Chapter 2

Current Design Practice

This chapter reviews current South African practices for the design of power line towers (*SABS 0280: 2001 - Overhead power lines for conditions prevailing in Southern Africa* 2001, *IEC 60826 - Design criteria of overhead transmission lines* 2003). Creative power line designs have been built from a range of construction materials. This may be seen in figures 2.1 to 2.7. Generally, distribution structures (voltages below $132kV$) are either constructed from wooden poles (figure 2.1) or reinforced concrete poles (figure 2.2) while transmission structures (voltages higher than $220kV$) are more often fabricated with lattice steel structures as may be seen in the $400kV$ running angle tower (figure 2.3). These towers can accommodate line deviations (a line deviation is typically where there is a bend in the transmission line) up to 30°. Suspension towers (figure 2.5) are installed for the main purpose of carrying the conductor in straight lines but they could also accommodate small line deviations up to 3°. At various intersections, determined by electrical parameters, transposition towers (figure 2.4) are placed in the line route in order to perform a phase swap in unsymmetrical or unbalanced phase configurations.

The towers of particular interest to this research may be seen in figures 2.6 and 2.7. These towers are known as double circuit power line towers. They are designed to support two electrical circuits on a single structure for the purpose of increasing transfer capacity in a designated servitude. They are notorious for being extremely tall structures, carrying large conductor bundles that significantly increase the load in the structure elements. This is exactly the type of structure that will benefit from circular hollow section members.

Figure 2.8 compares a conventional single circuit tower with a double circuit tower. The double circuit tower is approximately 1.75 times the height



Figure 2.1: 132 kV wood pole structure typically used in distribution lines.

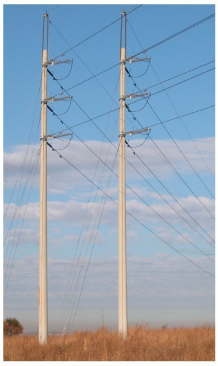


Figure 2.2: 132 kV wood pole structure typically used in distribution lines.



Figure 2.3: 400 kV running angle tower.



Figure 2.4: 400 kV transposition tower.

of the single circuit 765 kV tower.

As stated in the previous section, the objectives of this research are firstly to review current design practices and structural sections that are available, with which to fabricate power line towers; secondly, modelling techniques and practical connection layouts. The third objective is to look at designing the circular hollow section tower top using existing design software and design codes; and finally, to fabricate and test the tower top with existing fabrication and test facilities.

The rest of this chapter is dedicated to evaluating the design and fabri-



Figure 2.5: 400 kV suspension structures.

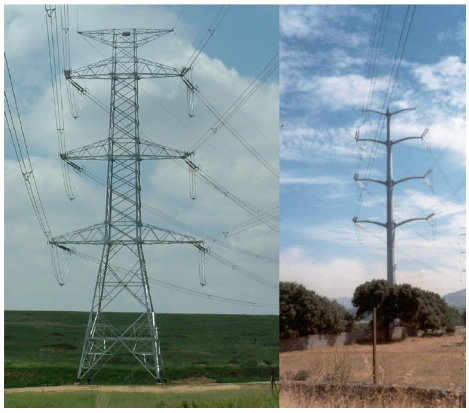


Figure 2.6: 400 kV double circuit structure, left: lattice type, Right: monopole type



Figure 2.7: 765 kV double circuit tower in Korea

cation methods for existing tower designs.

2.1 Loading on power line towers

The loads in power line towers may be categorized into three types: Environmental loads, e.g. wind, temperature changes and snow, construction and maintenance loads which relate to personnel safety and security loads. Security loads consist of accidental occurrences such as broken conductors or adjacent structure failure due to tornado's. Security loads are also referred to as failure containment loads. Tower loads are applied to structures in a vertical (V), transverse (T) and longitudinal direction (L). These loads will now briefly be discussed. Refer to figure 6.3 to see the load tree used in this

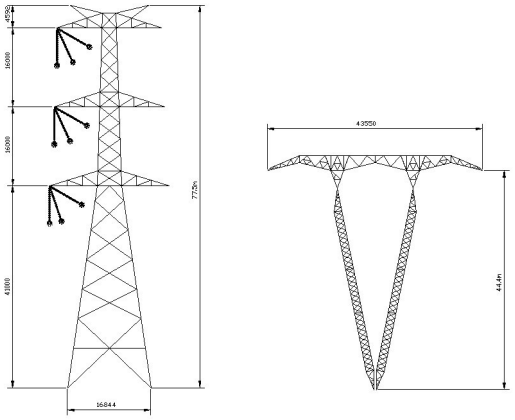


Figure 2.8: Comparison between single and double circuit 765 kV towers, Left: 765 kV double circuit tower, Right: 765 kV single circuit tower.

research to indicate the loads that were applied to the structural model and the test structure.

2.1.1 Vertical loads on towers

Vertical loads generally come from the weight of the conductors suspended on the cross arms and the self weight of the structure. Ice and snow loads must also be superimposed where towers are routed in such areas.

2.1.2 Transverse loads on towers

Transverse loads are due to an indirect wind load on conductors, a direct wind load on the tower members, and the transverse component of the line tension of towers that is placed at bend points accommodating line deviations.

2.1.2.1 Wind load on conductors

The force applied to a span of conductors may be written as follows, as specified by *IEC 60826 - Design criteria of overhead transmission lines* (2003):

$$A_c = q_0 C_{xc} G_c G_L dL Sin^2\Omega \tag{2.1}$$

where,

q_0 = dynamic wind pressure
$C_x c$ = drag coefficient of the conductor taken equal to 1.0
G_c = combined wind factor for conductors
G_L = span factor
d = diameter of the conductor
L = wind span
Ω = Angle between the wind direction and the conductor

Consider the two towers in figure 2.8. The conductor attachment heights (on the cross arm) for the double circuit tower is $32.7m$, $48.7m$ and $64.7m$ respectively. The conductor attachment height for the single circuit tower are $33.0m$. If we now consider only the transverse loading (equation 2.1) on the two different structures, based on their respective conductor attachment heights and respective number of conductors, the overturning moment at the base of the double circuit tower is 5.2 times greater than for the single circuit tower.

2.1.2.2 Wind load on tower members

The force that acts on a single panel (a tower panel is a smaller section in a structure) of a tower is the product of the wind pressure and the effective area of the tower panel. A force coefficient C_f that is determined by the shape and member type (round members or flat sided members) is also then multiplied by the calculated force that acts on the tower panel. For towers with flat sided members (angles iron) the force coefficient is 2.9 (*SABS 0160-1989:The general procedures and loadings to be adopted in the design of buildings* 1989) and for a similar tower with round members C_f is 1.7 (*SABS 0160-1989:The general procedures and loadings to be adopted in the design of buildings* 1989). Thus, the tower fabricated with CHS members will have a 41% reduction in wind load.

The force, F, acting on a tower panel may be calculated with:

$$F = C_f q_z A_e \tag{2.2}$$

where,

C_f = overall force coefficient for lattice towers
q_z = velocity pressure
A_e = effective frontal area

and

$$q_z = k_p V_z^2 \tag{2.3}$$

where,

k_p = factor for converting wind speed into velocity pressure
V_z = characteristic wind speed at height z $[m/s]$

1	2	3	4	5	6	7	8	9	10	11	12	13
Height z, m	Wind speed multiplier* k_z											
	Terrain Category 1			Terrain Category 2			Terrain Category 3			Terrain Category 4		
	Class of building or element*											
	A	B	C	A	B	C	A	B	C	A	B	C
Up to 5	1,03	1,02	1,00	0,94	0,92	0,88	0,67	0,64	0,60	0,65	0,62	0,57
10	1,09	1,08	1,05	1,00	0,98	0,95	0,74	0,71	0,68	0,65	0,62	0,57
15	1,12	1,11	1,09	1,04	1,02	0,99	0,81	0,78	0,76	0,65	0,62	0,57
20	1,14	1,13	1,11	1,07	1,05	1,02	0,86	0,83	0,81	0,65	0,62	0,57
50	1,22	1,21	1,20	1,16	1,15	1,13	1,00	0,98	0,96	0,86	0,84	0,80
100	1,28	1,27	1,27	1,23	1,22	1,21	1,11	1,10	1,08	1,00	0,98	0,95
150	1,31	1,31	1,31	1,28	1,27	1,26	1,18	1,17	1,16	1,08	1,06	1,04
200	1,34	1,34	1,34	1,31	1,31	1,30	1,23	1,23	1,22	1,15	1,13	1,11
250	1,36	1,36	1,36	1,34	1,34	1,34	1,27	1,27	1,26	1,20	1,19	1,17
300	1,36	1,36	1,36	1,36	1,36	1,36	1,31	1,31	1,31	1,24	1,23	1,23
350	1,36	1,36	1,36	1,36	1,36	1,36	1,34	1,34	1,34	1,27	1,27	1,27
400	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,31	1,31	1,31
450	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,33	1,33	1,33
500	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36
Above 500	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36	1,36

Figure 2.9: Variation of characteristic wind speed with terrain, height and class of structure (Table 5 in *SABS 0160-1989:The general procedures and loadings to be adopted in the design of buildings* (1989)).

Site altitude above sea level, m	k_p
0	0.60
500	0.56
1000	0.53
1500	0.50
2000	0.47

2.1.2.3 Transverse loads due to line angle

This load is present when there is a change in the angle of the line. This load case should be superimposed with the maximum transverse load due to high wind conditions. The transverse load due to line deviation is calculated as follow:

$$H = 2Tsin\theta/2 \tag{2.4}$$

where,

H = transverse load due to wire tension
T = wire tension
θ = line angle in degrees

2.1.3 Longitudinal loads

Longitudinal loads are created when there is an imbalance in the tension between adjacent sides of the tower cross arm. These imbalances create torsional loads in the structure that is normally resisted by the bracing members of the tower. Large imbalance loads are typically found at dead end structures, where only one side of the cross arm is fitted with conductors. Longitudinal loads are also applied to the cross arm tips when conductors are strung onto the line. Longitudinal loads are also used when designing for failure containment load cases.

2.1.4 Test tower loading

The previous sub-sections summarize the main loads that should be considered when designing power line towers. Although other design loads could be considered by the engineer, the tubular test tower will only be subjected to four common load cases. This is considered adequate in terms of proving the previously mentioned aims and objectives. The four load cases are:

C1 High transverse wind load: This is when the wind pressure is applied perpendicular to the conductor wind span.

C2 Cascade failure: This failure is a severe failure condition when all the conductors are broken on one side of the tower. This would occur when a tower collapse and the adjacent tower has conductor tension only to one side of the structure.

C3 One broken conductor + No broken conductor: This load case is to induce torsional loads on the tower; this would typically occur when an insulator breaks.

C4 One broken conductor only: This load case will induce torsional loads on the tower; this could occur under conductor stringing conditions.

Typically all load cases that will be used in the design of structures are graphically illustrated in a tower load tree. A similar approach has been used for the test tower. See figure 6.3.

2.2 Typical tower members and fabrication methods

Currently, all tower members (primary and secondary) are fabricated from angle iron sections (figure 2.10). Various reasons exist for using angular sections for tower members.

Firstly, angle members are fabricated at a relatively low cost compared with e.g. hollow sections. Angle iron sections are hot rolled in one continuous process compared with hollow sections that are cold formed from a hot rolled coil. Secondly, the fabrication of tower members is conducted on an automated cnc punching machine, which reduces the labor cost and the risk of making marking errors. Also, large quantities of members can be fabricated in a one day shift. Thirdly, due to the geometry of angle members (two flat sides), members can easily be bolted together with gusset plates. Circular hollow section connections on the other hand, are either fully welded or a combination of bolts and welds. Thus higher costs are associated with circular hollow section connections.

Angular tower members are more easily galvanized compared with circular hollow sections. More will be said about this in the next chapter. Finally, as seen in figure 2.10, angular members fit closely together in neat bundles for handling, storage and shipping. Circular hollow sections cannot however be packed as densely as angle members, thus will require more shipping trips to site compared with angle members.



Figure 2.10: Standard angle iron tower members packed for transportation to site.

2.3 Current tower design methods

Currently, power line structures are designed using a program called PLS Tower (Power Line Systems, 2012). PLS Tower forms part of a suit of programs which is used internationally for the design of structures and complete power line systems. The tower software is developed for self supporting structures as well as guide structures. This software is also capable of conducting both linear and non-linear analysis on power line structures.

The software is primarily developed to design structures using angle iron sections. The members are modeled as beams having only pinned connected ends. The design and behaviour of the member is then controlled by the slenderness curves previously mentioned. Although hollow sections may also be used in PLS Tower, the secondary bending moments due to connection eccentricities cannot be calculated with this software. The members in PLS Tower are only designed for axial tension and compression loads. Figure 2.11 shows typical views that may be found using the PLS Tower software.

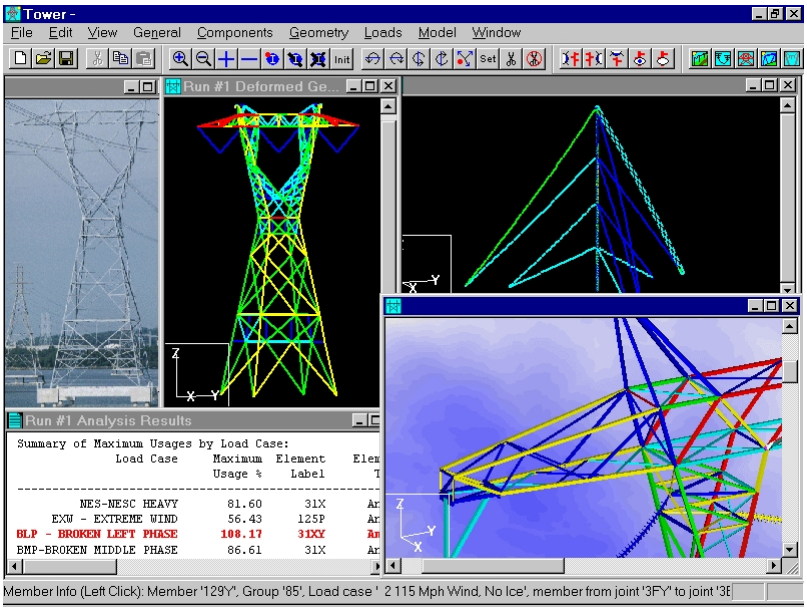


Figure 2.11: Typical tower views from PLS Tower.

Although this is a very powerful design tool currently in the transmission and distribution industry, the limitations on calculating secondary bending moments due to connection eccentricities limits its use of this software for this research. Alternative software that will be used to perform the structural analysis of the tubular test tower is Prokon . This software is capable of using any type of cross section as well as taking into consideration bending moments in the members. More will be said about this software in a later chapter.

2.4 Full scale testing of towers

It is common practice throughout the world to subject power line structures to full scale testing. In these tests, the structures are subjected to their full design loads. Although not all countries have access to full scale test facilities, we in South Africa are fortunate to have such a test facility. Eskom tower test station is situated in Gauteng. This test facility is capable of testing structures up to 70 meters with loadings associated with 765kV structures.

The leg of the structure is fixed to a steel base that is in turn anchored to the ground. Large latticed steel structures to the north and east end of the

test structure is fitted with hydraulic rams which are used to simulate the design loads. Steel wire ropes fitted with load cells are attached to the position where conductors will be fitted. The steel wire ropes are then connected to the hydraulic rams. Figure 2.12 shows a typical layout of a tower test facility.



Figure 2.12: Typical layout of tower test facility. Large latticed steel structures may be seen.

The tubular test tower will be subjected to a full-scale test according to the design loads mentioned in the previous section. The test tower will also be fitted with strain gauges to accurately measure the axial loads in the tower members. More detail will be given in a later chapter on the test and the outcome of the results.

A multidisciplinary team of design engineers and draftsmen is required to determine the most economical configuration electrically from which a structure is derived in order to support the conductors in position. Although a large amount of work is required before a power line tower can be designed, this chapter reviews only the members, loading criteria, member and connection design, structural analysis and full scale testing according to the existing practices for South Africa. A test tower designed and fabricated with circular hollow sections will be developed on the basis of this foundation and it will be proven that the use of existing design software, current design codes and current fabrication techniques may be used for this purpose.

2.5 The limitations of angular tower members

As mentioned previously, the increase of various aspects of double circuit transmission structures leads to the increase in structural loading of tower members. This section gives a comparison between the wind loadings on the conductor bundles of a single circuit structure compared with a double circuit structure. It shows that the overturning moment at the base of the double circuit structure is 5.2 times higher than that of a single circuit structure.

Although there is a relative increase in the tower-base width between single and double circuit structures Ryle (1945), the increase in load is at the practical limits of angular cross-sections available in South Africa. A simple calculation (Appendix A) was done to show the effect that the load increase of double circuit structures has on the selection of tower members.

The approach was to select a tower-base width (W) for a single circuit and double circuit transmission tower Ryle (1945). The overturning moment (M_s) for conventional single circuit towers was selected as unity and the overturning moment (M_d) for double circuit towers was taken as 5.2. The relative tower-base width (W_s) for the single circuit tower was 0.35, and for the double circuit (W_d) tower 0.8.

$$W = 0.35\sqrt{M} \tag{2.5}$$

From the above calculated tower widths, a relative force in the tower leg member was calculated. The relative force in the single circuit tower leg member was calculated at 2.86 and the relative load in the double circuit leg member 6.5. This is an increase in member load of 127%.

$$M = (F)(W) \tag{2.6}$$

To put this into practical terms, a typical leg member for a UHV suspension tower is 150x150x18. At an effective length of 2000mm, the factored compressive resistance is 1040kN *Southern African Steel Construction Handbook* (2008). An increase of 127% results in a member that must be able to resist an ultimate load of 2360.8kN. From the steel construction handbook, the next size up would have to be a 200x200x24 angular section. This is also at a reduced effective length of 1750mm. This means that additional secondary bracing would be required, which adds additional mass to the

structure.

If we have also to consider the effect of using this structure for small-line deviations, the effective length would have to be further reduced. However, the available factored resistance is only 4.6% by changing the effective length from 1750mm to 750mm *Southern African Steel Construction Handbook* (2008). The nett result is that the tower member density is further increased; this creates more environmental effects.

Although the loads in the strain towers were not calculated here, the effect of load increase will have an even more negative effect on strain towers than suspension towers.

Also, in order to resist the increased ultimate load for the double circuit tower, the 200x200x24 angle section must be 77% heavier than the 150x150x18 angle section.

The available range of angular cross sections is limited to 200mm. Circular hollow sections on the other hand extend beyond this and range in diameters of up to 508mm, and compressive resistance up to 5000kN.

2.6 Conclusion

This chapter reviews in a broad sense the wind loading on electrical conductors and tower members. Although only four load cases will be considered in this research project, a large amount of load combinations will be used to design a family of power line towers for a variation in terrain and functionality of each tower. Reference can be made to Appendix B and C for a brief review of the structural capabilities of angle iron section as well as connection design parameters. A brief overview of the design, fabrication and testing was also given.

Very importantly, it was shown that the use of conventional angle tower members has reached their limit when it comes to double circuit transmission structures. A simple calculation was used to show that the overturning moment at the base of a double circuit tower is 5.2 times greater than the single circuit tower. The nett effect of that is a 127% load increase in the tower leg member. The result on the overall tower is additional secondary members to reduce the effective length of tower members, an increased weight of tower members and a limit on actual members that is available in the South

African market. Circular hollow sections provides a good alternative as will be seen in the following section.