Analysis and Design of Transmission line Tower, Comparison of Bracing pattern and Materials.

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***Abstract*--A high voltage transmission line structure design is characterized by the special requirements to be met from both electrical and structural point of view. The work undertaken is an attempt to understand and compare the effect of different bracing pattern and materials namely high tensile steel, mild steel and aluminum in transmission line tower structure.**
Analysis and design of tower is carried out in Stadd Pro. From the analysis results obtained, connection and foundation design is successively carried out. The conclusions are drawn on the basis of analysis, member design and foundation design carried out. Parametric study is carried out with comparison of parameters like deflection, total weight of tower and final cost is derived. Results shows that vertical configuration of tower with quad bracing and material high tensile steel shows lowest weight as compared to simple bracing and material mild steel. Aluminum tower with simple and quad bracing shows excessive deflection.

***Index Terms*—Transmission line tower, bracing pattern, broken wire condition, anti cascading condition, material comparison.**

I. INTRODUCTION

"Tall structures with relatively small cross sections and with a large ratio between the height and the maximum width are known as tower". A tower is a single cantilever structure freely standing over the (foundation) self supporting structure fixed at its base. Towers like water tower, television tower, and radio tower are the one in which the governing criteria for design and geometry are dead loads, wind loads and seismic loads, where as in case of transmission line tower with addition to above loads, various criteria with respect to electrical clearances and span play an vital role in deciding the geometry which in turn affect the allover loading pattern. Hence the design of transmission line tower is distinctly classified into mechanical and electrical design. The basic intent of study is to economies tower design without acting its severability and safety. For achieving above objective, three main criteria chosen for study are particularly,

I) Changing the lattice arrangement by providing quad bracing instead of conventional diamond arrangement as shown in fig 1.

II) Studying the effect of different material like mild steel, high tensile steel and aluminum for structure of transmission line tower and their results in terms of behavior and economy.

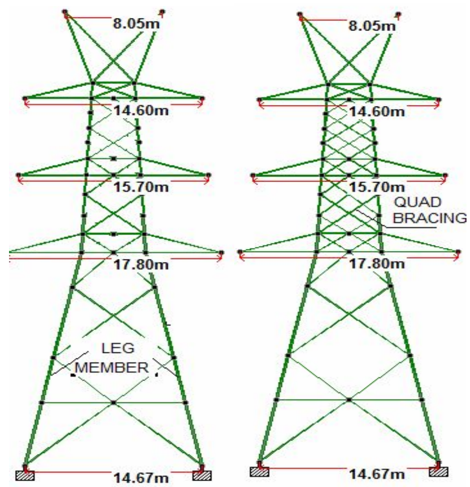

Fig 1. Tower with simple and quad bracing

With increase in transmission distances, electricity is transmitted at extra high voltage so as to minimize the transmission losses. This requires a greater ground clearance which means that taller and heavier transmission structures are required with increased costs. The transmission line tower constitutes about 28 to 42 percent of the cost of a transmission line. Therefore most optimum tower design can bring about significant economy in the cost of transmission lines.

II. PROBLEM DEFINATION AND ANALYSIS

1) General

Analysis of transmission line tower starts with finalization of layout or geometry in accordance with applicable electrical data and terrain conditions. The basic electrical and mechanical parameters are kept common for both the bracing patterns of towers. Tower layout is finalized on the basis of Electrical clearance criteria such as inter conductor clearance, body insulation clearances and ground wire conductor clearances. Wind loads acting on conductor, ground wire and load combinations for normal condition and broken wire condition are calculated as per IS 802. The final layout of tower is modeled in Stadd Pro. Load combinations calculated manually are applied in Stadd Pro model. Analysis and design are carried out in software as per IS 802

2) Problem Formulation and Load combinations

The present study is divided into two Cases,

Case-I: Study the change in behavior of change in bracing pattern in analysis, design and foundation loads of transmission line tower.
Case-II: Study the effect of different materials like Mild steel, High tensile Steel and Aluminum on analysis, design and foundation loads of towers. Fig 2. shows the distribution of parameters which are taken into consideration for study of Transmission line tower. Table 1 shows the data selected for the present study.

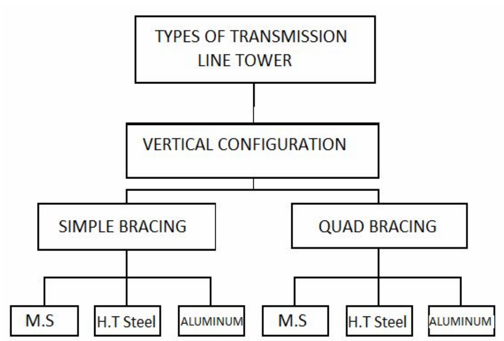

Fig 2. Problem definitions

TABLE I
PROBLEM DEFINITION

Sr. No.	Parameter	Specification	Units
1	Tower type	400 kV, Tangent	
	No of circuit	Double	
2	Angle of deviation	15°	
3	ground clearance		
4	Conductor		
	Diameter	3.177	cm
	unit wt	2.004	kg/m
	C/s areas	5.97	cm^2
	Ultimate tensile strength	16438	kg
	Coefficient Of linear expansion	0.0000193	/deg C°
	Young's modulus	703400	kg/cm^2
5	Ground wire		
	Diameter	1.098	cm
	unit wt	0.583	kg/m
	C/s areas	0.7365	cm^2
	Ultimate tensile strength	7112	kg
	Coefficient Of linear expansion	0.0000115	per C°
	Young's modulus	1933000	
6	Insulator	Suspension type	
7	Shield angle	20'	
8	Line span	400	m
9	Weight span	600	m
10	Temperature		
	Maximum	75	C°
	Minimum	0	C°

Analysis of transmission line tower is carried out for self weight and wind loads. Being a pin jointed light structure it is flexible and free to vibrate hence earthquake load is not considered in the analysis. However where earthquake is experienced very intensively, earthquake forces may be considered in the foundation design

Load cases for analysis of transmission line tower are classified into three groups.

a) Climatic loads related to reliability requirements.
b) Failure containment loads related to security requirements.
c) Construction and maintenance loads related to safety requirements.

- Reliability requirements
  i. Wind loads (Non snowy regions)
  ii. Wind loads with ice (Snowy regions)
  iii. Wind loads without ice. (Snowy regions)
- Security requirement- Failure containment loads under broken wire condition

i. Unbalanced longitudinal loads and torsion loads due to broken wire condition. All towers should have inherited strength for resisting longitudinal and transverse loads resulting from breakage of specific no of conductors and/or earth wires.

ii. Anti cascading Loads-Failure of items like insulators, hardware joints etc. As well as failure of major components like tower foundation and conductors may result in cascading condition. In order to prevent cascading failure angle tower shall be checked for anti cascading loads for all conductors and earth wires broken in the same span.

- Safety requirement-loads during construction and maintenance

i. Loads during construction. These are loads imposed on tower during the construction of transmission line.
ii. During maintenance. These are loads imposed on tower during the construction and maintenance period.

Nature of loads

I. Transverse loads (T)

These are loads imposed on tower structure, conductors, ground wires and insulators strings. Component of mechanical tension from conductor and ground wire.

II. Vertical loads (V)

Loads due weight of each conductor, ground wire based on appropriate weight span, weight of insulator strings and fittings, Self weight of structure, Loads during construction and maintenance.

III. Longitudinal loads (L)

Unbalanced horizontal loads in longitudinal direction due mechanical tension of conductor and or ground wire.

Load combinations are prepared as per guidelines of IS 802. Wind pressure calculations for tower are done taking wind zone 3 and reliability level 1. Table 2 shows calculations for wind pressure acting on ground wire, conductor, and insulators.

TABLE 2
WIND PRESSURE CALCULATIONS

Discription	Value	Unit	Reference
Reliability level	1		
Return period of design load	50	Years	Table no 1 IS 802[13]
wind zone	3		
Basic wind speed V_b	44	m/s	Cl no 8.1 IS 802[13]
Reference wind speed Vr	32	m/s	
Risk coefficient (K_1)	1		Table no 2 IS 802[13]
Terrain category	2		
Terrain Roughness coefficient K_2	1.08		Table no 3 IS 802[13]
Design wind speed V_d	34.56	m/s	
Design wind pressure.P_d	717	N/m^2	
	73	Kg/m^2	
Span	400	m	
Wind pressure on conductor			
Drag coefficient Cdc	1		
Average height of conductor	40.4	m	
Gust response factor for conductor G	2.2		Table no 7 IS 802[13]
Wind pressure on conductor	$P_d \times C_{dc} \times G_c$		
	1576.600	N/m^2	
	161	Kg/m^2	
Wind pressure on ground wire			
Drag coefficient C_{dc}	1.2		
Average height of groundwire	49.7	m	
Gust response factor forgroundwire G	2.28		
Wind pressure on ground wire	$P_d \times C_{dg} \times G_g$		
	1962.823	N/m^2	
	200.288	Kg/m^2	
Wind pressure on insulator			
Drag coefficient C_{dc}	1.2		
Average height of insulator	51.085	m	
Gust response factor for insulator G_i	2.488		Table no 7 IS 802[13]
Wind pressure on insulator	$P_d \times C_{di} \times G_i$		
	218.325	Kg/m^2	

Wind loads acting on tower body are calculated in table 3. These wind loads are assumed to be acting at different levels on tower body on transverse face. Level "GW" mentions ground wire level, "TC" stands for top cross, "BB" is bottom body level and "GL" is at ground level. Hence respective wind loads are redistributed at these levels and are assumed to be acting at tip of peak, cross arm tip, bottom body belt, and ground level. Loads acting due to sang tensions are calculated as per IS 5613, which are represented in table 4.

TABLE 3
WIND LOAD ON BODY TOWER

Level	Total area	Solidity ratio	Exposed area	Design wind pressure	Drag co-efficient	Gust factor	Applied wind load
	m^2	m^2	m^2	Kg/m^2	C_{dt}	G_t	Kg
GW							1053.19
	18.55	0.250	4.64	62.69	2.86	2.49	
TC							2634.63
	32.48	0.224	7.28	62.69	2.81	2.42	
MC							3467.78
	39.19	0.231	9.05	62.69	2.78	2.35	
BC							5451.35
	134.46	0.111	14.93	62.69	3.34	2.23	
BB							5194.43
	86.94	0.085	7.39	62.69	3.46	1.99	
GL							1629.42

TABLE 4
SAG TENSION LOADINGS

Terrain condition	Groundwire Tension(Kg)	Conductor Tension(Kg)
32' Full wind	3367.01	8017.1
32' no wind	1200	3587.7
32' 75% wind	2762	6667
min temp, No wind	1313	4061.1
min temp 36% wind	1922	5129.8
75' no wind	1132	3096.2

Loadings on transmission line tower are typified due to presence of an extra load case of broken wire condition. To integrate the effect of loads due to broken wire condition considering case of wire breakage at different levels a total of two sets of 16 load combinations are worked out considering angle of deviation 0° and 7.5° including anti-cascading loading condition which incorporates a condition in which all the conductors on one side of tower are considered broken sample load calculation is shown below for reliability condition, security condition and anti cascading condition.

LOAD CALCULATIONS FOR CONDUCTOR.Φ = 7.5

RELIABILITY CONDITION

LOAD TYPE	NORMAL CONDITION	
Transverse load		
Wind on wire	3506	
wind on Insulator/ clamp	410	
Deviation load	4185.8	
TOTAL (KG)	8101	
Vertical load		
Weight of wire	2405	
Weight of insulator clamp	1270	
TOTAL (KG)	3675	
Longitudinal load.		
Deviation load	0	
Wind on insulator/clamp	0	
TOTAL (KG)	0	

SECURITY CONDITION

LOAD TYPE	NORMAL CONDITION	BROKENWIRE CONDITION
Transverse load		(60% of clear span)
Wind on wire	3506	2103
wind on Insulator/ clamp	410	410
Deviation load	4186	2093
TOTAL (KG)	8101	4606
Vertical load		(60% 0f weight span)
Weight of wire	2405	1443
Weight of insulator clamp	1270	1270
TOTAL (KG)	3675	2713
Longitudinal load.		
Deviation load	0	16034
Wind on insulator/clamp	0	0
TOTAL (KG)	0	16034

ANTICASCADING CONDITION

LOAD TYPE		BROIKEN WIRE CONDITION
Transverse load		
Wind on wire		0
wind on Insulator/ clamp		0
Deviation load		0
TOTAL (KG)		0
Vertical load		
Weight of wire		1443
Weight of insulator clamp		1270
TOTAL (KG)		2713
Longitudinal load.		
Deviation load		7175
Wind on insulator/clamp		0
TOTAL (KG)		7175

In reliability condition none of the wire is considered to be broken and in security condition one side wire is considered to be broken hence component of longitudinal load comes into consideration.

These load combinations are represented in graphical form with the help of loading trees as shown in fig 3.

Fig. 3. Load Tree diagram

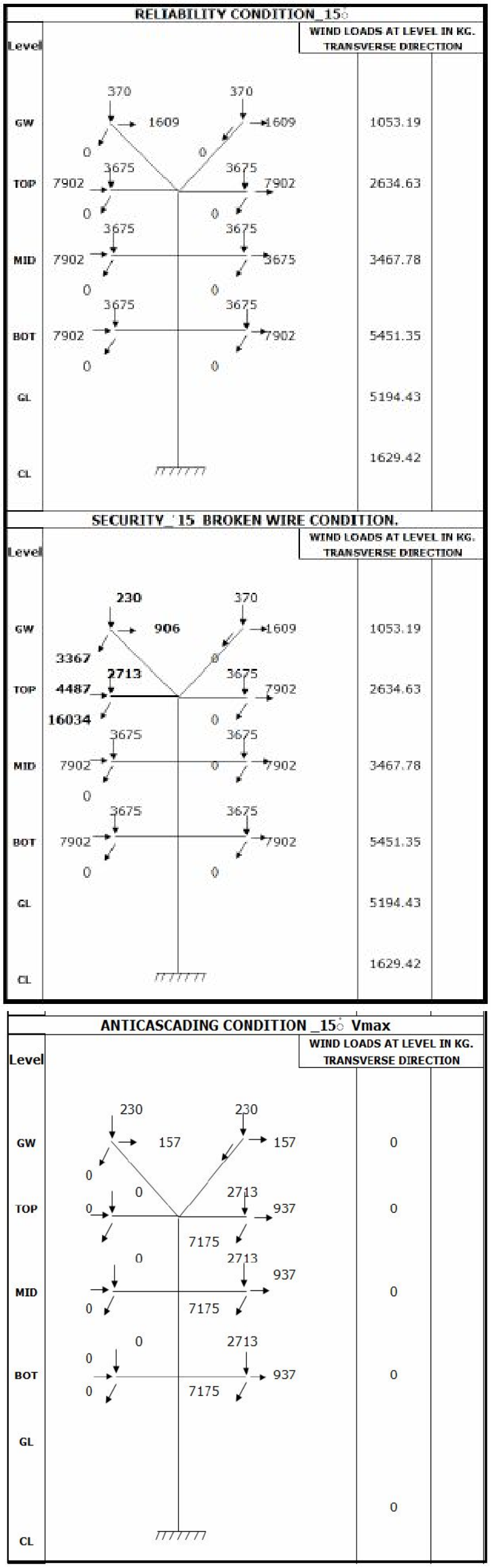

Fig 3. Loading tree diagrams

3) Analysis and Design of Tower

Analysis of transmission line tower is carried out using Stadd Pro software. Six different models were prepared in software according to fig 2. Fig 4 shows the modeling of load application in software

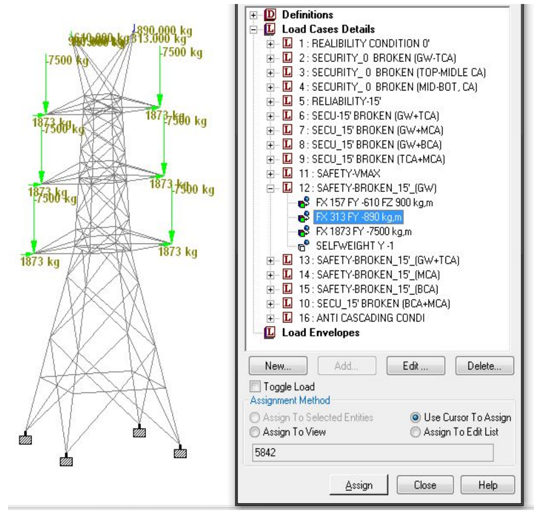

Fig. 4. Load application

Assumptions:

All members are pin jointed and connection is done using bolts in such a manner that the members carry axial load only.

- The bolt slippage through the structure are such that to allow the use of same modulus of elasticity for entire structure, thus permits use of principal of superimposition for stress analysis.
- Shear is distributed equally between two members of a bolted web system.
- Shear is carried by diagonal members under tension in Pratt truss system with member design for tension only. Tensional shear applied at cross arms level for square tower are resisted by all four tower faces equally.
- Plan members at level other than those at which external loads are applied or were leg slope changes are designed as redundant members.
- Any face of tower subjected to external load lie in the same plane of analysis of the particular face.
- Transverse load are shared by the members on the transverse face of the tower equally, similarly the longitudinal loads are shared equally by the two longitudinal faces.
- Vertical loads placed symmetrically and dead weights of the structure are shared equally by four legs

Analysis Steps

- Analysis and design process are run successively in Stadd pro in two stages as follows. The following analysis steps are performed for obtaining final member forces and sections.

I. Data formulation
II. Electrical diagrams
III. Load calculations
IV. Load combinations
V. Modeling in Stadd pro
VI. Generating load cases
VII. Assign member specifications

VIII. Assign member properties
IX. Perform analysis
X. Assign optimum member section properties
XI. Perform analysis
XII. Final member forces

Fig-5 shows the steel design performed in Stadd pro. as per IS 802. Towers with same loading, geometry and two types of bracing pattern were assigned with three material properties namely, mils steel, high tensile steel and aluminum. Bolted connections are provided and calculation for connection is done from the member forces obtained from Stadd Pro analysis.

R.C.C stepped footing type of foundation with chimney is provided for present study. Soil is assumed to be semi submerged with water level at a certain depth. Foundation is designed for normal loading and broken wire condition loadings. Chimney and base slab are designed for down ward thrust and vertical forces with bending.

Complete design process flow from problem formulation up to connection design and foundation is described in form of chart in fig 6.

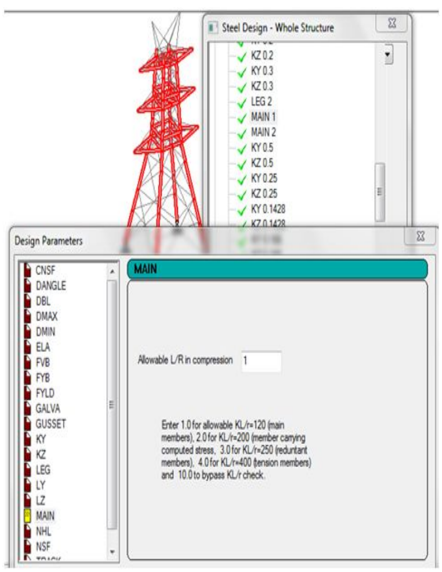

Fig 5. Member design in Stadd Pro.

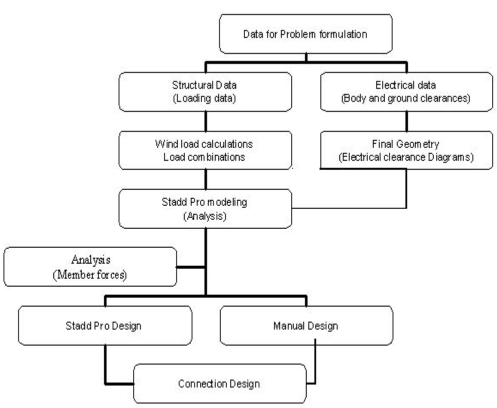

Fig-6 Layout of analysis and design process

4) Results and Discussions

Analysis and design results for towers with simple and quad bracing along with change in material properties, mild steel, high tensile steel and aluminum is carried out in terms of force distribution pattern, deflection, economy in overall weight and cost.

Foundation loads comprises a major component of uplift load and side thrust due to broken wire conditions. Due to broken wire condition an extra external longitudinal force of the broken conductor or ground wire comes into consideration. This external force is distributed into longitudinal and transverse and vertical components and hence this leads to increase in side thrust in both the direction and uplift load under broken wire condition as compared to normal condition where conductors on both sides of tower is connected which can be observed from the fig 7,8 and 9. Figure 7 shows the comparison of uplift forces for towers with both the bracing patterns and material property mild steel and HT steel. It can be observed that uplift foundation forces are higher under broken wire condition as compared to normal condition.

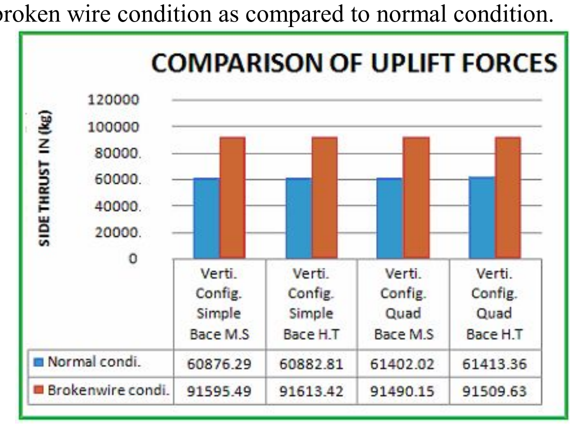

Fig 7. Comparison of uplift forces

In broken wire condition as conductors from one side is considered broken, the longitudinal sag tension force of the opposite side conductor becomes unbalanced which results in increase in longitudinal thrust. Fig 8. shows comparison of longitudinal thrust

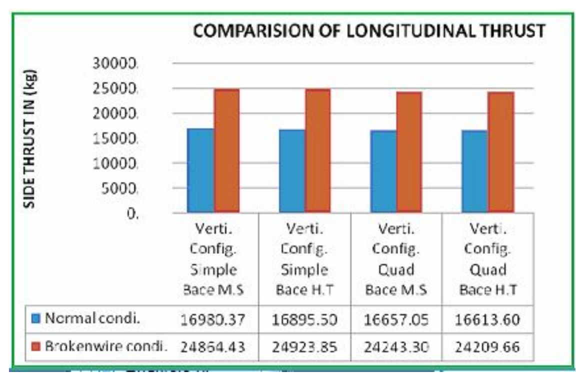

Fig 8. Comparison of longitudinal thrust

Depending upon the angle of deviation the transverse component of unbalanced longitudinal force adds to the side thrust in transverse direction. Fig 9 shows the increased side thrust in transverse direction under broken wire condition as compared to normal condition.

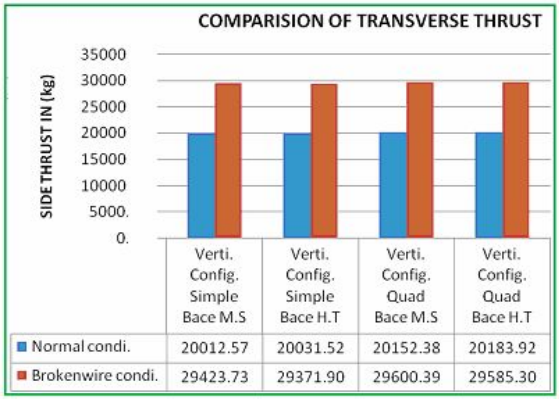

Fig 9. Comparison of transverse thrust

Foundation design is carried out for axial compression and tension with biaxial bending. Partially submerged soil is assumed. Checks against resistance against uplift, check for soil bearing capacity, check for one way and two way shear, check for uprooting of stub and overturning check are performed.

Two towers with same loading and different bracing pattern are observed. Table 5 shows the values of leg member forces in ascending order considering mild steel material property and same loading condition. It can be observed that up to leg member no 6 forces in tower with quad bracing are lower than that of in tower with simple bracing. As the effect of quad bracing comes into picture, the no of members intersecting leg member increases and the forces distributed to leg embers increases. Hence the section properties for lower leg members in tower with quad bracing are lighter than that of in tower with simple bracing.

TABLE 5
FORCES IN LEG MEMBERS

Member name	Quad Bracing (Kg)	Simple Bracing (Kg)
LEG-1	107202.49	106977.35
LEG-2	106783.42	106721.41
LEG-3	103526.48	103289.085
LEG-4	95033.93	97523.75
LEG-5	87837.25	92000.5
LEG-6	83366.203	90031.75
LEG-7	66702.38	58536.55
LEG-8	54550.75	45396.62
LEG-9	45955.52	43693.71
LEG-10	40354.44	31383.07
LEG-11	32580.94	16232.18
LEG-12	23308.61	10116.9

Tower loading and geometry is kept same and effects of different materials are studied. Three different materials are assigned in Stadd pro namely, High tensile steel, Mild steel and Aluminum. Observing the weights of towers from table 6, it shows lowest weight of tower of aluminum and the weight increases as we go from high tensile steel to mild steel. In spite of higher section property in tower with aluminum, as the density of material is low than steel it gives reduced overall weight. Because of high strength of HT steel, members are of lighter sections as compared to mild steel members so overall weight reduces when HT steel is used instead of mild steel.

As observed from table 6 it is found that tower with vertical configuration and material high tensile steel gives the most economy in terms of saving of material and cost.

TABLE 6
WEIGHT COMPARISON

Tower Designation	Lattice arrangement	Wt in (Kg)
Vertical configuration (M.S)	Diamond bracing	12977.06
Vertical configuration (H.T)	Diamond bracing	10991.79
Vertical configuration (M.S)	Quad bracing	13589.45
Vertical configuration (H.T)	Quad bracing	10799.90

Transverse deflection in millimeters, in tower with simple bracing and quad bracing with different material namely HT, MS, and aluminum are observed and the results for tower with simple and quad bracing are tabulated in Table: 7 and Table: 8 respectively. Observing deflection for towers from fig 10 and fig 11, it can be seen that in spite of less over all weight, aluminum tower shows maximum resultant defection. Reduction can be observed in resultant defection as we go for mild steel and high tensile steel. This is due because, modulus of elasticity of aluminum is 68.94 kg/mm^2 a and that of mild steel and HT steel are 205 kg/mm^2 and 349.975 kg/mm^2 respectively.

TABLE 7
DEFLECTION OF SIMPLE BRACING TOWER

Deflection for simple bracing			
Level	M.S	H.T	AL
P9	0	0	0
P8	4.866	2.85	11.201
P7	11.434	6.698	28.652
P6	21.288	12.47	51.867
P5	53.86	31.444	129.597
P3	83.645	48.995	184.126
P1	128.574	75.313	277.2668
PEAK	176.398	103.326	357.778

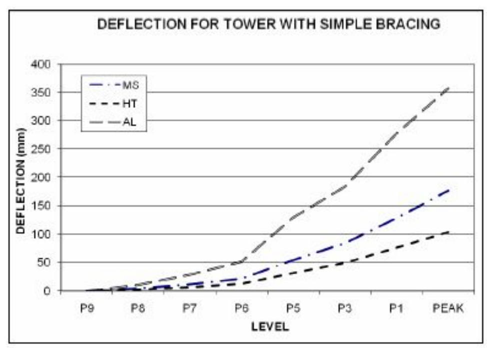

Fig 10. Comparison of deflection for simple bracing

TABLE 8
DEFLECTION OF SIMPLE BRACING TOWER

Deflection for Quad bracing			
Level	M.S	H.T	AL
P9	0	0	0
P8	5.11	2.993	11.188
P7	11.929	6.987	26.069
P6	21.667	12.691	48.004
P5	57.422	33.635	134.81
P3	94.402	55.297	203.047
P1	135.319	79.264	288.749
PEAK	183.487	107.479	392.269

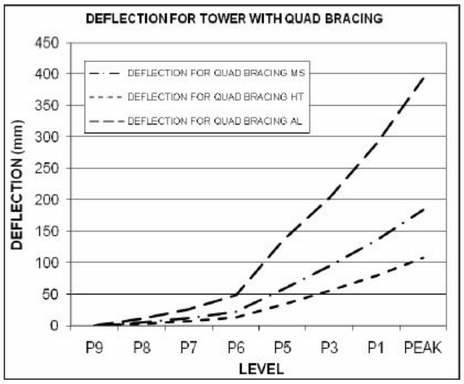

Fig 11. Comparison of deflection for quad bracing

Deflection results of aluminum tower for both the bracing patterns are very high and hence tower of aluminum is not regerded. Finally the total cost of the most light weighted tower which is tower with quad bracing with high tensile steel is as shown in table 9.

TABLE 9
TOTAL COST CALCULATION

Tower Designation	Wt of tower (Kgs).	Excavation (m^3)	R.C.C (m^3)	P.C.C	steel (Kg)	Amount (Rs)
Vertical config. Quad H.T Steel	10799.90	335.53	50.17	5.00	4683	1105156.17

5) Conclusion

The following conclusions are drawn from the present study:

- Comparison of simple bracing with quad bracing suggests that there is minor change in behavior and loadings in both the cases. Tower with quad racing gives less over all weight compared to tower with simple bracing thus resulting into economy.
- Comparison between high tensile steel and mild steel, for both the cases with simple bracing and quad bracing reveals that high tensile steel shows overall economy due to less overall weight and reduced resultant deflection.
- Comparison of aluminum tower with that of steel tower suggests that aluminum tower in spite of its less overall weight as compared to steel tower shows excessive deflection which makes it unfit under serviceability conditions.

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