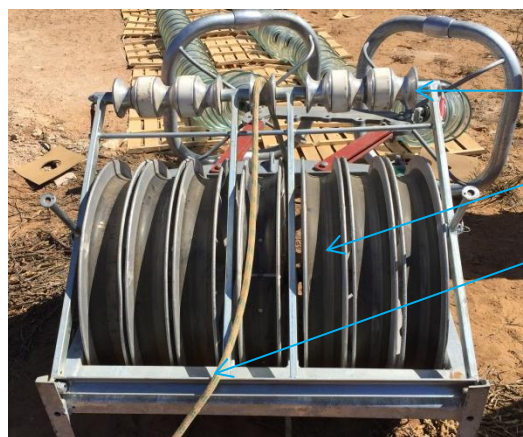


**Figure 44: Erection of a guyed-V suspension structure with all accessories**

The composite insulator supplier was concerned with the amount of bending that would incur during the lifting. The first lift was used to check and it turned out that this was less of a concern than anticipated. The weight of the running block causes enough friction to keep the insulator under slight tension during the time it is being lifted but still hanging on the ground. The result can be seen in Figure 45.



**Figure 45: Bending of composite insulator during erection of a guyed-V suspension structure**



**Figure 46: Running block with running earths installed**

The risk can be quantified for the guyed-V structure similarly to that of the guyed cross-rope suspension structure. If the structure is used 80% of the time in a line of 80 km long (765 kV does not use cross-rope structures) it will equate to 160 structures at a span length of 400m, then the risk is calculated with Table 9:

**Table 9: Risk calculation for erection of guyed-V suspension with hardware & insulators**

<b>What goes wrong?</b>	<b>How likely?</b>	<b>Exposure?</b>	<b>Severity / Consequence?</b>
Lifting tackle fails	0.0001 times per use	160 times per year	2 fatalities (\$100 000)
Crane breaks	0.003 times per use	160 times per year	Loss of time (\$10 000)
Weather delays	0.015 times per construction event	160 times per year	Loss of time (\$1000)
Winch causes collapse of hardware during dressing	0.001 times per use	0 times per year	2 fatalities (\$100 000)
Temporary stay collapses	0.0001 times per use	0 times per year	1 fatality (\$50 000)
Bolts not tightened causes part of structure to collapse	0.0025 times per event	160 times per year	1 serious injury (\$20 000)
Worker falls from structure	0.01 times per climb	640 times per year	1 fatality (\$100 000)
Tools fall on worker from structure	0.01 times per climb	640 times per year	1 injury (\$10 000)

**Equation 6: Unit risk calculated for erection of a guyed-V suspension structure with hardware and insulators attached**

$$\begin{aligned} UR &= (0.0001 \times 160 \times 100,000) + (0.003 \times 160 \times 10,000) + (0.015 \times 160 \times 1000) \\ &\quad + (0.001 \times 0 \times 100,000) + (0.0001 \times 0 \times 50,000) + (0.0025 \times 160 \\ &\quad \times 20,000) + (0.001 \times 640 \times 100,000) + (0.01 \times 640 \times 10,000) \\ &= \$144,800.00 \text{ per year} \end{aligned}$$

The risk quantified without the hardware and insulators attached equates to \$192,800.00, which shows a risk reduction of 24.9% when the dressing process is removed.

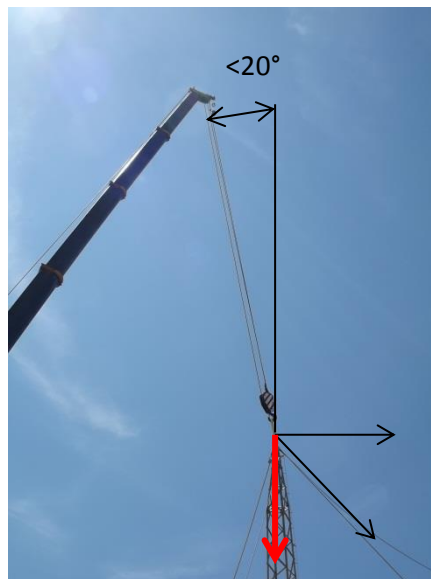
The method was tested in the field with the help of a willing contractor. It was completed successfully. The risk and quality benefit will have to be tested over the course of a few years or proposed for further study.

### 4.3. Guyed cross-rope suspension structures

#### 4.3.1. Two-crane method

Figure 47 below shows the lift being done on site on 20 January 2014, and was taken just after the tyres (serving as protective covers while the masts are dragged across the ground) are removed and the masts are positioned over the locating pins on the foundations.

A major concern was that the added weight of the running blocks would create a large tension in the cross-rope, and hence horizontal force on the crane hook which should be below 20°.



**Figure 47: Horizontal force on crane hook during erection with two-crane method**

The weight of the masts in Table 11 far outweigh the mass of the assemblies and running blocks and created a large enough force directly vertically below the hook and kept the crane hook within the 20° limit.

**Table 10: Weights of additions on lifting of cross-rope structure**

Weight of running block ( kg)	130 x 3
Weight of assembly ( kg)	40 x 3
Weight of glass insulators ( kg)	93.6 x 3
Weight of hook block ( kg)	275 (1 sheaves, 3 lines, 16t capacity)
Weight of lifting tackle ( kg)	50
Total ( kg)	1115.8

The weights in Table 10 are researched from suppliers [44], as well as contractors, and are rounded up for simplification to use and calculate on site and have an additional safety margin.

Table 11 shows that the tallest mast for a guyed cross-rope suspension structure with a 33m attachment height would weigh only 2351 kg. The attachments' weight would need to be divided between the two cranes.

**Table 11: Weights of 400 kV guyed cross-rope structure masts with additional weights**

Attachment height (m)	Structure weight per mast ( kg)	Total additional weight ( kg)	Weight on each crane ( kg)
18	1540	1115.8	2097.9
19.5	1654	1115.8	2211.9
21	1728	1115.8	2285.9
22.5	1800	1115.8	2357.9
24	1873	1115.8	2430.9
25.5	1946	1115.8	2503.9
27	2058	1115.8	2615.9
28.5	2133	1115.8	2690.9
30	2206	1115.8	2763.9
31.5	2278	1115.8	2835.9
33	2351	1115.8	2908.9

A 70-ton crane with a 50m boom length would still be able to lift 6.7t at a working radius of 9m which is well above the maximum required load for the tallest mast. It shows that the weight of the lift is not the limiting factor, which determines the capacity of crane, but rather the height of the masts. Whether the masts are lifted with the assemblies and running blocks in place or not, will make little difference.



**Figure 48: Erection of a guayed cross-rope suspension structure with two cranes**

It can be seen that the process of lifting both masts with the cross-rope and hardware assemblies in place (Figure 48) will be quite similar to that of lifting one mast with the previous method except that the dressing process will be eliminated and that climbers do not have to climb the structure that often. The lift can be done with no temporary backstays, and climbers only ascend the structure after erection is complete and the guy wires tightened.

If, in the future, one were to combine this method with the use of a bucket truck to do the clamping in of the conductor, the whole process of erection (and dressing), stringing/regulating and clamping in of the conductors, can be done with climbers only ascending the structure to disconnect the crane.

The risk benefit associated with the use of the new method is then calculated with Table 12:

**Table 12: Risk calculation for erection of cross-rope suspension with two cranes**

What goes wrong?	How likely?	Exposure?	Severity / Consequence?
Lifting tackle fails	0.0001 times per use	160 times per year	2 fatalities (\$100 000)
Crane breaks	0.003 times per use	320 times per year	Loss of time (\$10 000)

What goes wrong?	How likely?	Exposure?	Severity / Consequence?
Weather delays	0.015 times per construction event	160 times per year	Loss of time (\$1000)
Winch causes collapse of hardware during dressing	0.001 times per use	0 times per year	2 fatalities (\$100 000)
Temporary stay collapses	0.0001 times per use	0 times per year	1 fatality (\$50 000)
Bolts not tightened causes part of structure to collapse	0.0025 times per event	160 times per year	1 serious injury (\$20 000)
Worker falls from structure	0.01 times per climb	640 times per year	1 fatality (\$100 000)
Tools fall on worker from structure	0.01 times per climb	640 times per year	1 injury (\$10 000)

**Equation 7: Unit risk calculated for erection of a guyed cross-rope suspension structure with the two-crane method**

$$\begin{aligned}
 UR &= (0.0001 \times 160 \times 100,000) + (0.003 \times 320 \times 10,000) + (0.015 \times 160 \times 1000) \\
 &\quad + (0.001 \times 0 \times 100,000) + (0.0001 \times 0 \times 50,000) + (0.0025 \times 160 \\
 &\quad \times 20,000) + (0.001 \times 640 \times 100,000) + (0.01 \times 640 \times 10,000) \\
 &= \$149,600.00 \text{ per year}
 \end{aligned}$$

In 2.2.2 (Risk Quantification), the risk of erecting the guyed cross-rope suspension structure was showed to be \$304,000.00 per year with the currently used method of using one crane with two lifts. The risk is therefore reduced by 50.8% by removing the dressing procedure and using two cranes.

It is concluded that the old process would take more time because of repositioning the crane and climbing up and down the structure, which gives the new method a great time saving bonus. To specify exactly at what speed a contractor can build a line is difficult because it depends largely on the requirements of the client. If the client requires that 80 km of line be built over the period of a year, the contractor may only need one team of staff for structure erection.

If the client however, requires that 80 km of line be built over a short period the contractor would need two teams of staff working from opposite ends of the line for instance. With the addition of another team, the cost will increase as the supervision and management requirements will double. It is therefore clear that there is benefit in building the line quicker by doing the activities quicker and therefore reducing the cost and requirements placed on management and supervision. The new method shows a time saving of approximately 50% over the old method for erection of the structure and gives the added bonus of eliminating the dressing process.

The method was tested in the field with the help of a willing contractor. It was completed successfully and showed the expected time benefit. The risk benefit will have to be tested over a period of a few years.

Table 13 shows the cost of using two cranes with capable reach for erecting the guyed cross-rope suspension structure with the two-crane method.

**Table 13: Crane parameters for lifting of cross-rope with two cranes**

Cost of crane (R/h)	Crane boom height req. (m)	Crane capacity ( kg)	Weight of load ( kg)
2 x 900	47	8000	2908.9

If the cranes can be used to lift one tower per hour (same as with the two-crane method for comparative purposes), the cost of the crane per structure would be R1800.

One problem, as with the other lifting proposals, is that more running blocks would be needed to lift structures long in advance of stringing activities.

#### **4.3.2. Spreader beam method to erect guyed cross-rope structure**

For the spreader beam method of erecting the guyed cross-rope suspension structure, the weights mentioned in Table 10 and Table 11 still apply.

Below, in Figure 49 the lift being done successfully at the Eskom structure test facility in Rosherville in Johannesburg can be seen. It was taken just after the tyres (serving as protective covers while the masts are dragged across the ground) were removed and the masts were positioned over the locating pins on the foundations.

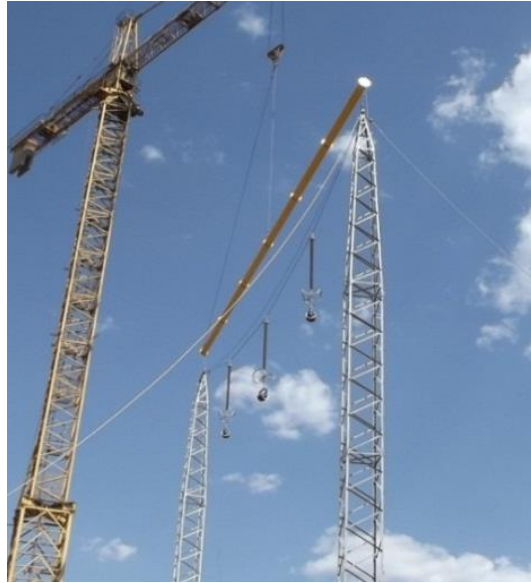
As a precaution during the first series of lifts, the cross-rope with hardware and insulators was left out to minimise the weight of the lift and simply focus on the layout of the lifting tackle and the working of the spreader beam.



**Figure 49: Erection of guyed cross-rope suspension structure with a spreader beam**

After the success of these lifts, the cross-rope was added with the hardware and insulators and running blocks. The test was repeated successfully as can be seen in Figure 50.

The process of lifting both beams with the cross-rope and hardware assemblies in place (with one crane) was similar to that of lifting both masts with two cranes. The lift was done with no temporary backstays, and climbers only ascended the structure after erection was completed and the guy wires tightened. It was concluded that the process of using two cranes, although showing a substantial benefit over the current method, would still show more risk than with the use of the spreader beam as there is one less crane in the process.



**Figure 50: Erection of a guyed cross-rope suspension structure (with hardware assemblies) with a spreader beam**

The risk (as quantified in Equation 7) for erecting the guyed cross-rope suspension structure with one crane and a spreader beam is reduced by 52.36% which is a further improvement on the method of using two cranes.

This method shows similar time benefits as expected with the two-crane method for erecting the guyed suspension cross-rope structure.

Table 14 shows the costing details (R/h) of a crane with a 12,400 kg capacity at a boom extension of 56m.

**Table 14: Crane parameters for lifting of cross-rope with spreader beam**

Cost of crane (R/h)	Crane boom height req. (m)	Crane capacity (kg)	Weight of load (kg)
1200	56	12400	6117.8

If the crane can be used to lift one tower per hour (same as with the two-crane method for comparative purposes), the cost of the crane per structure would be R1200.

It can be seen that the cost of the crane per structure is lower than with the two-crane method although the two methods show similar benefits in terms of time and risk saved.

The test was completed successfully and showed the expected time benefit. The risk benefit will have to be tested over a period of a few years.

Contractors questioned about the proposed method, were unsure about the requirements on such a long lifting beam, as it was never done before for a transmission line construction. It was believed that the beam would have to be inspected (or even tested) between every lift because it would have to be split in two and reassembled for the ease of transportation. The South African Load Testing Services (SALTS) were contacted in this regard and the opinion of a professionally registered lifting tackle inspector obtained. It revealed that the beam would only need to be inspected, as all other lifting tackle, and not after every use.

A further concern, as with the other lifting proposals, was that contractors would not have enough running blocks to lift structures long in advance of stringing activities.

#### 4.4. Self-supporting suspension structures

For the self-supporting suspension structure the method to erect the structure with the body, K-frames and beam assembled as one was done on site. The lift was done without any of the dressing additions (as was seen with the cross-rope method) but with the main focus on reducing the number of lifts required to erect the structure.

The weights in Table 15 are researched from suppliers, as well as contractors, and are rounded up for simplification when used for calculations on site, and to add an additional safety margin.

**Table 15: Weights of additions on lifting of self-supporting suspension structure**

<b>Weight of hook block ( kg)</b>	275 (1 sheaves, 3 lines, 16t capacity)
<b>Weight of lifting tackle ( kg)</b>	50
<b>Total ( kg)</b>	325

If these weights are then added to the weights of the larger sections of the structure, the results are as seen in Table 16.

**Table 16: Section weights of 400 kV 518H self-supporting suspension structure**

Structure section	Structure weight (kg)	Additional weight (kg)	Total weight on crane (kg)
Body and superstructure	8515.2	325	8840.2
6m body extension	3276.2	325	3601.2
12.0m leg	789.8	325	1114.8

In this case the factor determining the capacity of the crane will be the weight of the body and superstructure (beam and 2 x K-frames) as it is the heaviest load and needs to be lifted the highest.



**Figure 51: Example of a self-supporting suspension body, K-frames and beam being lifted**

Figure 51 shows the method of lifting the body and superstructure (beam, K-frame and body) which was tested by a contractor. The crane was able to pick up the load but the structure was supported by a truck-mounted crane to keep some loading off the loose members. After the structure was off the ground and supported completely by the cranes, without any damage to the structure, a climber disconnected the truck-mounted crane and the structure was placed on the legs and the assembly was completed.

The climber, however, had to climb a load supported by a crane to disconnect the truck-mounted crane when the quick release mechanism failed. The test proved that the method is feasible with precautionary methods put in place such as the use of temporary bracing to strengthen the loose members or a cherry picker to disconnect the truck-mounted crane.



**Figure 52: Foreign practice of assembling the legs of a structure as one piece before erection**

Foreign practice shows assembling of the structure with cherry pickers (Figure 52) to avoid climbing; it also shows assembling of all the legs into a single piece before lifting it as one.

The risk when erecting the self-supporting suspension structure with fewer lifts compared to the current practice was calculated using the same method as with the guyed cross-rope suspension structures and can be seen in Table 17.

If the same assumptions are made (for calculation purposes) as for the cross-rope suspension structure, an 80 km line would require 160 guyed cross-rope suspension structures and a possible twenty (10%) self-supporting suspension structures. If thirteen processes are required to lift the structure, then:

**Table 17: Risk calculation for erection of self-supporting structure**

What goes wrong?	How likely?	Exposure?	Severity / Consequence?
Lifting tackle fails	0.0001 times per use	260 times per year	2 fatality (\$100 000)
Crane breaks	0.003 times per use	260 times per year	Loss of time (\$10 000)
Weather delays	0.015 times per construction event	260 times per year	Loss of time (\$1000)
Winch causes collapse of hardware during dressing	0.001 times per use	60 times per year	2 fatalities (\$100 000)
Temporary stay collapses	0.0001 times per use	160 times per year	1 fatality (\$50 000)
Bolts not tightened causes part of structure to collapse	0.0025 times per event	260 times per year	1 serious injury (\$20 000)
Worker falls from structure	0.001 times per climb	260 times per year	1 fatality (\$100 000)
Tools fall on worker from structure	0.01 times per climb	260 times per year	1 injury (\$10 000)

**Equation 8: Unit risk calculated for erection of a self-supporting suspension structure in 13 lifts**

$$\begin{aligned}
 UR &= (0.0001 \times 260 \times 100,000) + (0.003 \times 260 \times 10,000) + (0.015 \times 260 \times 1000) \\
 &\quad + (0.001 \times 60 \times 100,000) + (0.0001 \times 160 \times 50,000) + (0.0025 \times 260 \\
 &\quad \times 20,000) + (0.001 \times 260 \times 100,000) + (0.01 \times 260 \times 10,000) \\
 &= \$86,100.00 \text{ per year}
 \end{aligned}$$

If the method was changed to pick up the structure in only eight lifts instead of thirteen, the risk is projected as follows:

**Equation 9: Unit risk calculated for erection of a self-supporting suspension structure  
in 8 lifts**

$$\begin{aligned} UR &= (0.0001 \times 160 \times 100,000) + (0.003 \times 160 \times 10,000) + (0.015 \times 160 \times 1000) \\ &\quad + (0.001 \times 60 \times 100,000) + (0.0001 \times 80 \times 50,000) + (0.0025 \times 160 \\ &\quad \times 20,000) + (0.001 \times 160 \times 100,000) + (0.01 \times 160 \times 10,000) \\ &= \$55,200.00 \text{ per year} \end{aligned}$$

The erection of the self-supporting suspension structure in eight lifts instead of thirteen would result in a reduction in the risk by 36%. It was also concluded that the old process would take more time because of the additional lifts and due to workers climbing up and down the structure, which gives the new method a great time saving bonus and further cost saving advantages.

#### **4.5. Case study**

To try and assess the impact on future projects in terms of costing requires the current cost of certain activities needing to be fixed. To fix the cost of these activities by market research is very difficult because some contractors would increase their tender price on foundations (built before the construction of structures start) to increase their cash flow at the beginning of the contract. They will then tender for less for stringing (as an example) to rectify this early digression.

To check the possible cost implications of the new proposed methods, a few assumptions had to be made while evaluating previous transmission line construction costs. A specific line was chosen which was divided into two almost equal sections and built by two contractors simultaneously. The line is approximately 80 km in length (2 x 40 km contracts) and consists of a conductor configuration and structure combination commonly used on 400 kV lines.

The total cost of the construction of the two sections of the transmission line was evaluated and the cost of guyed cross-rope suspension structures, as well as self-supporting suspension structures, foundations, stringing and dressing were compared and came out to vary by less than 2%.

It also showed that some contractors would add nearly 20% to the material cost of a structure for the assembly and erection cost while another would add only 10-12% to the material cost.

Firstly, an assumption was made about the soil conditions that would determine the foundation types. This is specified in Table 18.

Table 19 shows the assumptions that were made with regard to the costing between the two contractors. Contractor B was kept as the baseline as his cost for construction activities was assumed to have no tender deviances (compared to data from other contracts). The last column of Table 19 shows the assumed increase in tender activity costs by Contractor A in this regard.

**Table 18: Expected foundation type distribution**

Foundation type	Expected portion of line
Type 1	22.5%
Type 2	35%
Type 3	21.5%
Type 4	9.5%
Hard rock	4.5%
Soft rock	7%

The costing of the activities was then broken down between the two sections and the assumption was made that Contractor B did not make any changes to the pricing of his activities while the changes that Contractor A made can be seen below in Table 19.

**Table 19: Comparison between two contractors**

Activity	Structure Type	Contractor A cost (R)	Contractor B cost (R)	Contractor A Approx. Increase
Foundations	529A guy	859420.54	684701.27	+25%
	529A centre	431632.74	395793.21	+10%
	518H	4512705.08	3491683.62	+25%
Stringing	40 km	4684600.00	6485480.00	-27.5%
Structure assy. & erection	529A	409996.73	185434.12	+120%

Activity	Structure Type	Contractor A cost (R)	Contractor B cost (R)	Contractor A Approx. Increase
Structure assy. & erection	518H	3415723.69	1799889.21	+90%
Structure dressing	529A	39123.00	40080.00	+0%
Structure dressing	518H	41929.62	78156.00	-50%
Structure material	529A	2439727.05	2579207.28	-5%
	518H	14935238.96	16327098.63	-10%
Total		31770097.40	32067523.34	
Difference				0.93%

From this an average pricing of each activity was calculated and the pricing of the activities can be seen in Table 20.

**Table 20: Cost per structure activity**

Activity	Structure Type	Cost per structure (R)	Cost per structure leg (R)
Foundations	529A guy	34305.94	8576.49
	529A centre	19704.66	9852.33
	518H	98636.77	24659.19
Stringing	40 km	161837.45	N/A
Structure assy. & erection	529A	9294.91	N/A
Structure assy. & erection	518H	42980.65	N/A
Structure dressing	529A	1980.08	N/A

Activity	Structure Type	Cost per structure (R)	Cost per structure leg (R)
Structure dressing	518H	2077.12	N/A
Structure material	529A	128683.43	N/A
	518H	422072.34	N/A

These costs in Table 20 are however, not the costs involved with the use of the new proposed methods. To estimate the impact of these new methods requires knowing that the line that was used for the costing of the activities was built with the use of the single crane method and back staying of the cross-rope suspension structures and construction of the self-supporting suspension structures in the currently accepted method.

Further assumptions have to be made in terms of the time it takes with the three different methods proposed to construct the cross-rope suspension structure. These assumptions are shown in Table 21. It shows that if we assume that we currently erect a guyed cross-rope suspension structure in two hours with the old method, and we change this to the new method of erection with two cranes, we expect the process to take only one hour because both masts are lifted simultaneously. The same applies for the spreader beam method.

**Table 21: Assumption for lifting cross-rope suspension structure with different methods**

	Cranes	Lifts	Time (hours)	Cost per lift (R)
Current method	1 x 90ton	2	2	1800.00
2 Crane method	2 x 90ton	1	1	1800.00
1 Crane method	1 x 120ton	1	1	1200.00

It can be noted that if the guyed cross-rope suspension structure was erected using the two-crane method that there would be no cost impact although there would be a significant time-saving.

Table 22 shows that if one were to use the one-crane method with the spreader beam to erect the guyed cross-rope suspension structure, there is a cost saving in the erection method of up to 28% as the erection cost drops from R9294.91 to R8094.91 and the cost of dressing of the structure falls away completely.

**Table 22: Cost of different cross-rope suspension erection methods**

Activity	Structure type	Old cost (R)	Two-crane method (R)	Spreader beam method (R)
Structure erection	529A	9294.91	9294.91	8094.91
Structure dressing	529A	1980.08	0	0
Total		11274.99	9294.91	8094.91

If one were to apply these costing estimations on the construction of future lines such as the Medupi – Borutho 400 kV line, the cost for the erection of the guyed cross-rope structure with the two methods applied can be seen in Table 23.

**Table 23: Cost of guyed cross-rope structure erection applied on a new line**

Activity	Old cost (R)	Two-crane method (R)	Spreader beam method (R)
Structure assy. & erection	9294.91	9294.91	8094.91
Dressing	1980.08	0	0
Total cost for 263 structures	2965322	2444561	2128961
Expected saving	N/A	17.56%	28.2%

The cost therefore is not increasing and, as can be seen in Table 23, can in fact lower the cost of erecting and dressing the structure although it will only have a slight impact on the overall cost of the project.

If the census results are applied to these assumptions, the expected 80 km of line that is constructible per year per contractor (requiring 160 cross-rope suspension structures), can be built faster (as expected) and could be erected in half a year, although the speed of construction of the foundations could then become the governing factor.

#### **4.6. Expected impact on design for construction**

##### **4.6.1. Erecting the guyed cross-rope suspension structure with the two-crane method**

The two-crane method tested successfully and shows an expected reduction in risk of 50.8% largely due to the removal of the dressing process and the reduction in the need to climb the structure. In addition to this, the benefits foreseen include a greater assurance of quality as inspection of all critical joints of the cross-rope attachment and service rope attachment can be inspected on the ground prior to erection. Further benefits include the improvement in the speed of construction.

##### **4.6.2. Erecting the guyed cross-rope suspension structure with the spreader beam method**

The spreader beam method tested successfully and shows an expected reduction in risk of 52.36% largely due to the removal of the dressing process, the reduction in the need to climb the structure and using only one crane. In addition to this the benefits foreseen include a greater assurance of quality as inspection of all critical joints of the cross-rope attachment and service rope attachment can be inspected on the ground prior to erection. Further benefits include the improvement in the speed of construction, as well as cost savings.

#### **4.6.3. Erecting the self-supporting suspension structure in fewer lifts**

Although the test of the erection method for lifting the self-supporting suspension structure showed the need for additional safety precautions, the test was carried out successfully.

The expected reduction in risk is expected to be as much as 36% due to the reduction of lifts required for the erection from thirteen to eight. Greater quality assurance can be expected due to critical joints being completed and inspected on the ground prior to the lift.

#### **4.6.4. Erecting the self-supporting suspension structure in fewer lifts**

Testing of the erection method for lifting the guyed-V suspension structure proved to be successful. Reduction in the risk is estimated at 24.9% because of the removal of the dressing process. Improved quality insurance is expected because of inspection of critical hardware attachment joints on the ground before the erection. The calculations were done for use on a 765 kV line where it will have the biggest influence. On 400 kV lines the structure would likely be used as little as 3-5% of the time or less.

### **4.7. Summary**

The research into the weights that the contractor use in their methods to estimate their crane requirements shows that the industry is not sure of the weights of their equipment. Research show that running blocks weigh as little as 240 kg each for a hex bundle running block (not 800 kg as shown in Table 7) [45], [46], [44].

Proper rigging studies with accurate structure weights, as well as accurate lifting tackle weights and hardware and insulator weights will go a long way in ensuring a positive mind set on site and reassurance in the proposed new methods of structure erection.

The proper testing of the methods in the field was done and proves the technical feasibility thereof. The time saving benefits, as well as the cost saving benefits still need further study with input from the construction industry.

The method for erecting the self-supporting suspension structure in fewer lifts needs further testing with the help of willing contractors.

## **Chapter 5. Conclusions and recommendations**

### **5.1. Conclusions**

A fairly rapid increase in the demand for electricity in South Africa combined with the decrease in generating capacity and new grid code requirements has placed Eskom under strain to provide new infrastructure through an expansion programme. There is therefore pressure to develop new infrastructure cheaply, safely, quickly and still according to design standards.

Recent surveys into the capability of contractors showed that the contractors construct transmission lines with methods they have been taught long before the advance in technology paved the way for new safer and better methods [16].

As a result of very poor documentation (both historically and present) of the construction methods used to construct high-voltage transmission lines, as well as possible poor communication between contractors and designers in the transmission line construction industry, the industry has become bereft of new safer, better construction techniques.

A further effect of this is that new designs are done without the designer adding details to simplify construction of designs. These designs that are done with the purpose of being cheaper and simpler and reducing risk during construction end up being constructed in an unsafe manner and adding more risk and cost which could have been avoided if the designer simplified the construction details during his design and specified this to the contractor.

International practice, both historic and present, was studied to see if methods of construction have progressed with new technologies internationally while simultaneously comparing it to the progression of local practices.

From this it appears that the construction of lines has not been captured properly or if it has, has not been openly published. There are also no study groups at CIGRE regarding construction risk. There is a CIGRE study on overhead line construction but it does not compare different methods in terms of risk analysis. It indicates some risks with each activity although the activities are not all used in South Africa.

The information obtained did however, indicate that the methods of line construction, particularly with regards to self-supporting structure erection and dressing and clamping in processes, have progressed abroad with the introduction of new construction tools such as

cherry pickers, bucket trucks and high capacity off-road cranes. Locally, however, the methods have not changed for some time. The use of guyed suspension cross-rope structures is common in South Africa but not abroad and could therefore not be compared with abroad cases. The same principles as used on self-supporting structures abroad (minimising lifts during erection) could however, also be applied to develop new methods of structure erection for the cross-rope suspension structure. The use of cherry pickers and bucket trucks should be used as a safer alternative to climbing with double lanyard systems.

The new method for erection of the guyed cross-rope suspension structures with two cranes have been tested successfully on a selected project and forcefully applied on certain projects of the Eskom expansion programme.

The method for erection of the guyed cross-rope suspension structure with a spreader beam has been successfully tested at the Eskom transmission line structure test facility in Rosherville in Johannesburg.

The comparison of the three methods for erection of the guyed cross-rope suspension structure can be seen in Table 24:

**Table 24: Comparison between three methods for erecting guyed cross-rope suspension structures**

	Time/structure (h)	Cost/structure (R)	Risk saving (%)
<b>Current method</b>	2	1800	0
<b>Two-crane method</b>	1	1800	50.8
<b>One crane and spreader beam</b>	1	1200	52.36

It is clear that the erection method with one crane and a spreader beam has the possibility of saving on construction time, if the contractor still uses the same amount of workers and simply has a spreader beam and a higher capacity crane. It also has the possibility to save money in terms of saving on erection time without needing more cranes. Further it has the benefit of reducing risk because of elimination of the dressing process.

The method of erecting the guyed-V suspension structure with its running blocks, insulators and hardware assembled as one piece was discussed and applied in conjunction with a contractor on a 765 kV line currently in construction. The method proved very safe, showed a complete

elimination of the dressing process and therefore reduced risk. It also saved considerable time, allowed for inspection on the ground of critical joints and therefore increased quality assurance.

In conjunction with this, a contractor on the same line used newly procured running blocks with running earths installed to earth the conductor at the structure during stringing.

## **5.2. Recommendations**

### **5.2.1. Documentation of current methods of construction**

The continuous documentation of the method of construction, as well as open communication between the construction industry and the designers is of key importance. The methods of line construction shown in this dissertation should be openly discussed at forums such as POLASA locally, and CIGRE internationally.

The methods that have shown to pose less risk, and have been tested on site, should be taught to contractors with their advantages. They can then be asked to tender for their projects with these methods of construction such as the two-crane method for erecting the guyed cross-rope suspension structure. Once these methods of construction are used on site by a few contractors, its benefits can be documented such as:

- Positive impacts on project schedules.
- Reduction of site activities and risks.
- No significant cost impacts. Possibly less costly.
- Less working at heights (cause of most fatalities).

The publishing of results such as this study should be done on international online boards such as CIGRE to encourage further international documentation of new construction techniques. While looking for previous or current research in the construction risk field in CIGRE documents, very little was found.

### **5.2.2. Future study and research**

The effects of applying new construction methods on projects that hold possible cause for future study (or working on CIGRE workgroups/study groups) include:

- Project schedules if all the material needed is not available on site, and the mitigation of these problems.
- Environmental effects and their minimisation.

- Environmental benefits of the new methods and how this can speed up the environmental impact assessment processes.
- Reverting to old construction methods if site conditions restrain the use of new methods, and the use of other temporary risk mitigation measures in these cases.
- Investigating the progression of technology and their possible application on the transmission line construction industry (ongoing).

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## Appendix A: Construction regulations

*“(2) The designer of a structure shall—*

*(a) before the contract is put out to tender, make available to the client all relevant information about the design of the relevant structure that may affect the pricing of the construction work;*  
*(b) inform the contractor in writing of any known or anticipated dangers or hazards relating to the construction work, and make available all relevant information required for the safe execution of the work upon being designed or when the design is subsequently altered;*  
*(c) subject to the provisions of paragraph (a) and (b) ensure that the following information is included in a report and made available to the contractor—*

*(i) a geo-science technical report where appropriate;*

*(ii) the loading the structure is designed to withstand; and*

*(iii) the methods and sequence of construction.*

*(d) not include anything in the design of the structure necessitating the use of dangerous procedures or materials hazardous to the health and safety of persons, which could be avoided by modifying the design or by substituting materials;*

*(e) take into account the hazards relating to any subsequent maintenance of the relevant structure and should make provision in the design for that work to be performed to minimize the risk;*

*(f) carry out sufficient inspections at appropriate times of the construction work involving the design of the relevant structure in order to ensure compliance with the design and a record of those inspections is to be kept on site;*

*(g) stop any contractor from executing any construction work which is not in accordance with the relevant design;*

*(h) conduct a final inspection of the completed structure prior to its commissioning in order to render it safe for use and issue a completion certificate to the contractor; and*

*(i) ensure that when preparing the design, cognizance is taken of ergonomic design principles in order to minimize ergonomic related hazards in all phases of the life cycle of a structure.”*

## **Appendix B: Bolts and nuts**

### **Bolt and nut threads**

During the manufacturing of bolts and nuts, a rod is first cut to the desired length of the bolt with a little extra material which is then formed into the head of the bolt. The diameter of the bolt is at this stage uniform and still equal to the final diameter of the shank of the bolt. The bolt is then put in a thread cutter or roller to cut the thread of the desired length into the shank. The tolerance of the thread is closely monitored and as the thread cutter die starts to wear out the thread diameter will start to increase. In direct contradiction when the nut thread is cut, as the die starts to wear, the diameter of the threaded hole will start to decrease. This means that if the dies wear more than the allowed tolerance, that the nut will not fit onto the bolt or will fit very tightly. It is thus clear that there should in theory never be a nut that fits too loosely although this is sometimes found on site. To explain this, the process of thread cutting to allow for galvanising should be explained.

When it is specified that the bolt and nut be galvanised the diameter of either the bolt thread or the diameter of the nut thread, it needs to be overcut to allow for the 45µm that will be added by galvanising. It sometimes happens that the nuts and bolts are ordered from different suppliers. When the order is placed for galvanised nuts, the supplier then assumes that it will fit onto a galvanised bolt and hence overcuts the thread of the nut to allow for this. Similarly, the manufacturer of the bolt overcuts the thread to allow for the galvanising. This means that the nut will fit too loosely over the bolt because of the double compensation for the thickness of the galvanising. This will greatly reduce the strength of the bolt thread and can lead to the stripping of the thread when tightening it.

The simple solution to this is to specify that all bolts be of standard thread diameter and that only nut threads be allowed to be overcut to allow for the increase in diameter of the bolt thread due to galvanising.

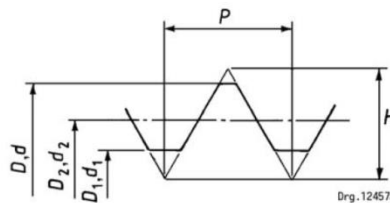
### **Difference in the shear strength of a bolt in the thread and the shank**

The strength of a material differs depending on whether the force applied to it is trying to shear the material or whether it only places it in tension. This can be simply explained by the example of taking a piece of paper and gripping it with two fingers on opposite sides and pulling in opposite directions. The paper is placed in tension and can resist considerable amounts of force.

In contrast to this when gripping the paper on only one side and pulling in opposite directions the paper very easily tears (shears).

The **tensile** strength of a typical bolt (will use a grade 6.8 bolt as example) is around 600MPa [47]. The **shear** strength of the bolt is around  $0.577 \times 600\text{MPa}$  or 346.2MPa.

To calculate the maximum shear force that a bolt can withstand, two things are required; namely the area of the bolt where the force is applied and the shear strength of the material. When looking at one bolt it is clear that the shear strength of the material will remain the same throughout, although the area might change depending on whether the force is applied on the shank of the bolt or over the thread [Figure 53].



**Figure 53 : Details of the thread of a bolt**

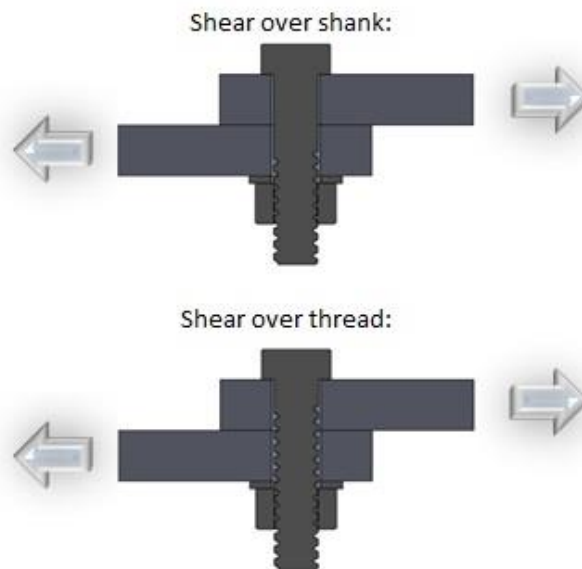
To see the difference we can use an example for comparison:

**Table 25: Mechanical properties of an example fastener**

Mechanical properties:	Tensile strength	Shear strength	
Grade 6.8 bolt	600 MPa	$\sim 0.577 = 346.2 \text{ MPa}$	
	Shank:	Thread:	Reduction:
Diameter:	$D=12 \text{ mm}$	$D_2 = 10.86 \text{ mm}$	
Area:	$113.1 \text{ mm}^2$	$92.63 \text{ mm}^2$	
Shear capacity:	$346.2 \text{ MPa} \times 113.1 \text{ mm}^2$	$346.2 \text{ MPa} \times 92.63 \text{ mm}^2$	
	39.2 kN	32.1 kN	18%

This example clearly shows an 18% reduction in the strength of an M12 bolt if the shear force is applied over the thread rather than the shank. In the assembly of lattice steel structures such as transmission line structures, this can become one of the major risks as there are so many bolts used to assemble the structures.

The image below (Figure 54) showing two plates to which forces are applied will show this problem more clearly. It is easy to see that from the first image the two plates pulling in opposite direction cause a shear force in the shank of the bolt. If a bolt is used that is too short the shear force applied will be applied in the threaded area of the bolt, immediately reducing the strength of the connection as shown in the above example.



**Figure 54: Difference in the shear of a bolt over the shank and the thread**

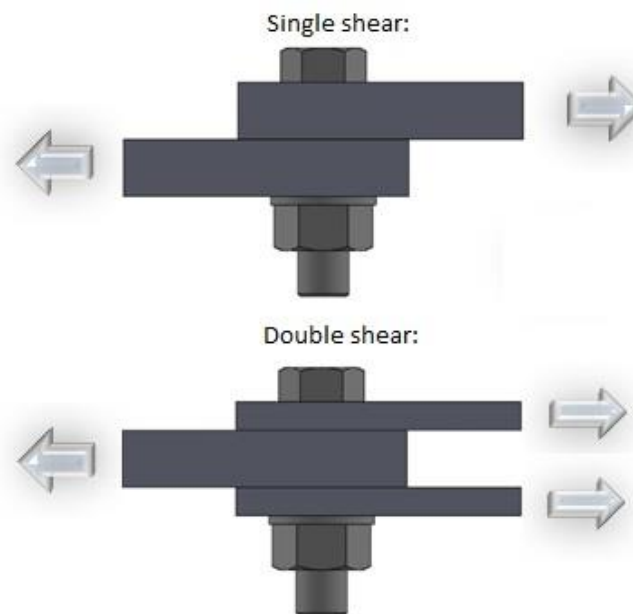
In conclusion, the use of the incorrect length of bolt used in the assembly of lattice steel structures can drastically reduce the strength of joints. A simple mitigation of this is to specify that a certain number of threads be visible after final tightening of the bolt and nut, which can then be inspected by a supervisor on site. The problem with the current situation is that structures are assembled on ground level in sections such as the beam, the K-frames, the body etc. and then picked up and bolted together in position which means that critical joints are bolted together above ground and can only be inspected from the ground with binoculars which makes it impossible to ensure that an adequate amount of thread protrudes at the nut end which creates a possibility for a serious engineering hazard.

### Single and double shear

The concept of single and double shear has in the past been overlooked as a hazard because it has been focused on as a risk during the detailing phase of structural design. Structures were detailed to avoid this as far as possible because it reduces the hazards during assembly, as well as simplifies the assembly on site. It is also very difficult to show this type of detail on 2D drawings. It has been seen though that just because this was overlooked as a hazard in the past, the few joints that do occur have been misassembled on site creating a much weakened structure.

To explain the concept of single versus double shear it is helpful to again use the example of the tearing paper. If one were to hold up one paper by gripping it with both hands on one side and pulling in opposite directions, the paper tears easily down the middle. If one were to do the same but instead of holding one paper, hold two sheets, the force required to tear the paper is greatly increased.

To apply this concept on lattice structures one should look at the following illustration:



**Figure 55: Single shear vs. Double shear of a bolt**

In the first illustration in Figure 55 it is easy to see that surface area provided by the bolts, which is used to counter the force in the member, is exactly half of that in the second example even though both have the same amount of bolts (one). This is because the second example uses a plate on both sides of the member to spread the load over shear surfaces on both sides whereas

the first example directs the force on only one side of the member and thus only on half the bolt surface.

The concept shows that if the structures were detailed with joining plates on both sides of members at joint positions, that half the amount of bolts would be required to assemble that structure than if it were detailed with joining plates on only one side to be able to carry the same design loads.

While at first this seems to be a great advantage because of the known problems with bolts with regards to their corrosion resistance, manufacturing problems of over- and undercut threads, shear capacity on threaded sections etc., and fewer bolts will drastically ease the proper inspection of the ones needed on the structure, the main risk is that if one of the joining plates are not placed in the assembly, or placed on the wrong side (placing the bolts in single shear) the structural joint instantaneously loses half of its strength. If however, the detailing is done to only use joining plates on one side of members and to use more bolts which are only placed in single shear, this problem would never occur, the biggest problem would be that a few bolts are not used in the joint, slightly reducing the joint capacity, or the bolts used are too short causing an 18% reduction of the joint capacity.

In the detailing of structures, from time to time it is expected that special cases restrict the length of joining members, and thus require the use of double shear designed joints. This needs to be kept in mind while assembly of structures is done to ensure that structure joints are not assembled incorrectly and thereby lessening its performance.

### **Corrosion of bolts**

When bolts are galvanised the whole bolt is manufactured and then galvanised. When nuts are manufactured however, the nut is made and galvanised and after galvanising the nut thread is cut. This is done because the process to galvanise bolts and nuts uses a centrifugal force of a spinning machine to clean off excessive galvanising, which would remain in the threads on the inside of the nuts and cause a blocking when trying to fit it with a bolt.

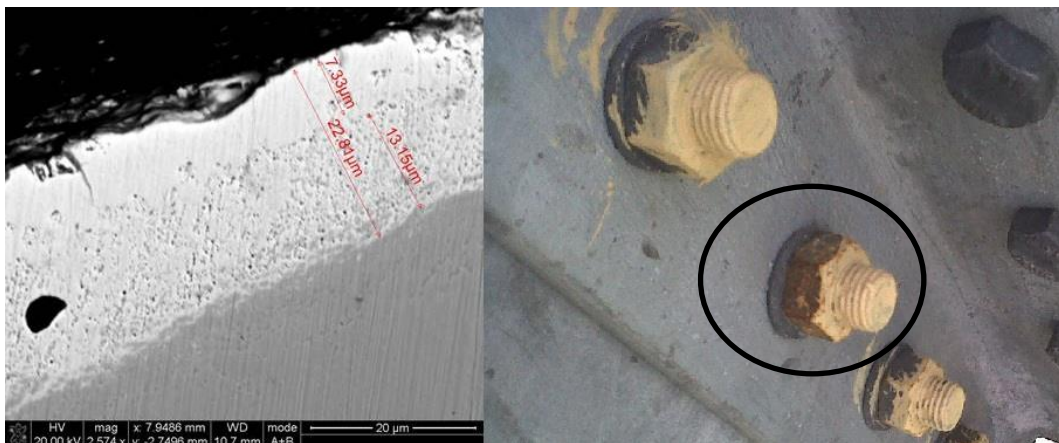
The thread of the nut is therefore exposed to corrosion until it is assembled with the bolt where the bolt thread sacrifices some of its galvanising to help protect the nut thread with which it is in direct contact [48].

Although this is ideal, it is however, not exactly what happens in practice; when in highly corrosive environments water collects in the crevice at the connection between the nut and the

bolt and starts corroding the nut and bolt thread which are two surfaces which are collectively protected with only 45 to 55  $\mu\text{m}$  of galvanising [49].

This can be fixed by using alternative types of coatings, such as thermo-diffusion zinc coatings, which can coat the thread of the nut and provide more corrosion protection. The thread of the bolt and the nut is then overcut to allow for the coating thickness and a product is used which gives a better corrosion resistance.

In general it is however, clear that bolts - especially galvanised bolts, are more prone to corrosion than the steel members that they hold together and are a hazard to the structure if they start corroding.



**Figure 56: Corrosion of bolts and nuts**

## Appendix C: Defects due to manufacturing and assembly

### Damage to steel members

Another hazard affecting transmission line structures is damage to members / plates during manufacturing. Carbon steel can sometimes show cracking because of different quantities of elements in the alloy combined with heating before bending. If the cracks are highly visible as seen in Figure 57, the member can be rejected. The cracks can sometimes be microscopic and still have a negative effect on the strength of the end product and can be unseen in inspection, especially if covered by a galvanised coating.



**Figure 57 : Crack in bended member of K-frame**

### Manufacturing defects in the steel angles and plates

Manufacturing defects that have a negative impact on the strength of a design include:

- Cracking and tearing at holes due to fixing of holes with welding prior to punching, or due to damaged punches (Figure 58).
- Delamination of the ends of a member after galvanising (Figure 59).



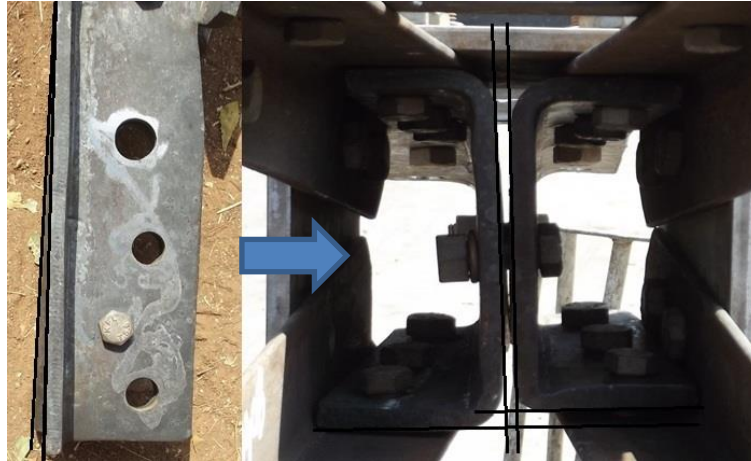
**Figure 58 : Cracking and tearing of punched holes**



**Figure 59 : Delamination of ends of members after galvanising**

### **Cross-ropes top cap assembly sequence**

In Figure 60 it can be seen that because the top cap of a guyed cross-rope suspension structure is assembled in the incorrect sequence, the members do not line up further in the assembly process. It is crucial that the two heads of the top cap are tightened together with all bent sides lining up before continuing to install angles on it. If not, the results can be seen on the right of Figure 60.



**Figure 60: Defects in the lining up of members due to incorrect assembly sequence**

## **Appendix D: Stringing**

### **Tools : Pullers and Tensioners**

While the conductor is pulled off the conductor drums, which it is supplied on, it has to be kept under tension to keep the weight of the conductor from creating sag in between the structures which will cause it to get dragged on the ground damaging it, or sagging into roads or other lines being crossed.

To keep the conductor under tension it has to be passed through a tensioner which has three rolls of the conductor on wheels to create a frictional grip on the conductor and a hydraulic brake. While on the opposite side of the section a similar configuration machine is used but with an engine and a clutch to pull the conductor in.

Figure 61 shows machines like these used in 1969 [50]. Although the concept has not changed much (using a tensioner with conductor drum station on one end and a puller on the other end of a stringing section), the technology of the tensioners have changed.



**Figure 61: Stringing of Boulder transmission line (266 miles) near Victorville in 1969**

Over the years it has become a requirement that a whole phase has to be strung at once (not one conductor at a time). This requires that the pilot cable be attached to a running board (Figure 62) and that the tension in each wheel of the tensioner has to be able to adjust individually with a clutch to ensure similar tension in each conductor and therefore the correct “attitude” of the running board as it passes through the running blocks [46] [45] [44].



**Figure 62: Stringing running board**

If the terrain makes it difficult to string with this method, single conductor pulls of the pulling of the pilot cable can still be done with a helicopter as shown in Figure 63.

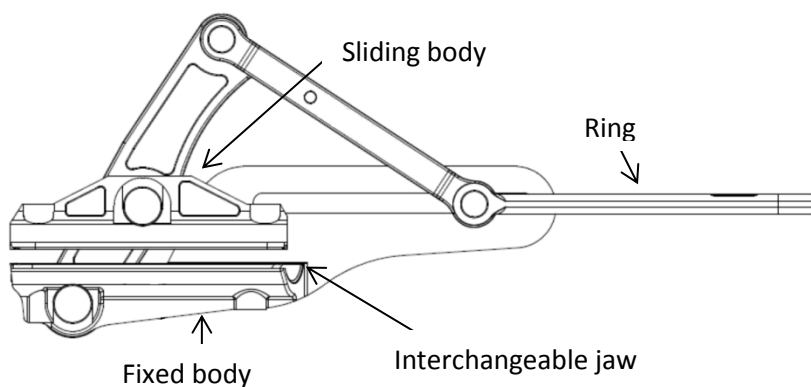


**Figure 63: Pulling pilot cable with helicopter on the Pacific Intertie line in 1968**

**Tools: Come-along clamps**

On various projects and construction sites, incidents have occurred on many occasions because of various reasons all of which surrounds come-along clamps (Figure 64). Some incidents have happened because of misuse of the clamps, others because of using the clamps incorrectly. Before looking at some of these incidents it is necessary to first look at the composition of the typical come-along clamp.

The clamp consists of a fixed body, a sliding body and a ring attached to the sliding body. Some clamps have interchangeable jaws made of a special material so as not to damage the conductor it is made to grip, such as soft copper jaws or aluminium jaws to grip the ACSR conductor (Aluminium conductor, steel reinforced). The different parts are illustrated clearly below.



**Figure 64: Come-along clamp components**

The clamp works on the same principle as a Formula One car (F1 car). The car has only its own weight to keep it on the ground when it is standing still but the moment it starts moving forward the downforce created by the air moving over its fenders presses the car onto the ground to create greater grip. The faster the car goes, the higher the downforce created, as well as the associated downforce pushing the car into the ground.

Similar to the concept of the F1 car's downforce, when a come-along clamp gets put onto a wire, the force with which it grips the wire is the same as the force of the spring pressing the sliding body onto the wire (just as with the weight of the F1 car). As you start pulling on the ring however, the force increases in magnitude directly equal to the force that you are pulling with and the harder you pull the greater the force becomes (same as the downforce increases as the speed increases).

In a controlled test conducted on a test bed it was seen that when a clamp is placed on a 19/2.7 steel wire and the force increases linearly, the steel wire will break before the clamp will slip or break. It then seems that the normal come-along clamp is an almost fool proof piece of equipment which is very safe to use because of its few moving parts which makes it durable and reliable, as well as the simplicity of the concept behind the design. However, incidents with this type of clamp still occur on construction sites and can be fatal. Which brings us to the question: why do these clamps fail? To answer this warrants a look at a few incident investigations.

In an incident investigation where a come-along clamp failed during the regulating process on a 765 kV line, it showed the importance of the correct attachment method to the ring. During the regulating process the conductor was gripped with a come-along clamp about 40m from a strain structure and anchored to the structure by a rope and pulley block. There was a shackle attached to the ring which was used to apply the load to the clamp. At some stage during the process the rope pulley block was attached directly to the ring without firstly removing the shackle. The two components competing for the same space (Figure 65) under load caused irregular forces which ultimately led to the failure of the ring at the pin connecting it to the sliding body.



**Figure 65: Incident investigation of come-along clamp failure with multiple components**



**Figure 66: Come-along clamp with bent open ring**

The effects of this can be seen clearly in Figure 66. The pin holding the ring to the sliding body was not designed to handle loads in the applied transverse directions and the ring pulled out and bent open. The worker that was attached to the conductor fell to the ground and was sadly killed.

In a separate incident the come-along clamp holding the earth wire in place while the crimping on the dead end was being done slipped, which showed the importance of having the correct clamp for the diameter of conductor being used.

The conductor tension station was placed in front of a strain structure, which is different from the norm of placing it behind the strain structure in the direction of the pull. This was done simply because the strain structure was close to a ledge and there was not enough space between the structure and the ledge for the puller station. The earth wire was pulled past the puller station some distance to allow the workers to connect the dead end and connect it to the earth peak. Similar to the previously discussed incident, the clamp was placed some distance in front of the puller station and reeled in closer to the anchor that was behind the puller station. After this the workers proceeded in placing the dead end and doing the crimping during which the slight dynamic moving of the wire, due to the workers tugging and moving to get it into the crimping position, caused the come-along clamp to slip. The dead end hit a worker placed closer to the puller station fatally injuring him.

From the inspection done after the incident it was seen that the incorrect size of come-along clamp was used during this process. A clamp that was suitable for conductor diameter ranging from 16 – 32 mm was used (safe working load 3 ton as seen in Figure 67) and the wire being pulled was a 19/2.7 steel earth wire with a diameter of 13.5 mm. The correct clamp to be used would have been a clamp for a diameter range of 4 – 22 mm with a SWL of 2 ton.



**Figure 67: 3 ton come-along clamp**



**Figure 68: Visual comparison of a 2 ton and 3 ton come-along clamp**

From Figure 68 it can be seen that the clamps look very similar at first glance, and when in a hurry a worker could easily take the wrong size clamp for the job. If a worker was not clearly taught what the impact could be of using a clamp with a diameter range that did not fit to the conductor being pulled, he could even think that taking the bigger, 3 ton clamp would be better and safer than taking the smaller 2 ton clamp. Further to this it also shows that using a clamp in a situation where dynamic loading is applied to the clamp such as handling of the wire etc. it will increase the possibility of failure of the clamp.

In another incident which at first glance seemed less dangerous because no one was injured, a come-along clamp also slipped because of the inserts (used to minimise the damage caused by the gripping force on an ACSR conductor) which was applied incorrectly.

The clamp was placed on a conductor a small distance from an anchor point and attached with a lever hoist and tension slowly applied to the conductor to allow the workers to work on the slack end of the conductor. The clamp gripped to the conductor but as the tension rose broke the outer layer of the conductor strands and the strands piled up behind the clamp as the rest of the inner layers of the conductor slipped through the clamp. The result can be seen in Figure 69.



**Figure 69: Slipping of a come-along clamp damaging the conductor strands**

The clamp was correctly quarantined for inspection which showed some interesting findings. The clamp was designed so that the inserts on the fixed and sliding jaw could not be swapped around because of the difference in the distance between the attaching holes as seen in Figure 70.



**Figure 70: Difference between attaching holes of inserts in come-along clamp**

Further to this the clamp was correctly and clearly marked with the diameter range of the conductor it was designed for and similarly the insert was also marked as seen in Figure 71.



**Figure 71: Difference in diameter range of clamp and insert**

It can however, immediately be seen that the diameter range of the insert falls outside that of the clamp design although it was suitable for that of the conductor being worked on. The conductor being tensioned was 1 x "Bear" (OD = 23.45mm).

Further inspection found that the insert had a negative lipped rim which was made to fit into small positively lipped rim in the clamp. The smaller insert however, could fit the wrong way round in the clamp because of the larger diameter of the clamp. Both the correct and incorrect fitments can be seen below in Figure 72.



**Figure 72: Come-along clamp insert placed the wrong way around**

By fitting the insert the wrong way around, the insert could not apply even pressure across the surface of the entire conductor when the clamp was closed. It rather made a wedge which created a sharp point of pressure at the front end of the conductor which led to the severance of the outer layer of strands when the clamp is closed and the tension increased (as discussed with the downforce principle).

From these three incidents it can be seen that the initial perception of the standard come-along clamp being an “almost fool proof piece of equipment” and being very safe to use is clearly incorrect and that it can be very dangerous when used incorrectly.

In two cases the slight dynamically applied loads applied to the conductor by workers, added to by the incorrect size of clamp for the application (bigger is not always better), caused the conductor to slip resulting in serious incidents because the clamp is already heavily loaded.

When taking all of this into account, one can start looking for alternative equipment to be used rather than the standard come-along clamp which can then be specified by the design engineer.

The first requirement would be that the conductor would not be able to slip out of the clamp while under load.

The OHS act enforces that all lifting tackle is visually inspected every six months and that the SWL is clearly indicated on the equipment. When looking at the construction setup locally as a whole, where the majority of the workforce is uneducated:

- Most of the workers do not understand the importance of these indications.
- None of the workers actually read the specifications.
- No one actually walks into an equipment storage room with the exact conductor diameter from the specification that they will be working on in mind.

Taking a clamp with higher UTS to be sure that it will be adequate can surely be understood if not condoned. To try and educate all of the workforce (some of which do not understand English), in an overnight exercise to understand the whole concept of conductor diameters, clamp sizes, ultimate tensile strengths and safe working loads etc. is clearly not a realistic idea although to teach and to share information as we learn ourselves and construct new lines should always be an ongoing exercise that should be high on the list of everyone’s agenda. A more realistic approach to the problem should therefore be investigated.

Firstly, the elimination of the clamp from the process as a whole is not an option as the tension of the conductor attached to lifting tackle such as socks and running boards after stringing has to be slackened before removal of the equipment to regulate the conductor and accurately fit in a permanent manner. The clear direction is then to either enforce a method of marking clamps and conductors in some way that clearly indicate a match in diameter, or to have another alternative to the come-along clamp which works on the same principle of that explained by the downforce of the F1 car.

The clamp below in Figure 73 could be seen as a safer alternative even though the whole design is changed completely from that of the sliding body and ring across a fixed body. It comprises of two halves joined permanently with a hinge and which has to be bolted together around the conductor before it can be used. A wedge (also made from a softer material) is then slid in to protect the conductor and in the same principle as the F1 car's downforce, as tension is applied to the conductor the force with which the wedge presses on the conductor increases. In parallel to this, the reactant force presses the two halves of the clamp apart and hence tightens the bolts that are holding it in place and they cannot be undone until the tension on the conductor is released.



**Figure 73: Fold-over clamp as an alternative to the come-along clamp**

The conductor can therefore not slip out on the side of the moving jaw, multiple parts of lifting tackle can be applied to the clamp as it is done on a flexible sling, and the fitting of the inserts can be more clearly inspected and can never fit the incorrect way around.

Although this type of equipment looks to be able to increase the safe use of conductor clamps the selection of the wrong size of clamp might still cause it to create less gripping force than is required and hence making it slip.

A solution that could make a more immediate difference, even though it at first seems to be no change in the current setup, is to have a simple plastic marker placed on each clamp at the storage room, before the project they will be used on, starts. To colour code the marker and have printed clearly on it simply the name of the conductor it should be used on (like “Panther” or “Tern”) can definitely lessen the possibility of the wrong size of clamp being taken from storage room even when in a rush or by a lesser trained worker. The approach will however, only work if the markers are adequately and skilfully applied by a single person that understands the concept of the come-along clamp, has read the specification of the conductors to be used on the line, knows the importance of having the correct diameter clamp and making sure that the markers cannot be confused with that on similar clamps and is explained to all the workers.

### Appendix E: Guy wire example calculations

If one were to take for example an attachment point on a structure 40m high and an anchor point on the ground 40m away and thus at a 45° angle, trigonometry will give a straight line length of 56,5685m.

If one were to use simple catenary equations to calculate the length with a tension of 10% of the UTS of the guy wire, the wire specification would be required and would lead to a length of 56,5715m.

**Table 26: Specifications of a typical guy wire used on 400 kV transmission lines**

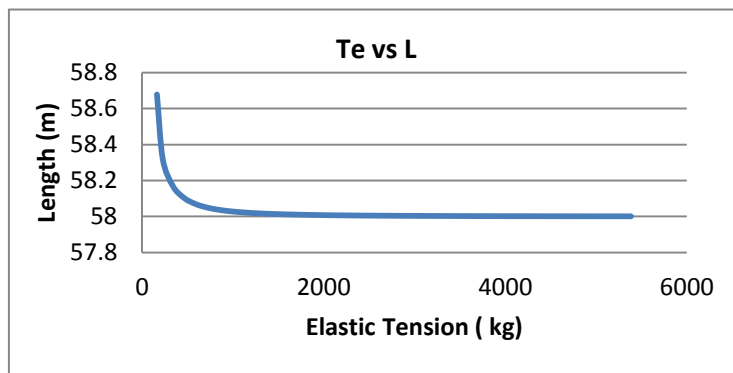
UTS	189 kN
Mass	1215 kg/km
Diameter	16 mm
Modulus of elasticity	19300 kg/mm <sup>2</sup>

If the same parameters (Table 26) were used the elastic catenary length would be 56,5705m. The length is slightly shorter as one would need a shorter wire, which would then stretch to cover the same distance. The difference in length is therefore as follows:

**Table 27: Comparative calculated results for a sample length of guy wire**

Straight line	Catenary	Elastic catenary
56,569 m	56,572 m	56,571 m
	3 mm	2 mm

During the preload testing of a fixed-length guy wire at the factory, the permanent deformation of the guy leads to a lower elasticity. As a result of this, the tension in the guy wire vs. length is not a linear relationship which means that beyond a certain point of elongation, an installed guy tension will increase a lot for a very small increase in length. A graph depicting this relationship is shown below (Figure 74). If a tower was being pulled plumb, a small adjustment in the adjustable guy U-bolt will therefore lead to a large increase in guy tension.



**Figure 74: Relationship between guy length and elastic tension**