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# Parametric Optimization of Wind Turbine Lattice Towers

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## Abstract

In the Indian context, if wind turbine installations have to exploit the estimated potential then the need of the hour is to utilize the complex terrains as most of the good windy sites in flat terrains have already been exhausted. The retrospective analysis of 25 years of wind speed was carried out using numerical weather prediction (NWP) model for a complex hilly terrain at Iddukki district of Kerala and the same was validated by onsite measurement using C-WET met mast for a period of one year with an objective to increase the accuracy of the model by reducing the bias. The data so obtained was used to arrive at the wind shear force which is the major governing parameter acting on the top of wind turbine towers. In this paper, various geometric configurations both for 73 m & 30m tall lattice type wind turbine towers were analyzed using STAAD PRO tool to arrive at the most optimal/least weight configuration by changing the base width and keeping the top width bare minimum and constant as per the requirements for housing the nacelle at the top, with in the limits of allowable blade deflections.

*Key words:* wind turbine(WT), wind turbine tower, lattice tower, wind shear force, renewable energy and parametric optimization.

## 1.0 **Introduction**

In view of the rapid depletion of the fossil fuels the present thrust for generating power is on the renewable Energy, across the globe as well as in India. Out of the two weather driven renewables wind and solar, wind has come to occupy a prominent place in India with Installed capacity as on date of about 14500 MW which would mean that the penetration into the Indian grid by wind is about 7-8 %. The total estimated installable wind potential in the country is about 49000 MW assuming one percent of average land availability in windy sites thus at the present moment a target of about 30% is achieved. This indicates that much of the potential (70%) still needs to be tapped to meet the estimated target. Most of the present installed wind turbine installations in India are on the flat terrains where one year onsite/measured wind data is sufficient enough to decide the 20 year operational design life of the project as per international criteria. However good windy sites on these flat terrains have almost been exhausted and the need of the hour is to capture wind in the complex hilly terrains, to achieve the said target. In complex terrains the variance/variability of the wind needs to be studied rather carefully and one year onsite/ measured data is not sufficient enough to mitigate the developer's risk of under performance. The long term onsite wind measurements in the complex terrains is costly and time consuming and to avoid the delay the technique being used now-a-days is Numerical Weather Prediction (NWP) technique. By blending the mix of long term NWP data with the short term onsite/ measured data the accuracy levels of wind resource assessment can be enhanced thereby increasing the developer's confidence of installing the wind farm projects in complex terrains. Accordingly retrospective NWP model data for 25 years was taken for a complex hilly terrain site at Iddukki district of Kerala. The same was then validated by using the one year C-WET met mast data for the same location with an objective to increase the accuracy of the model data by reducing the variance/bias[1,2]. This data was used for calculating the wind shear force which is the major governing parameter acting on the top of the towers. It must be mentioned that designing lattice tower is governed both by extreme wind as well as fatigue loads due to operation. The optimization used in this paper does not imply the modern tools such as minimization of objective function grounded by constraints or methods such as genetic algorithm. However it was a practical design office approach involving iterative analysis and design. In this paper an attempt using parametric study has been made to optimizes an existing 73m & 30m tall lattice type tower by choosing the various geometric configurations in terms of base width using STAAD pro tool, particularly suitable for complex hilly terrains, suiting to the Indian context.

## 2.0 *Generic methodology/approach followed:*

The wind turbine lattice type towers even though highly suitable for quality factory production with 15-20 % of total cost, support the high-tech and costly nacelle, turbine's electro-mechanical components and the rotor and provide necessary elevation to the nacelle to keep it off the ground and to bring it up to the level where the wind resources are available. As such design analysis have to be done rather carefully to obtain an optimal/least weight design. The simpler structures having small numbers of joints can be analysed by analytical methods. But the complex structures having large number of redundant members and joints are tedious to obtain analytical solution. With the advent of High Speed Digital Computers, one of the most powerful techniques that has been developed in the value of engineering analysis is the Finite Element Method (FEM), and the method being general can be used for the analysis of structures of complex shapes and complicated boundary conditions[3]. Lattice Towers with bolted connection are basically designed and analyzed like a space truss. It is an articulated structure composed of straight members jointed together at their ends to form a stable frame work supporting the external loads like self weight of the tower and nacelle assembly together with live loads and wind loads acting on each node of the tower. The lattice structure basically behaves like a cantilever subjected to concentrated load/moments at the tower top hub due to wind shear and varying wind loads along the height of the tower. Due to the fixity at the bottom the moment at the base are the highest as it increases from the top to bottom and therefore higher width at the bottom is provided thereby tapering towards the top. The blades have a tendency of bowing/ bending due to the action of the wind, the maximum deflection being at the tip of the blade and hence it needs to be ensured that the tip of the blade does not touch the body of the tower while passing by the side of the tower. This poses a restriction on the plan dimensions of the top segment of the tower having the height equal to the length of the blade. Hence the splaying of the tower can be designed only below the level of the tip of the down pointed blade[4]. In the present study the focus is to carry out the weight optimization by changing the base width keeping the top width unchanged due the reasons described above. Accordingly two different basic models of lattice towers one for 73 m and another for 30m height were developed and analyzed using STAAD PRO tool (refer Fig. 1&2). Thereafter number of iterations were carried out by changing the base width in steps of 1/0.5m and by keeping the top width unchanged and keeping other design parameters/loading conditions as same so as to arrive at the least/optimum weight.

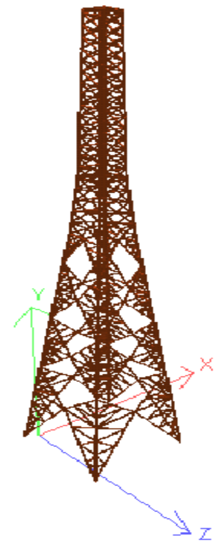


Fig.1 Model for 73 m high Lattice Tower

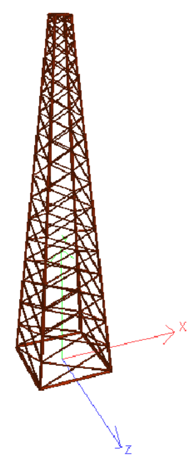


Fig. 2 Model for 30 m high Lattice Tower

3.0 *Configuration of the towers :*

Any lattice tower which is usually 3-dimentional(3-D) may be categorized as a plane frame(2-D) or a space frame(3-D) depending upon its analysis model configuration. In the present study two different lattice type towers one with 73m and another with 30m were modeled as described above with base width ranging from 12 to 18m and 4.5 to 7.5m respectively. For 73m tower the iteration with varying base widths were carried out starting in steps of every 1m interval and whereas for 30m tower the iterations were carried out in steps of 0.5m with the following structural data (Refer Table 1):

Table 1. Structural Data

| Description | 73 m WT lattice tower | 30m WT lattice tower |
|---|---|---|
| Type | Space | Space |
| Base width | 12m (changing from 12 to 18m in steps of 1 m) | 4.5m (changing from 4.5 m to 7.5m in steps of 0.5m) |
| Top width | 2.6 m | 1.2 m |
| Height of tower | 73 m | 30.6 m |
| Number of nodes | 352 | 144 |
| Number of elements | 897 | 352 |
| Degree of freedom per Node. | 6 d.o.f | 6 d.o.f |
| `Total degree of freedom | 2112 | 864 |
| Net degree of freedom | 2100 | 852 |
| Member element | linear | linear |

The top width was kept constant as 2.6 m for 73m tower for all the configurations which is minimum required for housing the nacelle assembly. This top width was kept constant up to 30.5 m from the top (up to the tip of the blade). The lattice tower basically consists of main leg members, bracing members and secondary bracing members. The structure behaves like a cantilever structure, bending moment and the vertical load due to rotor assembly/blades, gear box and generator together with self weight of tower will be resisted by main leg members while the shear force is transferred by the bracings. The secondary bracings help in reducing the unsupported length of the bracing members to reduce the buckling effect. The tensile/ compressive force in the leg members due to the bending moment is inversely proportional to the distance between the legs. Thus by increasing the base width the force in the leg members will be reduced and hence the weight of the main leg members reduces thereby achieving the economy. However, by increasing the base width, the length of the bracing member increases, thereby increasing the weight of the bracing apart from reduction in buckling strength and hence offsetting the economy achieved. Thus the aim was to examine the net effect in reduction of the weight and to arrive at the least/optimal weight for a given base width, other design configurational parameters being constant.

## 4.0 *Modeling of the tower :*

The main leg members for both towers were modeled using 3-D space truss while the bracings were modeled using 3-D beam elements. The bracings are modeled as beam elements in order to avoid instability problems. The legs are assumed to be hinged at the base the first two models were developed based on the existing tower configuration with base width as 12 m and top width as 2.6 m for 73 m and base width as 4.6m and top width as 1.2m for 30 m tower. The same was analyzed using

STAAD PRO tool and similar analysis was carried out for different models by changing the base widths. The typical 3-D view of one of the model both for 73m and 30m is shown in Fig. 3(a), (b) and plans are shown in Fig. 4(a) & (b)

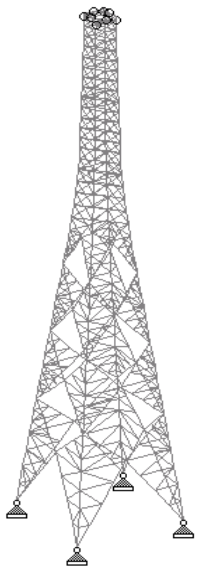


Fig. 3(a) 3-D View of 73 m high Lattice Tower

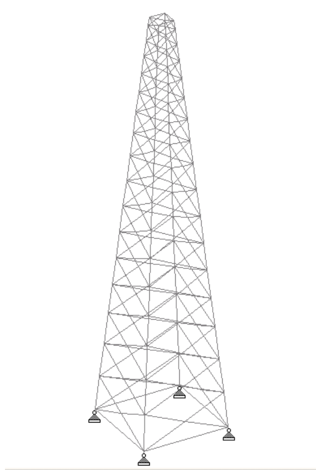


Fig. 3(b) 3-D View for 30 m high Lattice Tower

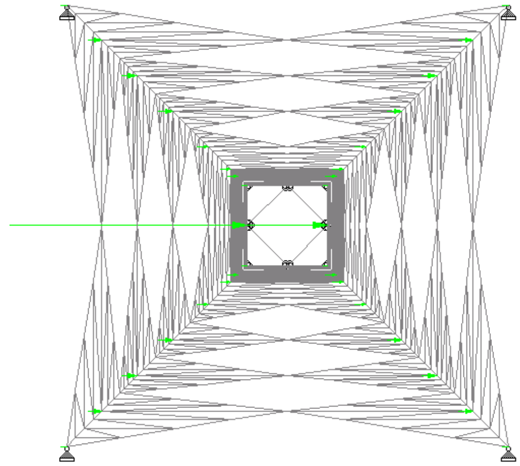


Fig-4(a) Plan view of 73 m high Lattice Tower

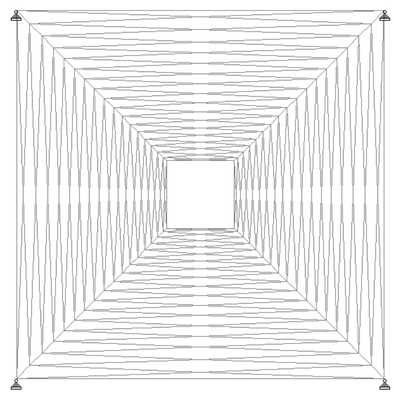


Fig. 4(b) Plan view of 30 m high Lattice Tower

5.0 *Loads on the tower :*

The three loads which are mainly acting on the top of the tower are hub level wind shear arising due to wind loading on the non-operating rotor, vertical load due to the self weight of the nacelle and moment due to the wind shear. Apart from this lattice tower is subjected to wind forces together with the self weight acting along the height of the tower.

The various loads acting on the tower are described in detail as under:

5.1 *Hub level wind shear force :*

The hub shear force is calculated using the aero foil characteristics of the blades and the wind pressure both at 73 m and 30 m level respectively. This value is normally provided by the wind turbine manufacturer and in the present study the hub level shear value of 29.6 tons has been worked out using the NWP model data and is applied at the top of the tower which is shared by two nodes for 73 m tower as shown in Fig. 5 and hub shear value of 14 tons for 30 m tower as shown in Fig. 6.

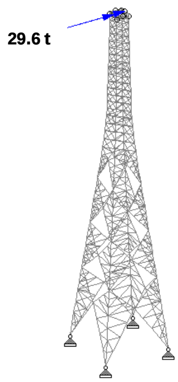



Fig. 5 Hub level Shear Force acting at 73 m Lattice Tower

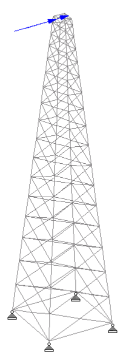


Fig.6 Hub level Shear Force acting at 30 m Lattice Tower

5.2 *Vertical load and moment:*

The vertical load consists of self weight of nacelle comprising of rotor assembly/ blades, gear box and generator mounted at the top of the tower. This load is also furnished by the manufacturer and is applied at the top four nodes of the tower and is shared equally assuming no eccentricity with respect to CG line tower. The vertical load in this study was 36 MT and 10.4MT. In addition to this the moment (119MT) wind shear was considered to be acting at the top of the tower. The vertical load and moment acting at top of the tower are shown in fig-7 and 8, respectively.

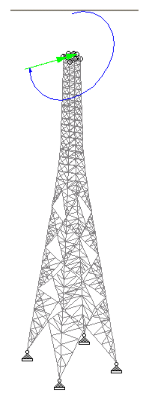


Fig. 7 Vertical load acting at 73 m Lattice Tower

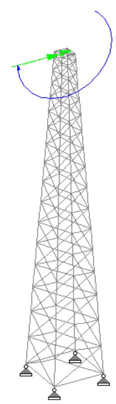


Fig. 8 Vertical load acting at 30 m Lattice Tower

5.3 *Wind load on tower :*

The wind load on the tower was calculated strictly in accordance with IS 875-part 3 codal provisions[5]. The basic wind speed for complex hilly terrain was considered 39 m/s. The risk coefficient ($k_1$) was taken as 1.06 assuming the maximum life span of tower as 100 years. The terrain category ($k_2$) was chosen as III with class C for obstructions closely spaced suiting to complex hilly terrains. The value of k2 for above conditions was chosen from the code in accordance with the height. The topography factor ($k_3$) was chosen as 1.0 assessing absence of steep slopes or ridges/valleys. Using these values the design wind speed was calculated for different height along the tower using the relation:

$$V_z = V_b\ k_1 \times k_2 \times k_3 \quad (1)$$

The design wind pressure is given by the following relation:

$$P_z = 0.6\ V_z^2 \quad \text{where Pz is N/m}^2 \quad (2)$$

The tower was sub divided into several panels and the exposed area (Ae) of each panel was calculated for the assumed size of leg and bracing members. The total area of the panel is calculated using trapezoidal formula:

$$Ap = (D_t + D_b)/2 \ X\ H. \quad (3)$$

Where

$D_t$ - Top width

$D_b$ - Bottom width

The solidity ratio $\phi$ of the panel was calculated using the following relation:

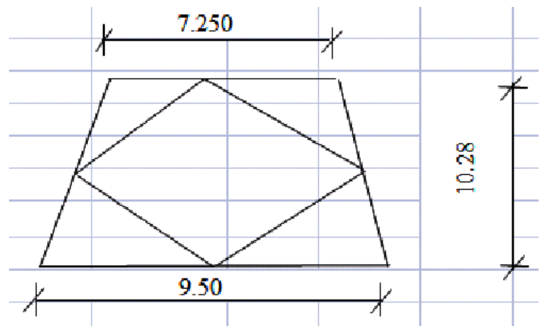
$$\phi = Ae/Ap \quad (4)$$

The overall force coefficient ($C_f$) corresponding to the above solidity ratio was taken from the IS 875-part 3, Table 32

The total wind force on the panel is given by following relation:

$$Fp = Pz \times Ae \times C_f \quad (5)$$

One of the sample calculations (refer Table 2 Sr.No.3) for the optimized tower for 73 m height at 30.834 m level are detailed below:




**Projected Area of Steel** = (2 x Panel height x leg angle size)+(4 x length of bracing x bracing angle size)+
(Bot width of panel x panel angle size)+
(Top width of panel x panel angle size)

= (2 x 10.278 x 0.4) + (4 x 10.53 x 0.1) + (9.5 x 0.1) + (7.25 x 0.1)

= 14.11-m2

**Area of Panel** = ( 9.5 +7.25) x 10.278/2

= 86.08-$m^2$

**Solidity Ratio Φ** = Area of steel / Area of Panel

= 14.11 / 86.08

= 0.17

**Drag co-efficient** = 2.82 (From Table 30 of IS 875)

**Panel Force** = Wind Pressure X Area of steel X Drag co-efficient

= 117.54 x 14.11 x 2.82

= **4676.95 Kg**

The wind forces were calculated for 73m and 30m high towers for various iterations. The wind force acting on each panel for 73 m height optimized tower (base with 14m) is detailed in Table-2.

Table-2 Wind Forces acting on each Panel (73 M Tower)

| Sl No. | Levels | Panel ht | Bottom width | Length of Leg Member | length of Bracing Member | Bracing angle (m) | Leg angle (m) | Drag Co-Efficient | Wind Pressure (Kg/$m^2$) | Total Panel Force (Kgs) | Force on Each Panel (Kgs) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 73.00 | 12.040 | 2.585 | 12.060 | 3.410 | 0.10 | 0.40 | 1.74 | 117.54 | 3067.80 | 383.48 |
| 6 | 60.952 | 10.740 | 3.098 | 10.750 | 3.850 | 0.10 | 0.40 | 1.82 | 117.54 | 3136.11 | 775.49 |
| 5 | 50.212 | 9.100 | 3.557 | 9.220 | 4.920 | 0.10 | 0.40 | 2.22 | 117.54 | 3175.63 | 788.97 |
| 4 | 41.112 | 10.278 | 5.011 | 10.520 | 5.720 | 0.10 | 0.40 | 2.86 | 117.54 | 3368.37 | 818.00 |
| **3** | **30.834** | **10.278** | **7.250** | **10.530** | **6.290** | **0.10** | **0.40** | **2.82** | **117.54** | **4676.95** | **1005.67** |
| 2 | 20.556 | 10.278 | 9.500 | 10.520 | 7.000 | 0.10 | 0.40 | 3.06 | 117.54 | 4294.49 | 1121.43 |
| 1 | 10.278 | 10.278 | 11.740 | 10.530 | 12.440 | 0.10 | 0.40 | 3.10 | 117.54 | 3498.00 | 974.07 |
| 0 | 0.000 | 0.00 | 14.000 | 0.000 | 0.000 | 0.10 | 0.40 | | | | 437.25 |

The wind force acting on each panel for 30m height optimized tower (base with 5.5m) is detailed in Table-3.

Table 3. Wind Forces acting on each Panel (30 M Tower)

| Sl No. | Levels | Panel ht | Bottom width | Length of Leg Member | length of Bracing Member | Bracing angle (m) | Leg angle (m) | Drag Co-Efficient | Wind Pressure (Kg/$m^2$) | Total Panel Force (Kgs) | Force on Each Panel (Kgs) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 30.687 | 5.844 | 1.200 | 5.920 | 2.990 | 0.10 | 0.15 | 1.62 | 184.14 | 1345.37 | 168.18 |
| 3 | 24.843 | 6.885 | 2.130 | 6.940 | 3.610 | 0.10 | 0.15 | 2.22 | 169.21 | 2062.30 | 425.96 |
| 2 | 17.958 | 8.120 | 2.980 | 8.200 | 4.330 | 0.10 | 0.15 | 2.54 | 148.58 | 2505.90 | 571.03 |
| 1 | 9.838 | 9.838 | 4.120 | 9.940 | 10.220 | 0.10 | 0.20 | 2.38 | 116.79 | 3646.84 | 769.10 |
| 0 | 0.000 | 0.00 | 5.500 | 0.000 | 0.000 | 0.10 | 0.20 | | | | 455.86 |

The above wind force is distributed to the 8 nodes of the said panel equally. The fig-9(a) & (b) indicates the wind force being applied at each node both for 3-D and plan view for 73 m tower while wind forces acting on 30 m tower is shown in Fig. 10(a) & (b).

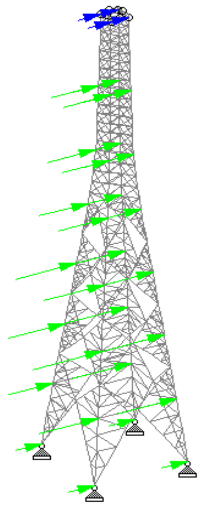


Fig. 9(a) Wind Force for 73 m Lattice Tower (3-D view)

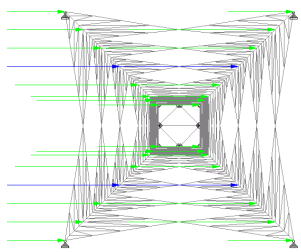


Fig. 9(b) Wind Force for 73 m Lattice Tower (plan view)

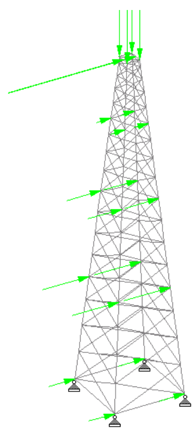


Fig. 10(a) Wind Force for 30 m Lattice Tower (3-D view)

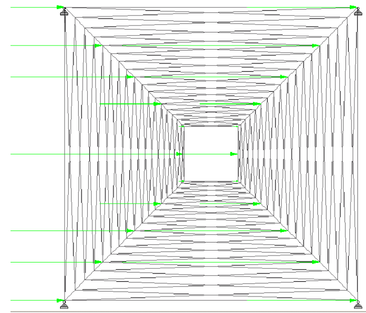


Fig. 10(b) Wind Force for 30 m Lattice Tower (plan view)

The wind loads obtained from the above procedure are applied as nodal loads on the model and the analysis is performed.

It is found that the leg forces increase when the wind is blowing along the diagonal direction to take care of this the leg forces obtained for the face wind condition are multiplied by the factor of 1.7.

6.0 *Design of the lattice tower :*

Having obtained forces in each leg as well as bracing members the members are designed for both compression and tension as per IS800 codal provisions[6]. In case the member was found to have higher factor of safety [FS] the size of the member was reduced and in case it was found to be failing the size of the member was increased and the program was re-run for ensuring that all the members are passing.

7.0 **Results and Discussions**

The seven different models with base width changing from 12m to 18m in steps of 1 m interval were developed and was analyzed for same loading conditions *viz.* wind shear force, vertical loads and moment for 73 m lattice tower. The total weight of the tower/ steel take off for different base width was determined as indicated in Table-4 below:

Table 4. Steel take-off for various Base Widths (73 m Tower)

| Models | Base width (M) | Weight/Steel take off (MT) | Height / Base |
|---|---|---|---|
| 1 | 12 | 50.48 | 6.08 |
| 2 | 13 | 47.858 | 5.62 |
| **3** | **14** | **47.58** | **5.21** |
| 4 | 15 | 48.202 | 4.87 |
| 5 | 16 | 62.207 | 4.56 |
| 6 | 17 | 63.627 | 4.29 |
| 7 | 18 | 74.129 | 4.06 |

A similar exercise was carried out for 30m high lattice tower and the total weight of tower /steel take off for different base width are shown in Table 5 below:

Table 5. Steel take-off for various Base Widths (30 m Tower)

| Models | Base width (M) | Weight/Steel take off (MT) | Height / Base |
|---|---|---|---|
| 1 | 4.5 | 11.367 | 6.67 |
| 2 | 5 | 10.838 | 6.00 |
| **3** | **5.5** | **10.287** | **5.45** |
| 4 | 6 | 10.498 | 5.00 |
| 5 | 6.5 | 10.64 | 4.62 |
| 6 | 7 | 10.922 | 4.29 |
| 7 | 7.5 | 11.168 | 4.00 |

The graphs figure 11 & 12 indicates the variation of total weight/steel take off with respect to the base width for both 73 as well as 30 m tower. It was concluded that for 73 m tower the base width corresponding to the least weight was 14m similarly for 30 m tower the base width corresponding the least weight was 5.5 m. Thus the ratio of the height of the wind turbine to the base width works out to about 5 to achieve the least/optimized weight.

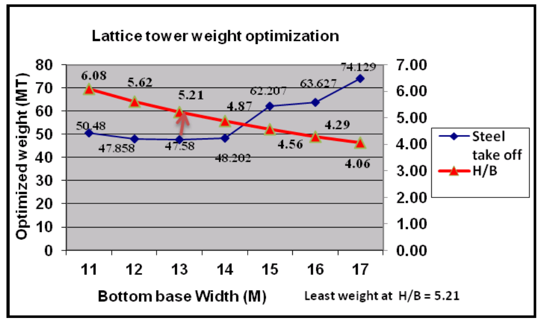



Fig. 11 Variations of Steel take off with varying Base Width (for 73m) Tower

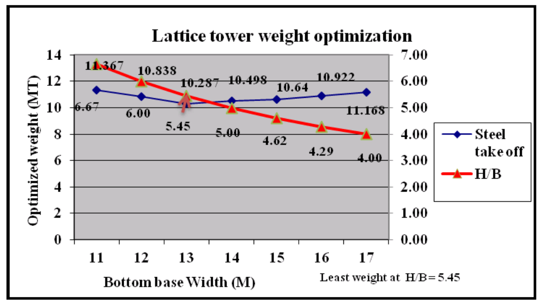



Fig. 12 Variations of Steel take off with varying Base Width (for 30m) Tower

## 8.0 **Conclusions**

In the present study, 2 lattice towers used for wind turbine applications, one for 73 m height and another 30 m height were modeled and analyzed using different geometric configurations by changing their base widths keeping the top width as constant. The top width was kept constant due to the constraint that the tip of the blade should not touch the body while passing by the tower. The results indicated that the least/ optimum weight of

47.58MT was obtained for the base width of 14m for 73 m high tower. Thus the H/B ratio so obtained was 5.21. Similarly the least weight / optimum weight for 30m tower of 10.287MT was obtained for base width of 5.5m, thus the H/B ratio so obtained was 5.45m. Hence, inference drawn from the parametric study is that for selecting the optimized tower suiting to complex terrains, in Indian context the designer/ developer shall choose the base width about 1/5th of the height particularly for lattice towers with which sizeable saving in steel can be achieved, within the limits of the analysis used in the present study.

The study will further be carried out for Tubular towers with an objective to determine Height to Base Diameter ratio (H/D) for achieving the least/optimal weight and the comparison between the lattice / tubular tower will be projected. The lessons learnt will be incorporated in the future protocol.

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