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Research article

A Comparison of Lattice Tower Design using Stress Diagrams and Finite Element Analysis Methods

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Abstract

Most of the lattice transmission towers in the US were designed before 1960 and are still in service. These structures often need to be analyzed for upgrades to the conductors, shield wires, cellular antenna add-ons, damage repairs, or electrical clearance checks. On some of these structures, computer analysis shows that few members are overstressed. However, these structures have no history of member failures. This difference in results can be attributed to the difference in the analysis methodology between the original graphical stress analysis and current non-linear finite element analysis. To understand these differences, lattice towers are analyzed using graphical stress analysis and finite element analysis. This paper will present a comparison of results from these two design approaches.

Introduction

The first transmission line in the US was built in 1889. This thirteen-mile transmission line was built between the generating station at Willamette Falls, Oregon City, Oregon, and downtown Portland, Oregon [1]. Currently, the US has more than 600,000 miles of transmission lines [2]. Most of this transmission line infrastructure was developed before the 1960s, and lattice towers were the most common transmission structures. Cremona Diagram, commonly known as stress diagram, is a graphical method for determining stresses in trusses. This analysis method was developed by the British physicist J.C. Maxwell and Italian mathematician L. Cremona in the 19th century. It was the most widely used method for lattice tower analysis before the advent of computers. There is a need to analyze these existing structures for new loading due to conductor upgrades, marker ball installation, or repair of damaged structures. Some members are overstressed when these towers are analyzed in Finite Element Analysis (FEA) software like TOWER for the original design loads [3]. However, these structures have been in service for several decades without any problems. To understand the reason for these overstresses, this paper will compare the analysis results obtained from stress diagrams and TOWER.

In this paper, four towers are selected for comparison

a) Tower A - 58’ tall suspension tower

a) Tower B - 74’ tall suspension tower

b) Tower C - 88’ tall suspension tower

c) Tower D - 92’ tall terminal tower

Towers A, C and D are selected from ‘Transmission Towers’, [4] an American Bridge publication from 1925 and tower B has been in service for more than 90 years. Each of the four towers are analyzed using graphical stress diagrams and again using TOWER. The analysis results are compared and presented in this paper (Figures 1-33).

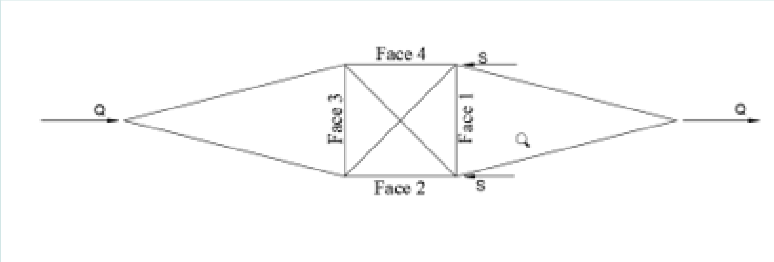


Figure 1: (a) Shear load (S) due to transverse load (Q) on the conductor.

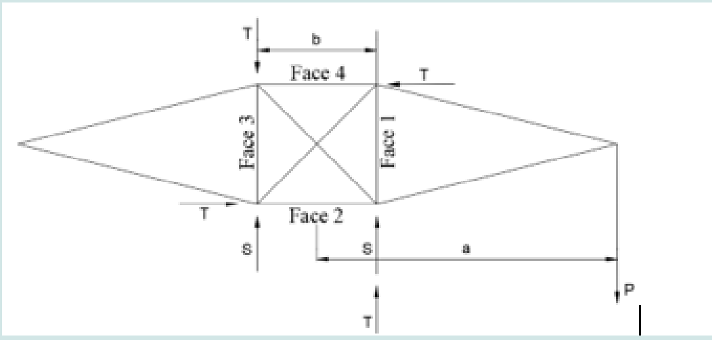


Figure 2: (b) Shear (S) and Torsional force (T) due to longitudinal load (P) on crossarm.

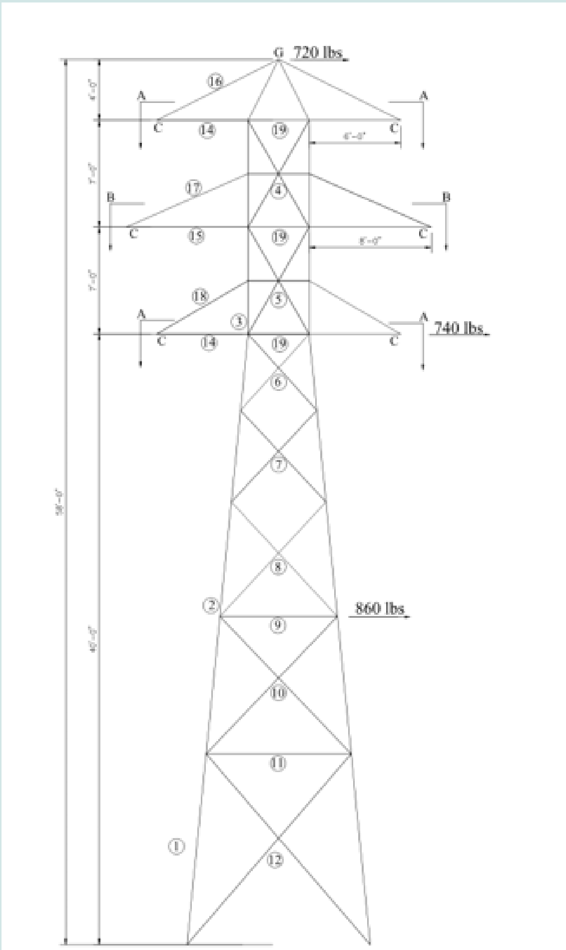


Figure 3: (a) Tower A geometry

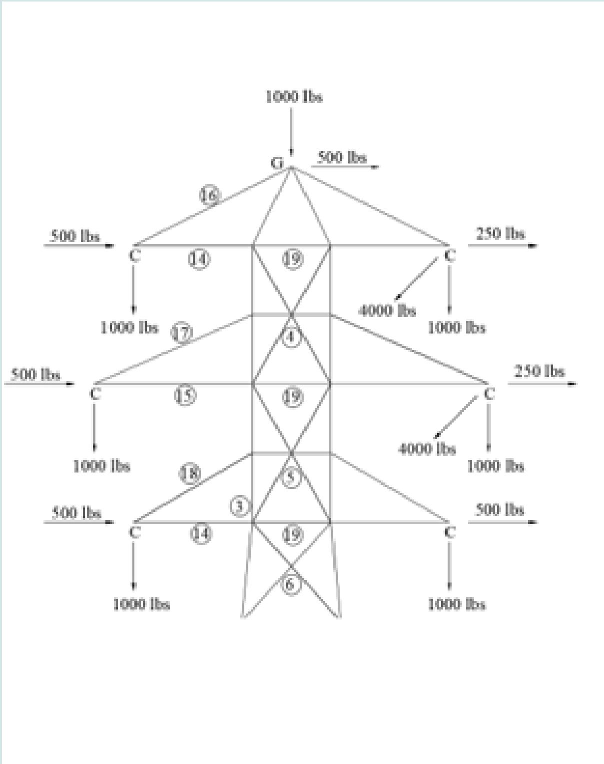


Figure 4: (b) Loads on Tower A. Wind load is shown in Figure 2a.

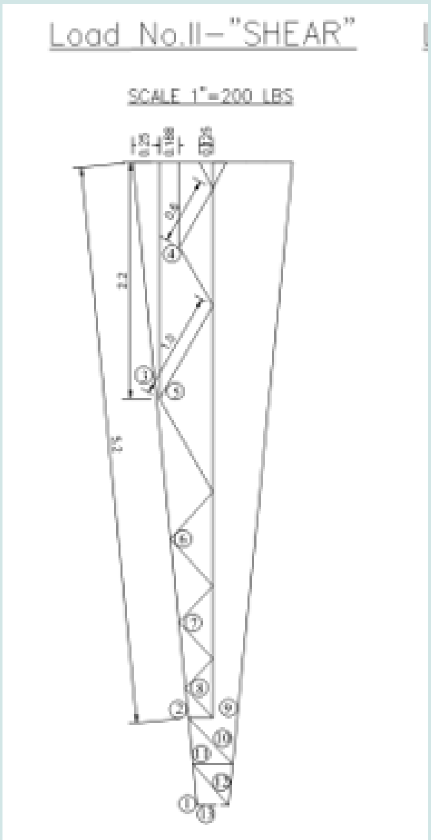


Figure 5

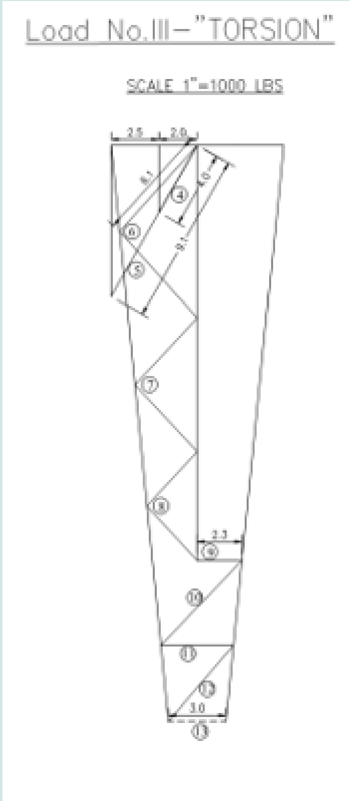
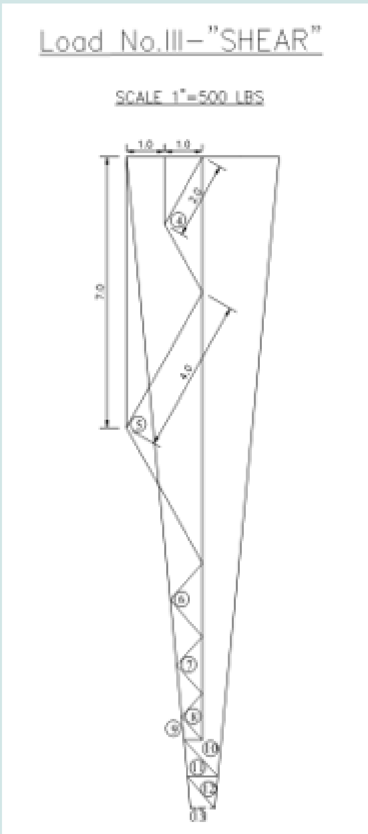


Figure 6



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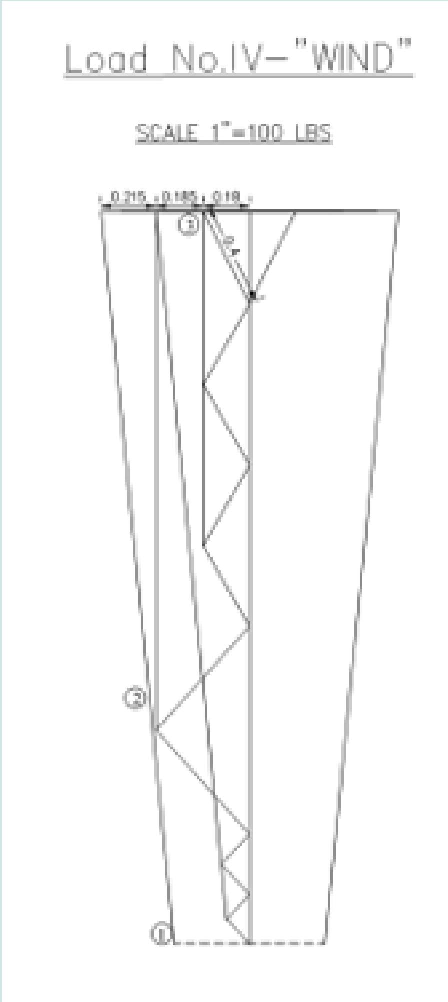


Figure 8: Stress Diagrams of Tower A.

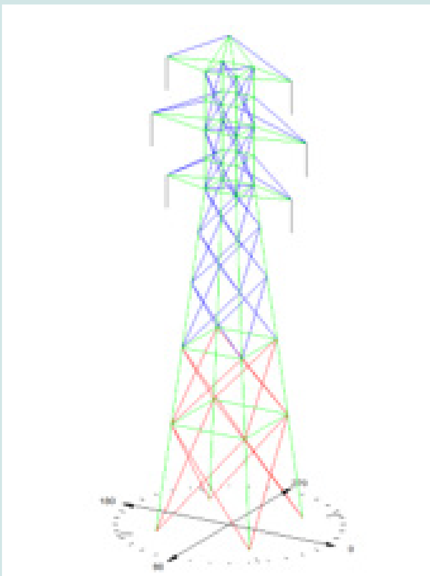


Figure 9:(a) Tower A Model

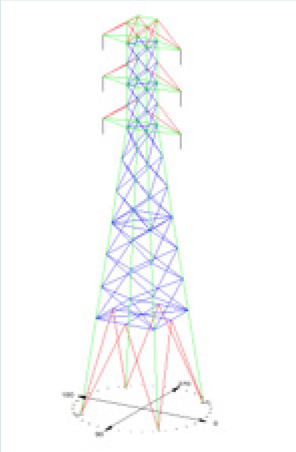


Figure 10:(b) Tower B Model.

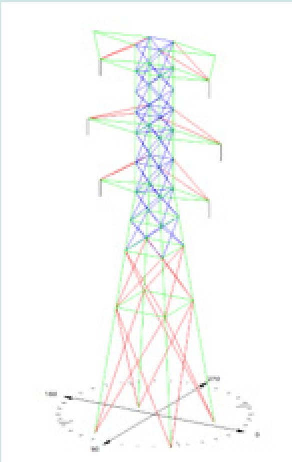


Figure 11:(c) Tower C Model.

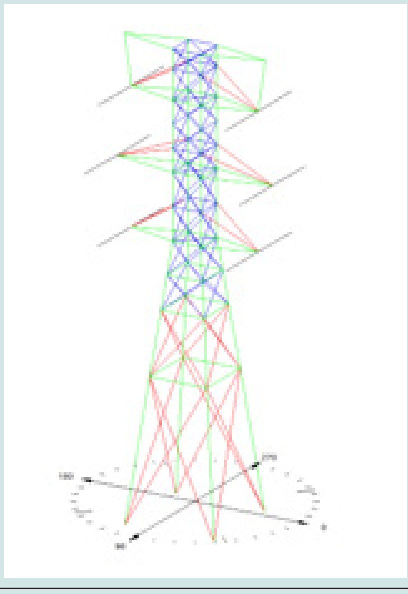


Figure 12:(d) Tower D Model. Tower models

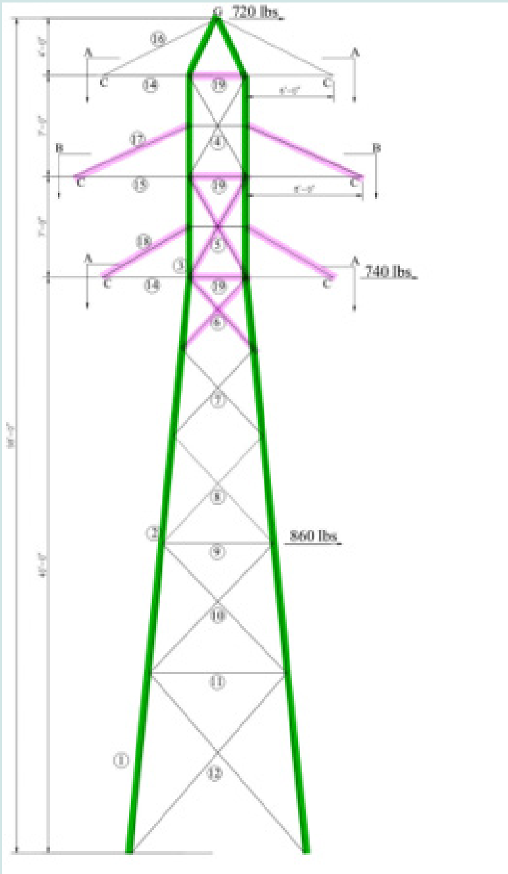


Figure 13

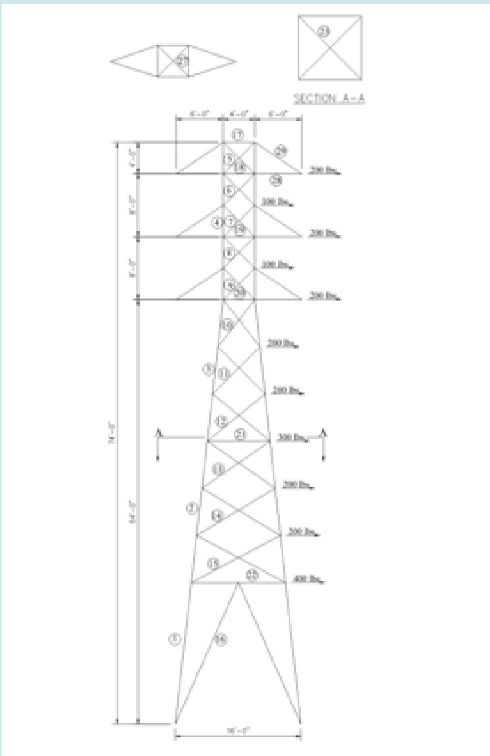


Figure 14:(a) Tower B geometry

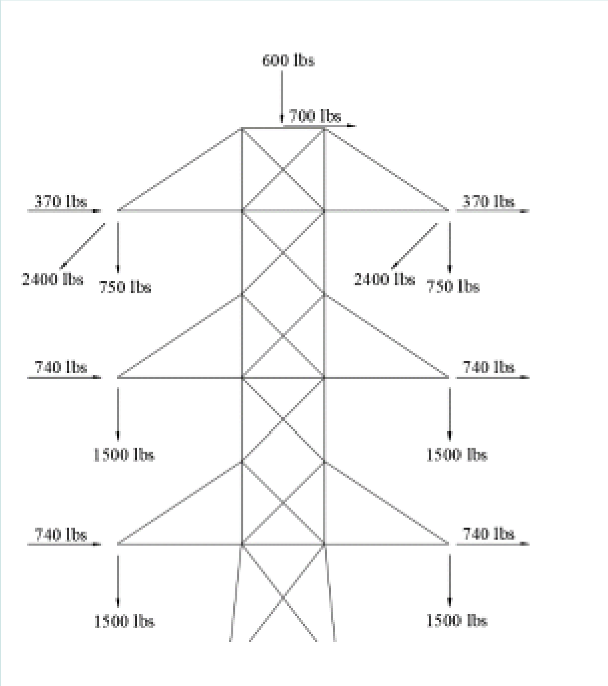


Figure 15:(b) Loads on Tower B. Wind load is shown in Figure 5a.

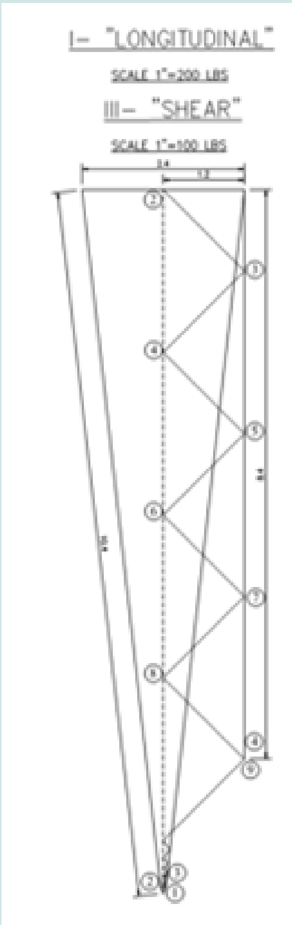


Figure 16

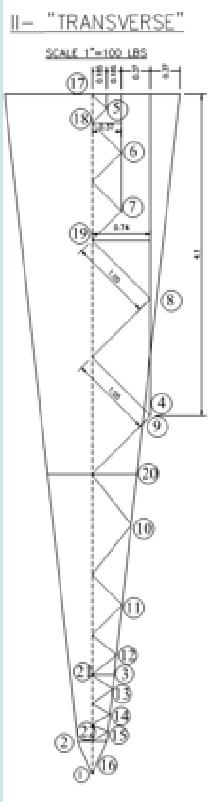
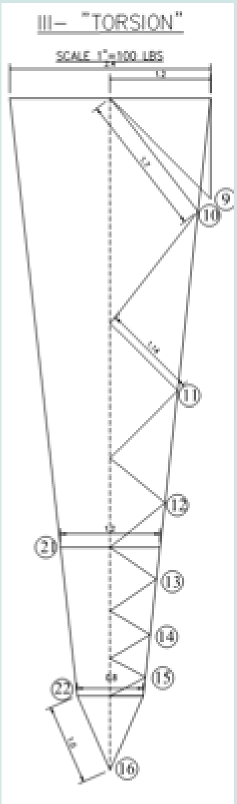


Figure 17



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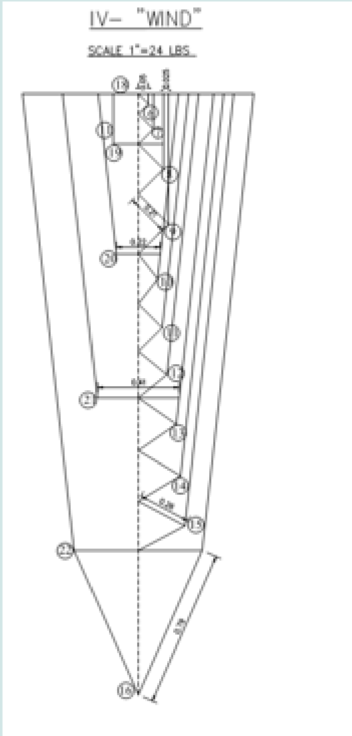


Figure 19: Stress Diagrams of Tower B for different load cases.

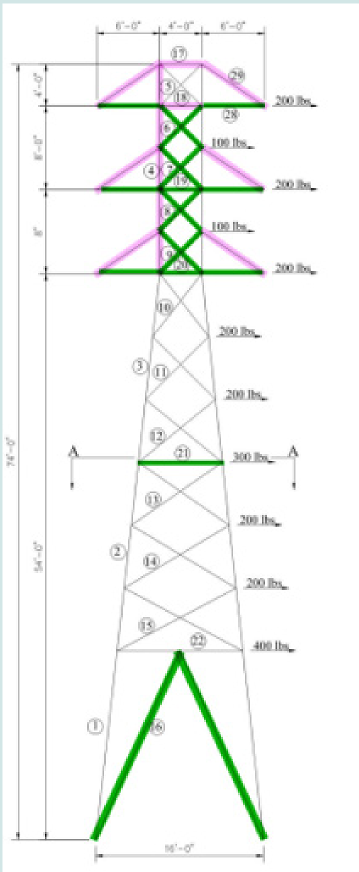


Figure 20

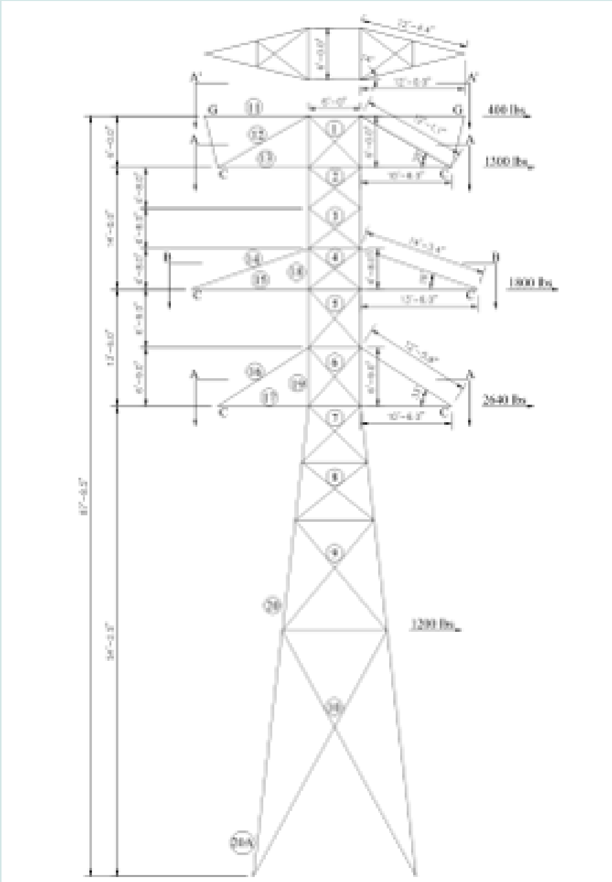


Figure 21:(a) Tower C geometry

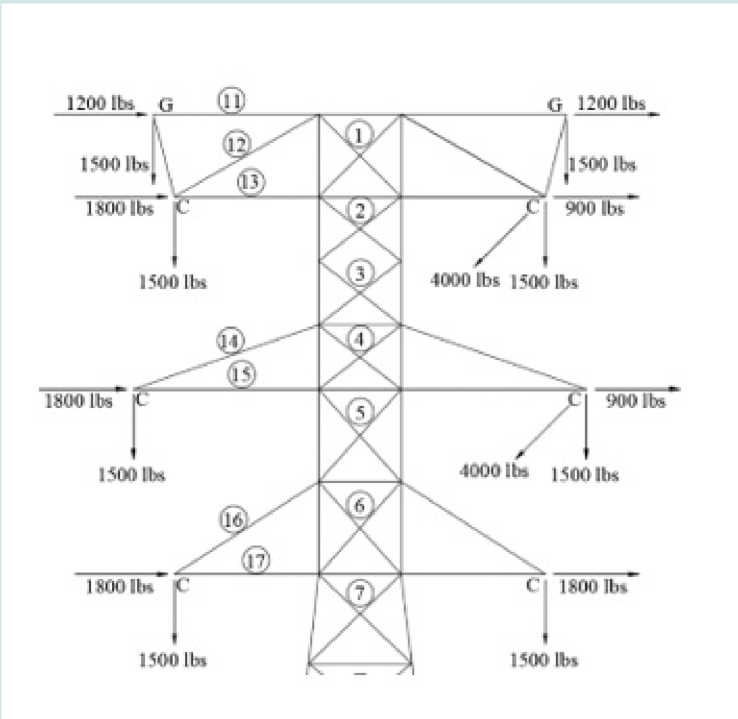
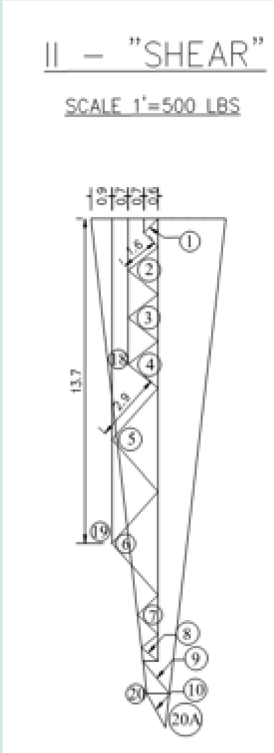


Figure 22:(b) Loads on Tower C. Wind load is shown on Figure 7a.



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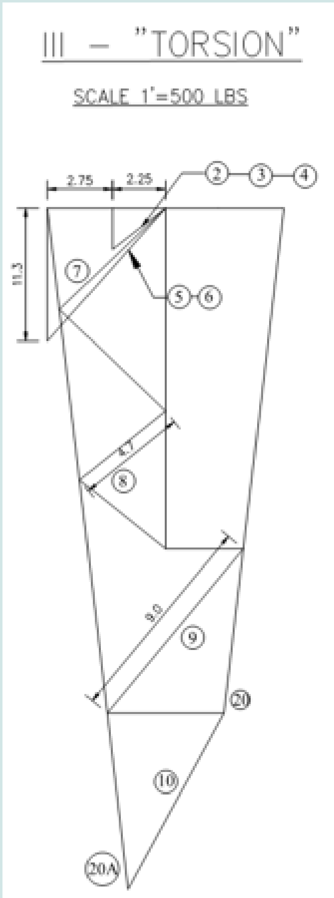

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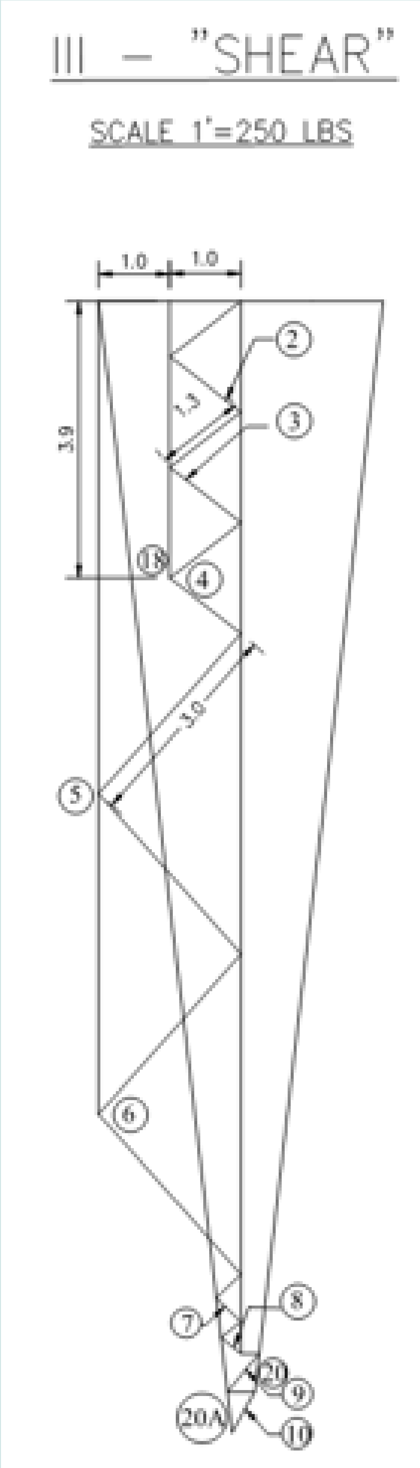

Figure 25

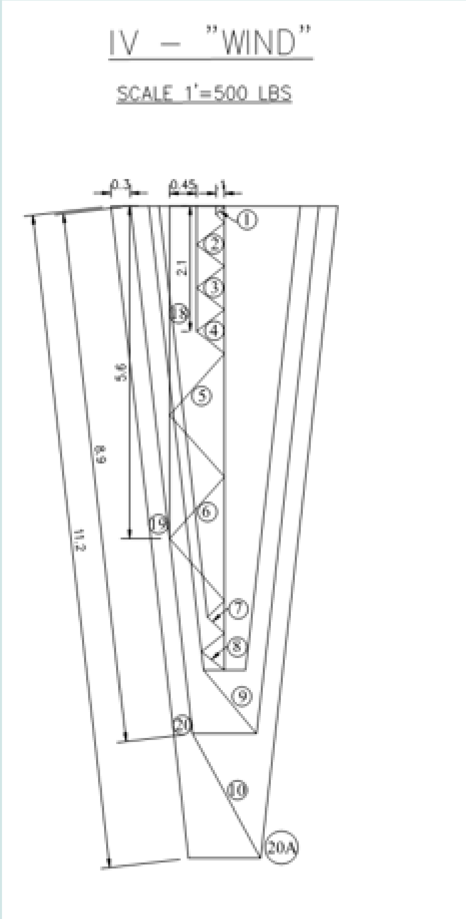

Figure 26: Stress Diagrams of Tower C for different load cases.

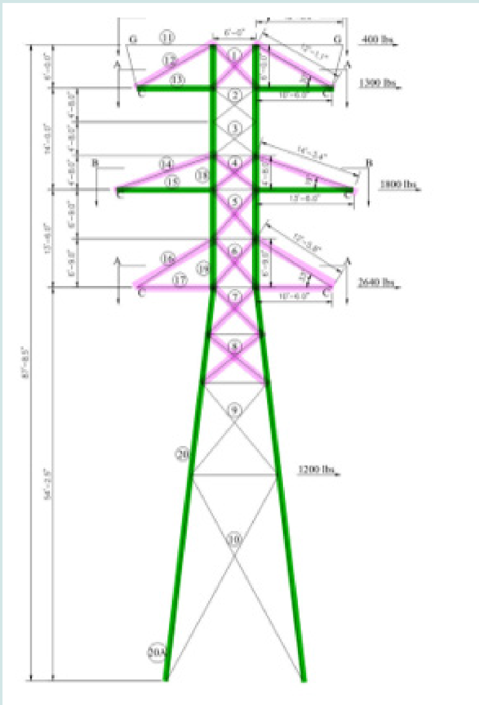

Figure 27

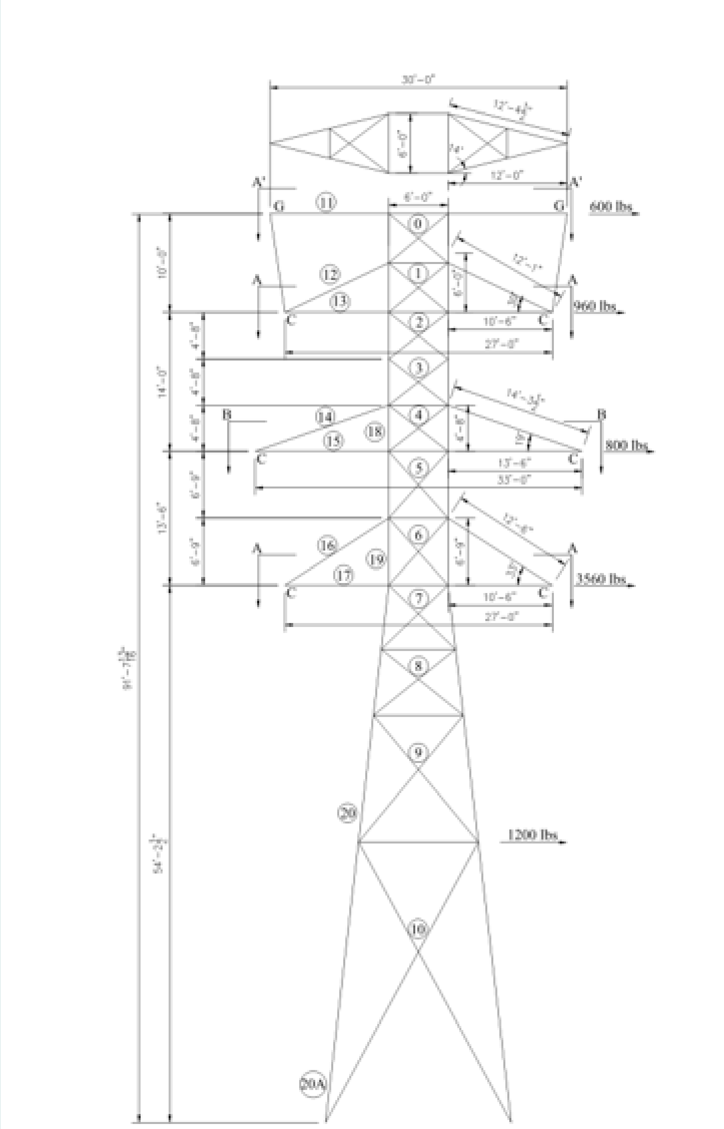

Figure 28: (a) Tower D Geometry

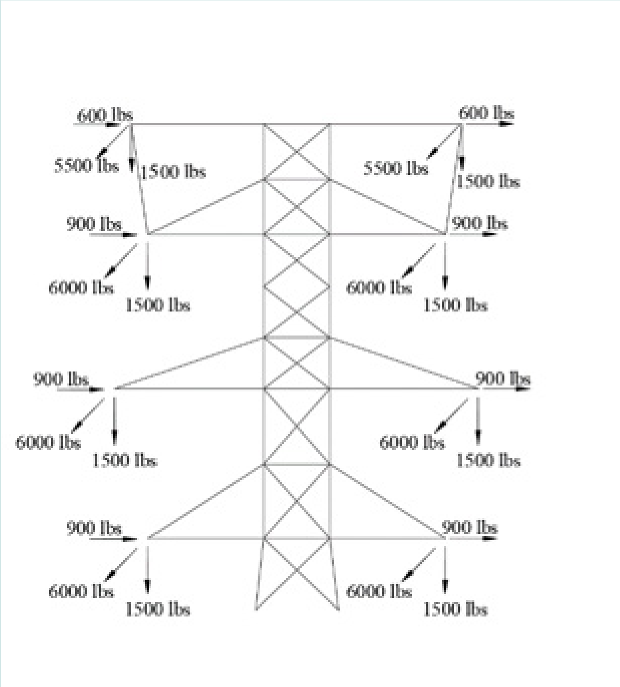

Figure 29:(b) Loads on Tower D. Wind load shown on Figure 9a.

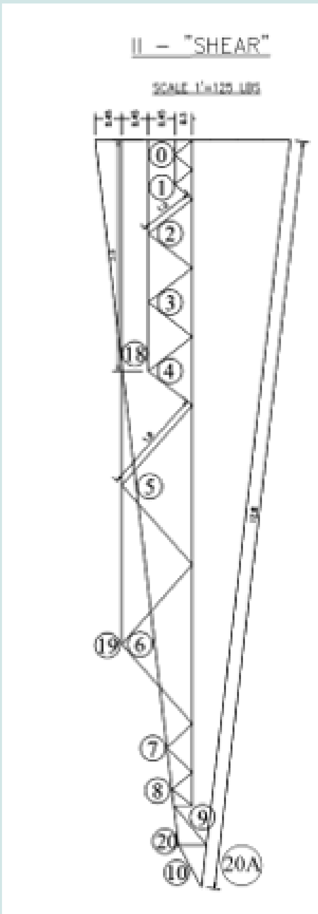

Figure 30

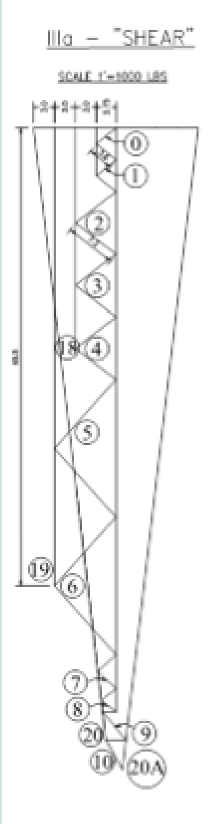

Figure 31

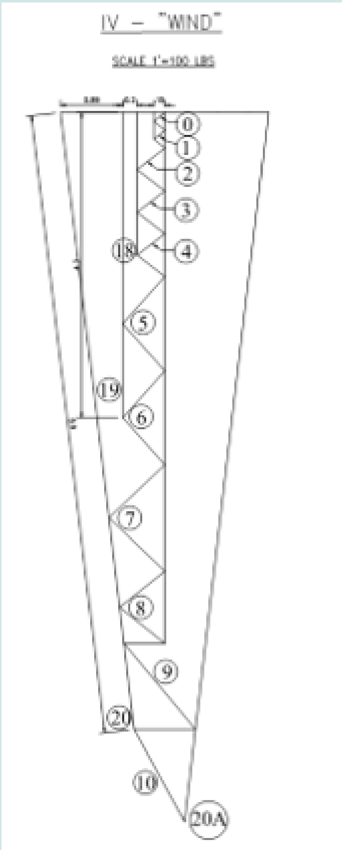

Figure 32: Stress Diagrams of Tower D

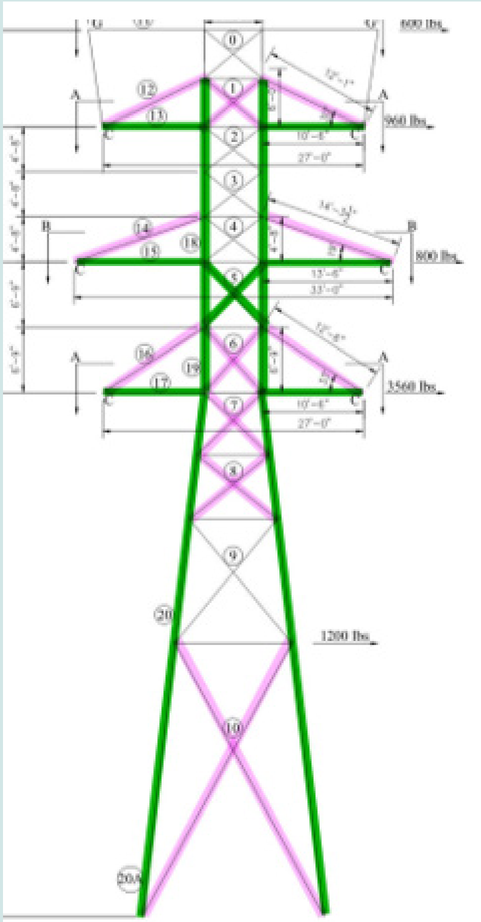

Figure 33

Tower A Analysis

Tower A is a double circuit suspension tower with a total structure height of 58’-0”. The tower configuration includes a single shield wire peak, three crossarms and a common body with four equal leg extensions [5]. See Figure 2a. Tower cage and body have square configuration and all four faces are alike. Tower has a line angle of 0deg.

Typical Tower Design Loads

a) Vertical loads: This includes self-weight of the tower, weight of conductor, ice, insulator and other hardware.

b) Wind pressure: Wind pressure acts normal to the conductor, acting both on the tower and the conductor.

c) Conductor tension: Longitudinal loads due to broken wires, longitudinal and transverse loads due to line angle.

d) Tower A is to be designed for the following simultaneous loads:

e) Load No. I - A vertical load of 1000 lbs at each cable support. Total 7000 lbs.

f) Load No. II - A transverse load, normal to the direction of the line, due to wind on cables at each cable support. 500 lbs load is applied for normal spans and 250 lbs for the broken span.

g) Load No. III - A longitudinal load in the direction of the line applied at the conductor supports to simulate broken conductors. 4000lbs is applied at the top, and middle right conductor supports.

h) Load No. IV - Wind on tower normal to the line, equivalent to 40 lbs per vertical foot of the tower.

i) Load No. V– Self-weight of the tower.

Stress Diagram Analysis Methodology

The analysis of transmission tower by stress diagram method involves calculating the total stress in each member of the tower under a combination of externally applied loads and the self-weight of the structure.

It is assumed that the members on the transverse faces resist transverse loads and members on the longitudinal faces resist longitudinal loads. Stresses are calculated in the members at the level of the externally applied load and below it.

A stress diagram is drawn for each of the five loads listed above in AutoCAD, and member forces are calculated using the scale shown on the drawing. The principle of superposition is used to compute the total force in a member by summing up the loads in the member due to each load case.[6] For the crossarm analysis, it is assumed that the bottom chords of the crossarm carry transverse, longitudinal and a part of vertical load, and the top chord of crossarms carry the vertical loads only. The loads in the crossarm bottom and top chords are calculated using the method of joints. 2D analysis is used to calculate the crossarm loads in 'Transmission Towers' [7]. This method is not accurate. For this paper, crossarm loads are calculated by resolving the loads in three dimensions.

Load No. I and V: Vertical conductor loads are applied at the tip of the crossarms. The crossarm member loads are calculated using the method of joints. Vertical conductor loads and tower self-weight are equally divided between the four tower legs.

Load No. II: The transverse load acts as a shear load and causes no torsion on the tower. The shear load in the crossarm is given by the following equation:

$$S = \frac{Q}{2}$$

Where,

a) Q - Transverse load on the conductor.

b) S - Shear load is carried equally by the two transverse faces 2 and 4 shown in Figure 1a.

Load No. III: Longitudinal loads are applied at the top, and middle right conductor supports. These loads will cause torsion on the tower. Forces in the tower faces are calculated as follows:

Load P shown in Figure 1b. represents the longitudinal pull. The resulting forces acting on the tower faces are calculated by substituting a load equal and parallel to P (shear), acting at the canter of the tower, and a moment P.a. The shear force is divided equally between faces 1 and 3 (longitudinal faces), while two couples in four faces resist the moment P.a.

$$S = \frac{P}{2}$$

$$T = \frac{P.a}{2b}$$

Where,

a) S - Shear load is carried equally by the two longitudinal faces 1 and 3 shown in Figure 1b.

b) P - Longitudinal load on the conductor.

c) T - Torsional force acting on all the four faces causing a couple (*T.b*) in four faces.

d) a - Distance of point of attachment of conductor from the center of the tower. b - Moment arm, is equal to the width of the tower.

Finite Element Analysis

A 3D model is built in TOWER, a finite element software. Figure 4 shows the models developed for the analysis of all four towers. The tower was analyzed using the non-linear option for the loads used in the stress diagram analysis. Wind load was specified as 40lbs per linear foot and was applied as point load in stress diagram analysis. This was simulated in TOWER by adjusting wind pressure till the total wind load was equivalent to the load used in stress diagram analysis. The member sizes were designed to avoid overstresses in the members. The self-weight of the tower is assumed in the stress diagram analysis. The self-weight is adjusted in TOWER to match the weight used in the stress diagram analysis by modifying the dead load factor in the lca file. The red members in Figure 4 are modelled as Tension Only members with 0% compression load capacity.

Observations

The member loads from both stress diagram analysis and TOWER analysis are compared in Table 2. Member load variations of less than 0.5 kips are ignored to account for differences between the two analysis approaches. If the loads from the TOWER analysis are higher than those from stress diagram analysis, the members will most likely be overstressed. Such members are highlighted in pink. If load from TOWER analysis is less than those obtained from stress diagram analysis, members are highlighted in green. If the loads are equal, members are not highlighted. The general observations from the analysis are listed below.

a) Leg loads are lower under TOWER analysis

b) Bracing members in the cage have higher loads in TOWER analysis

c) Crossarm top chord (hanger) has higher loads in TOWER analysis.

d) Foundation reactions closely match between the two analyses

Tower B Analysis

Tower B is a double circuit suspension tower with a total structure height of 74'-0". The tower has a single shield wire peak, three crossarms, and a common body with four equal leg extensions. The Tower cage and body have a square configuration, and all four faces are alike. The Tower line angle is 0 deg.

The tower is to be designed for the following simultaneous loads:

Load No. I - A longitudinal load in the direction of the line applied at the conductor supports to simulate broken conductors. 2400 lbs is applied at conductor supports on both top crossarms.

Load No. II - A transverse load, normal to the direction of the line, due to wind on cables at each cable support. 700 lbs is applied for normal ground wire span, 740 lbs is applied for normal conductor spans, and 370 lbs for the broken conductor span.

Table 1: Member forces in Tower A calculated using stress diagram.

					Loads*(kips)			
Member Groups	**Groups Description**	**I -"LN"**	**II -"TR"**	**III -"T"**	**III -"S"**	**IV - "W"**	**V-"DL"**	**Total Load(kips)**
1	Bottom Leg Member	1.8	6.1	16.9	4.5	2.9	1	33.2
2	Middle Leg Member	1.8	5.2	15.1		2	0.8	24.9
3	Cage Leg Member	1.8	2.2	7		0.4	0.5	11.9
4	Top Cage Bracing Member		0.6	2	4			6
5	Bottom Cage Bracing Member		1	4	9.1			13.1
6	Pedestal Bracing Member 1		0.6	1.3	6.1			7.4
7	Pedestal Bracing Member 2		0.5	1	4.8			5.8
8	Pedestal Bracing Member 3		0.4	0.8	3.9			4.7
9	Pedestal Belt Member		0.2	0.5	2.3			2.8
10	Body Extn Bracing Member		0.6	1.3	6.1			7.4
11	Leg Belt Member		0.4	0.8	3.8			4.6
12	Leg Diagonal Member		0.5	1.1	5.2			6.3
14	Crossarm Bottom Member	0.9	0.1		6.3			7.4
15	Crossarm Bottom Member	1.2	0.1		8.3			9.6
16	Crossarm Top Member	2.2						2.2
17	Crossarm Top Member	1.3						1.3
18	Crossarm Top Member	1						1
19	Cage Bottom Belt Member			2.8	3.5			0.7
Foundation	Compression							28.7
Reactions	Uplift							23.1

'*'-''V'' is Vertical, "S" Shear, "T" is Torsion, "W" is Wind and "DL" is Dead Load.

Table 2: Comparison of member forces from Stress Diagram and TOWER model for Tower A.

Member Groups	Group Description		Force from stress diagram(kips)	Difference*%
1	Bottom Leg Member	30	33.2	11
2	Middle Leg Member	22.5	24.9	11
3	Cage Leg Member	7	11.9	70
4	Top Cage Bracing Member	6.3	6	0
5	Bottom Cage Bracing Member	14.2	13.1	-8
6	Pedestal Bracing Member 1	8	7.4	-8
7	Pedestal Bracing Member 2	6.3	5.8	0
8	Pedestal Bracing Member 3	4.8	4.7	0
9	Pedestal Belt Member	3.1	2.8	0
10	Body Extn Bracing Member	7.4	7.4	0
11	Leg Belt Member	4.8	4.6	0
12	Leg Diagonal Member	6.7	6.3	0
14	Crossarm Bottom Member	7.2	7.4	0
15	Crossarm Bottom Member	9.1	9.6	0
16	Crossarm Top Member	2.3	2.2	0
17	Crossarm Top Member	3.5	1.3	-63

18	Crossarm Top Member	4.1	1	-76
19	Cage Bottom Belt Member	3	0.7	-77
Foundation	Compression	27.8	28.7	3
Reactions	Uplift	23.7	23.1	-2
'*'-Difference in load of less than 0.5 kips is ignored.				
Force from stress diagram is more compared to force in the TOWER model.				
Force from stress diagram is less compared to force in the TOWER model.				

Table 3: Member forces in Tower B obtained using stress diagram.

Member Groups	Groups Description				Loads*(kips)			
		I -"LN"	II -"TR"	III -"T"	III -"S"	IV - "W"	V-"DL"	Total Load(kips)
1	18LX- Main Leg	10.4	8.3			2.4	3.4	24.5
2	BODY -Main Leg2	10.4	8.2			2.3	3	23.9
3	BODY -Main Leg1	10.2	7.4			1.5	2.6	21.7
4	CAGE-Main Leg	8.4	4.1			0.7	1.6	14.8
5	CAGE_X-Diag1		0.3					0.3
6	CAGE_X-Diag2			1.7	0.9	0.1		2.6
7	CAGE_X-Diag2			1.7	0.9	0.1		2.7
8	CAGE_X-Diag2		1.1	1.7		0.2		2.9
9	CAGE_X-Diag2		1.1	1.7		0.2		3
10	BODY_X-Diag1		0.8	1.7		0.2		2.7
11	BODY_X-Diag2		0.5	1.1		0.2		1.9
12	BODY_X-Diag3		0.4	0.9		0.2		1.4
13	BODY_X-Diag4		0.3	0.7		0.2		1.3
14	BODY_X-Diag5		0.3	0.6		0.2		1.1
15	BODY_X-Diag6		0.2	0.5		0.3		1
16	18XL_Knee Brace		0.5	1		0.8		2.2
17	CAGE_Strut_trans		0.4					0.4
18	CAGE_Strut_trans		0.4	2.4		0.1		2.9
19	CAGE_Strut_trans		0.7	2.4		0.3		3.4
20	CAGE_Strut_trans		1.1	2.4		0.2		3.7
21	BODY_Diaphragm Strut		0.3	1.2		0.4		1.9
22	BODY_Diaphragm Strut		0.2	0.8		0.3		1.3
23	BODY_Diaphragm X-Diag			2.3				2.3
24	BODY_Diaphragm Redt			1.1				1.1
27	CAGE_Crossarm Diaphragm			1.7				1.7
28	X-ARM_Bottom Chord	3.8	0.2				0.6	4.6
29	X-ARM_Hanger						1.4	1.4

Foundation	Compression	25.5	25.5
Reactions	Uplift	19	18.7

'*'-"LN" is Longitudinal Load,"TR" is Transverse Load,"T" is Torsion,"S" is Shear from Torsion, "W" is Wind Load and "DL" is Dead Load.

Table 4: Comparison of member forces from stress diagram with TOWER model for Tower B.

Member Groups	Groups Description	Force From TOWER Model (kips)	Force from stress Diagram (kips)	Difference*%
1	18LX- Main Leg	24.3	24.5	0
2	BODY -Main Leg2	23.8	23.9	0
3	BODY -Main Leg1	21.5	21.7	0
4	CAGE-Main Leg	15.3	14.8	-4
5	CAGE_X-Diag1	0.6	0.3	0
6	CAGE_X-Diag2	2.1	2.6	25
7	CAGE_X-Diag2	2	2.7	31
8	CAGE_X-Diag2	2.1	2.9	38
9	CAGE_X-Diag2	2.3	3	28
10	BODY_X-Diag1	2.5	2.7	0
11	BODY_X-Diag2	1.7	1.9	0
12	BODY_X-Diag3	1.3	1.4	0
13	BODY_X-Diag4	1.3	1.3	0
14	BODY_X-Diag5	1.1	1.1	0
15	BODY_X-Diag6	1	1	0
16	18XL_Knee Brace	1.3	2.2	76
17	CAGE_Strut_trans	0.9	0.4	-60
18	CAGE_Strut_trans	4.3	2.9	-33
19	CAGE_Strut_trans	2.2	3.4	58
20	CAGE_Strut_trans	1.8	3.7	101
21	BODY_Diaphragm Strut	1	1.9	97
22	BODY_Diaphragm Strut	1.4	1.3	0
23	BODY_Diaphragm X-Diag	0.1	2.3	#
24	BODY_Diaphragm Redt	1	1.1	0
27	CAGE_Crossarm Diaphragm	0.3	1.7	#
28	X-ARM_Bottom Chord	4.3	4.6	7
29	X-ARM_Hanger	1.9	1.4	-25

Foundation	Compression	25.5	25.5	0
Reactions	Uplift	19	18.7	0
'*'- Difference in loads of less than 0.5 kips is ignored.				
#'-Tower does not show any loads in this member.				
Force from stress diagram is **more** compared to force in the TOWER model.				
Force from stress diagram is **less** compared to force in the TOWER model.				

Table 5: Member forces in Tower C obtained by using Stress Diagram.

Member Groups	Groups Description				Loads*(kips)			
		I -"V"	II -"S"	III -"T"	III -"S"	IV -"W"	V-"DL"	Total Load(kips)
1	Cage Bracing 1		0.8					1
2	Cage Bracing 2		1.6	2.9	1.3	0.2		5.1
3	Cage Bracing 3		1.6	2.9	1.3	0.6		5.1
4	Cage Bracing 4		1.6	2.9	1.3	0.6		5.1

5	Cage Bracing 5		2.9	7.5	3	0.6		11.6
6	Cage Bracing 6		2.9	7.5	3	1.4		11.9
7	Body Bracing 7		1.2	6.2	0.5	1.4		7.8
8	Body Bracing 8		0.9	4.7	0.4	0.4		6.1
9	Body Bracing 9		1.8	9	0.7	0.5		12.2
10	Bottom Leg Bracing 10		1.7	8.5	0.7	1.4		12.5
11	Top X-Arm Peak Member		0.6			2.4		0.6
12	Top X-Arm Top Member	3.1						3.1
13	Top X-Arm Bottom Member	2.7	0.5	7.3				10.5
14	Middle X-Arm Top Member	2.3						2.3
15	Middle X-Arm Bottom Member	2.2	0.5	9.2				11.9
16	Bottom X-Arm Top Member	1.4						1.4
17	Bottom X-Bottom Member	1.2	0.9	0				2.1
18	Top Cage Leg (4)	3	6.2		3.9	2	0.5	15.5
19	Bottom Cage Leg (6)	3	13.7		11.4	5.5	1.5	35.1
20	Basic Body Leg (9)	3	20.2	7	15.4	8.6	3	57.2
20A	Bottom Leg (10)	3	21.7	7.5	16	11.2	4	63.4

'*'-"V" is Vertical Load, ""S" is Shear, "T" is Torsion, "W" is Wind and "DL" is Dead Load.

Table 6: Comparison of member forces from Stress Diagram with TOWER model for Tower C.

Member Groups	Groups Description	Force From TOWER Model (kips)	Force from stress Diagram (kips)	Difference*%
1	Cage Bracing 1	1.6	1	-35
2	Cage Bracing 2	5.2	5.1	0
3	Cage Bracing 3	5.2	5.1	0
4	Cage Bracing 4	5.9	5.1	-15
5	Cage Bracing 5	12.5	11.9	-5
6	Cage Bracing 6	13.1	11.9	-9
7	Body Bracing 7	9	7.8	-13
8	Body Bracing 8	7.7	6.1	-21
9	Body Bracing 9	12	12.2	0
10	Bottom Leg Bracing 10	12.4	12.5	0
11	Top X-Arm Peak Member	0.9	0.6	0
12	Top X-Arm Top Member	5	3.1	-39
13	Top X-Arm Bottom Member	8.2	10.5	28
14	Middle X-Arm Top Member	4.2	2.3	-45
15	Middle X-Arm Bottom Member	9.9	11.9	21
16	Bottom X-Arm Top Member	3	1.4	-53
17	Bottom X-Bottom Member	3.6	2.1	-41
18	Top Cage Leg (4)	12	16.5	37
19	Bottom Cage Leg (6)	27.3	35.1	29
20	Basic Body Leg (9)	51.2	57.2	12
20A	Bottom Leg (10)	55.3	63.4	15

*'-Difference in loads of less than 0.5 kips is ignored.

Force from stress diagram is **more** compared to force in the TOWER model.
Force from stress diagram is **less** compared to force in the TOWER model.

Table 7: Member forces in Tower D obtained from stress diagram.

Member Groups	Groups Description				Loads*(kips)		
		I -"V"	II -"S"	IIIa-"S"	IV -"W"	V-"DL"	Total Load (kips)
0	Cage Bracing 0		0.4	3.6	0.2		3.8
1	Cage Bracing 1		0.4	3.6	0.2		3.8
2	Cage Bracing 2		1	7.3	0.5		7.8
3	Cage Bracing 3		1	7.3	0.5		7.8
4	Cage Bracing 4		1	7.3	0.5		7.8
5	Cage Bracing 5		1.8	13.2	0.9		14.1
6	Cage Bracing 6		1.8	13.2	0.9		14.1
7	Body Bracing 7		0.6	3.5	1.1		4.6
8	Body Bracing 8		0.5	2.7	0.8		3.5
9	Body Bracing 9		0.9	5.2	1.6		6.8
10	Leg Bracing10		0.8	4.8	1.4		6.2
11	Top X-Arm Peak Member		0.3	11.4			11.7
12	Top X-Arm Top Member	3.7					3.7
13	Top X-Arm Bottom Member	3.3	0.5	11			14.8
14	Middle X-Arm Top Member	2.3					2.3
15	Middle X-Arm Bottom Member	2.2	0.5	13.8			16.5
16	Bottom X-Arm Top Member	1.4					1.4
17	Bottom X-Bottom Member	1.2	0.5	11			12.7
18	Top Cage Leg (4)	3	3.9	31.5	2	1	41.4
19	Bottom Cage Leg (6)	3	8.6	65.5	4.3	2	83.4
20	Basic Body Leg (9)	3	12	88.1	8.9	3.5	115.5
20A	Bottom Leg (10)	3	12.8	92.4	10.1	4.5	122.8

'*'-"V" is Vertical Load, ""S" is Shear, "T" is Torsion, "W" is Wind and "DL" is Dead Load.

Table 8: Comparison of member forces from Stress Diagram with TOWER model for Tower D.

Member Groups	Groups Description	Force From TOWER Model (kips)	Force from stress Diagram (kips)	Difference*%
0	Cage Bracing 0	3.4	3.8	0
1	Cage Bracing 1	5.2	3.8	-27
2	Cage Bracing 2	7.6	7.8	0
3	Cage Bracing 3	7.7	7.8	0
4	Cage Bracing 4	8.1	7.8	0
5	Cage Bracing 5	13.1	14.1	8
6	Cage Bracing 6	16.8	14.1	-16
7	Body Bracing 7	8.1	4.6	-44
8	Body Bracing 8	4.3	3.5	-18
9	Body Bracing 9	6.8	6.8	0
10	Leg Bracing10	9.6	6.2	-35
11	Top X-Arm Peak Member	11.8	11.7	0
12	Top X-Arm Top Member	6.1	3.7	-39
13	Top X-Arm Bottom Member	11.9	14.8	25
14	Middle X-Arm Top Member	4.9	2.3	-53

15	Middle X-Arm Bottom Member	14.4	16.5	15
16	Bottom X-Arm Top Member	2.9	1.4	-52
17	Bottom X-Bottom Member	11.5	12.7	11
18	Top Cage Leg (4)	36.5	41.4	14
19	Bottom Cage Leg (6)	76.1	83.4	10
20	Basic Body Leg (9)	110.7	115.5	4
20A	Bottom Leg (10)	115.7	122.8	6

*'-Difference in loads of less than 0.5 kips is ignored.

Force from stress diagram is **more** compared to force in the TOWER model.
Force from stress diagram is **less** compared to force in the TOWER model.

Load No. III - A vertical load of 600 lbs at ground wire support, 1500 lbs at each intact conductor support, and 750 lbs for the broken conductor support.

Load No. IV - Wind on tower normal to the line, equivalent to 40 lbs per linear vertical foot of the tower.

Load No. V– Self weight of the tower.

Observations

a) Leg loads closely match both analyses, but cage leg has slightly higher loads in TOWER analysis.

b) Bracing members in cage have lower loads in TOWER analysis.

c) Crossarm bottom chord has lower loads in TOWER analysis.

d) Crossarm top chord (hanger) has higher loads in TOWER analysis.

e) Foundation reactions closely match between the two analyses

Tower C Analysis

Tower C is a double circuit suspension tower with a total structure height of 87'-8". The tower configuration includes a double shield wire peak, three crossarms, and a common body with four equal leg extensions. The Tower cage and body have a square configuration, and all four faces are alike. Tower has a line angle of 0deg. The tower is designed for the following simultaneous loads:

Load No. I - A vertical load of 1500 lbs at each cable support. Total 12,000 lbs.

Load No. II - A transverse load, normal to the direction of the line due to wind on cables at each cable support. 1200 lbs is applied for intact ground wire spans, 1800 lbs for intact conductor span, and 900 lbs for the broken conductor spans.

Load No. III - A longitudinal load in the direction of the line applied at the conductor supports to simulate broken conductors. 4000 lbs load is applied at the top, and middle right conductor supports.

Load No. IV - Wind on tower normal to the line, equivalent to 40 lbs per square foot on 1 ½time the projected area of one face of the tower.

Load No. V– Self-weight of the tower.

Observations

a) Leg loads are lower in TOWER analysis.

b) Crossarm bottom chord (except for bottom crossarm) has lower loads in TOWER analysis.

c) Bracing members in cage and below waist have higher loads in TOWER analysis

d) Crossarm top chord (hanger) has higher loads in TOWER analysis.

Tower D Analysis

Tower D is a double circuit inline dead-end tower with a total structure height of 91'-8". The tower configuration includes a double shield wire peak, three crossarms, and a common body with four equal leg extensions. The Tower cage and body have a square configuration, and all four faces are alike. All wires are dead ended on the structure. The tower is to be designed for the following simultaneous loads:

Load No. I - A vertical load of 1500 lbs at each cable support. Total: 12,000 lbs.

Load No. II - A transverse load, normal to the direction of the line, due to wind on cables at each cable support. 600 lbs is applied for intact ground wire spans, 900 lbs to intact conductor spans.

Load No. III - A longitudinal load in the direction of the line applied at all the ground wire and conductor supports to simulate terminal condition. 5,500 lbs is applied at ground wire supports, and 6,000lbs is applied at conductor support in one direction. Total: 47,000 lbs.

Load No. IV - Wind on tower normal to the line, equivalent to 40psf on 1 ½ times the projected area of one face of the tower.

Load No. V– Self weight of the tower.

Observations

a) Leg and crossarm bottom chord loads are lower in TOWER analysis.

b) Bracing members have higher loads in TOWER analysis

c) Crossarm top chord (hanger) has higher loads in TOWER analysis.

Conclusions

Comparing the two analyses methodologies, the following conclusions can be drawn

a) Load in tower legs is less when analyzed in TOWER.

b) Few bracing members have more load when analyzed in TOWER but loads in most bracing members match closely between the two analyses techniques.

c) Crossarm hangers have a higher load when analyzed in TOWER.

d) The use of tension-only members for crossarm hangers changes the load in the crossarm hanger members.

The analysis methodology for the graphical stress diagram method is different from the finite element analysis method. Under the stress diagram method, the shear load is split equally between the two parallel faces, and the vertical load is divided equally between four legs. As a result, the vertical and shear load distribute statically between the tower leg and web members. In finite element analysis, a part of the vertical load is resisted by the web members. As a result, loads in the web members go up, and load in the leg members decrease. This is more pronounced as the magnitude of the load increases and loads are applied in both transverse and longitudinal directions [8]. Crossarm top chords (hangers) are assumed to carry vertical load only in the stress diagram analysis. However, in TOWER analysis, crossarm hangers carry all three vertical, transverse, and longitudinal loads. Moreover, hanger members can be designed as tension only or tension-compression members. The member loads will change depending upon the modelling technique. This change in force distribution from the original design methodology could lead to member overstress in TOWER analysis. According to ASCE 10-15 [8], historic performance of the tower must be considered before any member modifications are recommended.

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