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Optimum design of a 100-meter high meteorological mast

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ABSTRACT

Meteorological mast (met mast) is a tower-like structure in which wind resource measuring equipment is installed with an objective to estimate the wind power potential of the region of interest. Met mast can be either be a self-supporting tower or guy supported tower. In this study, the analysis and design of guyed steel lattice met mast of 100m height is carried out using STAAD. Pro software. The towers are modeled using base configuration triangular. As stated in IS 800-2007, in addition to the self-weight, the wind forces are predominant on the tower and guy wires. This study focuses on optimizing the met mast using the 'X' bracings, and Static analysis is performed by varying the sections. The usage of 'X' bracing for the structure has resulted in the significant structure's weight reduction. The appropriate levels of guy wire anchoring positions and the optimum guy wire diameter are chosen using preliminary analysis. Towers are modeled using different section shapes viz. tubular section and pipe section, and finally, an optimum section shape has arrived. The towers are analyzed under various load combinations as given in IS 875 (part 3:2015), IEC 61400-12-1 standards, Meanest standards, etc., and designed considering the provisions provided in IS 800-2007. The results are correlated and finally, an optimum design has arrived.

***Keywords**: Meteorological Mast, Guy Supported Towers, Lattice Towers, Bracing System, Optimization, Staad. Pro*

1. INTRODUCTION

Sustainable energy with the focus on affordable and reliable energy is part of the UN sustainable development goals and in this regard wind generation is playing the pivotal role in recent decades. Wind generation has expanded in both size by scaling up in tens of MW per turbine and also in energy capture in the last 20 years. It began the century as a niche energy source in Europe, Asia and the US, and ended 2019 as a mainstream source of clean, cost-effective and proven renewable energy technologies to meet increasing electricity demands in a sustainable manner.

Wind in nature is a very dynamic meteorological phenomenon with a dominant characteristic of constant and often violent variations which will influence in designing site specific wind turbines to capture ample energy from the wind and the withstand the wind loads. This contributes to the intervention of the met. Mast with requisite wind sensors at difference level to understand the wind characteristics prevailing in the region, the turbulence intensity, gust wind speeds etc., The different configuration of towers are Tubular, Lattice, Guyed Pole and Hybrid towers. Lattice towers require lower capital costs, ease of transportation and a lower impact on the environment. Towers can be categorized into circular, rectangular, triangular, delta, hexagonal and polygonal towers, based on the tower section. The weight of the tower increases with the increase in the number of faces, hence an optimal section is required. Eventually, triangular lattice towers have been adopted in this study as it requires less weight, ease of fabrication and transportation, flexible erection and a lesser impact on the environment enabling sustainability.

M. Amala, V. Gokul, G. Salaiamuthavalli, K. G. Akshaya et.al.[1] carried out design and optimization of the tower by altering the tower base width, bracing sizes and material properties of the members for arriving the economical section using STAAD.PRO software. The wind loads assigned is based on IS 802-1995 standards. The best cost-effective, the optimized tower has finally arrived.

Jay Prakash Goit, Susumu Shimada and Tetsuya Kogaki et.al.[2] examined whether LiDARs can replace meteorological tower without compromising accuracy for wind resource assessment. The wind speeds measured by LiDAR using OpenFAST simulation software were compared with the sonic anemometer, the results of LiDAR were good which was within the regression line criteria. The results showed that wind speeds and turbulence intensities can be calculated with reasonable precision by LiDARs.

Recent technological advances have accelerated the push for renewable energy. Before installing a wind park, it is necessary to collect bankable wind data at a potential location for a couple of years. Mounika Mallela, C. R. Suribabu, Kiran Alluri, Mangipudi Venkata Ramana Murthy et.al.[3] has taken an initiative of finding a low-cost and feasible structure for the gathering of wind data by replacing the conventional onshore guyed mast with suction pile foundation. The structure was modelled in FEM (Finite Element Method) software and analysed for environmental loads. The results of deflected profiles, free vibration and Earthquake analysis of the structure was in acceptable limits. The cost estimates of the structure analysed were compared with conventional met mast and LiDAR results.

Alina de la Cruz López et.al.[4] has discussed the current design standards in Cuba as there is no general-purpose design methodology due to the inherent nonlinearity in the structural behaviour of a guyed mast, thereby it requires optimization and review of the existing Guy Mast models. Using NC 285: 2003 (current Cuban code) and the Patch Load method as per British standard, structural behaviour under extreme winds was examined by the author[4]. The results indicated that the tubular column sections reduce the maximum axial force up to 24 per cent and the forces were found to be increased due to the application of the Patch Load method.

Optimization using the meta-heuristic techniques is feasible and applicable to the structures with a large number of design constraints. To optimise the weight of the transmission line tower, R. Nagavinothini, C. Subramanian et.al.[5] applied the Cuckoo Search Algorithm technique which is a meta-heuristic algorithm. The authors[5] analysed and optimised the structure with STAAD.Pro software and compared the results of STAAD.Pro with the results of a Cuckoo Search(CS) Algorithm.
Due to the second order effect, the tower designed for angle section and X-bracing usually has a higher displacement. Vinay. R Ranjith. A et.al.[6] studied this effect with different loading conditions on the structure to finalize the case that will cause the larger deflection in the tower model and to arrive the best optimization. The authors modelled the 400kV double circuit tower using the STAAD.Pro software. The authors[6] analysed the structure using linear static and P- delta analysis and the structure has been designed with angle and tubular sections. The displacement results were in permissible limits stated as per standards. A savings of up to 20.9 per cent in steel weight resulted from the use of a tubular section compared to an angular section in terms of cost optimization.

Pedro Americo Almeida Magalhaes Júnior, Igor Guasti Rios, Tiago Simão Ferreira et.al.[7] studied about the self-supporting truss towers using FEM (Finite Element Method) software. The static and dynamic analyses were performed. The displacement and maximum stresses acting on the tower were correlated for lattice and tubular towers. The mode frequency of lattice towers was slightly lower when compared with tubular towers on an average of 8%.

As the demand for electrical energy has been increasing rapidly, C. Preethi and K. Jagan Mohan et.al.[8] has made an effort to construct the transmission line tower more cost-effective by modifying the geometry of the structure. The selection of a 220kV single circuit transmission line towers with square base fulfills this purpose. To optimise the geometry, the authors have replaced one of the existing suspension towers to a triangular base self-supporting tower. Towers were analysed and designed in STAAD.Pro software and the results are compared with existing tower model results. The findings showed that the use of triangular base self-supporting towers would save the weight of structural steel by 9.23 per cent, allowing structural optimization.
A four-legged self-supporting 220kV steel transmission line towers are analysed and designed for three configurations namely angular, tubular and channel by Archana R, Aswathy S Kumar et.al.[9] using the STAAD.Pro software for arriving the most cost-effective design. The height of the tower is 40m and the square base width is 11.5 m. The results reveal that the angular and tubular sections result in cost-effective optimisation.

K. M. Somayaji, R. Venkatesan and S. Gomathinayagam et.al.[10] carried out atmospheric dispersion studies by the implementation of meteorological measurement facility towers at Kalpakkam of 50m height. Cost-effective structural design, remote data acquisition system (RDAS) covering different sensor models for real-time data, user-friendly software and online data communication via Ethernet, e-mail, RF transceivers were the salient features of the tower. The practical challenges faced during this study were maintenance, access to sensors at various levels; design constraints were heavy foundation requirements for a stand-alone tower.

2. METHODOLOGY

- Initially, the Site was selected.
- Soil Testing. Soil properties & variations in topography and terrain obstacles of the selected site were studied.
- In AutoCAD software, a met mast model of 100 m height is drawn. The AutoCAD model is then imported into the STAAD.PRO software and the structure is analyzed.
- Finally, the structure is designed using STAAD.PRO software.

Predominantly, four-legged (square) lattice masts are commissioned in India. The maximum height of the met mast installed in India is about 175 m height. As there will be a demand for higher wind turbine heights in future for power production, the meteorological mast of 100m height becomes necessary to study wind flow characteristics for commissioning the wind turbine projects to a height of 100m. As many countries do not have the in-house structural engineering capacity and machinery to test modern designs according to their specifications, thereby four-legged structures are still being the accepted standard. A three-legged (triangular) tower is aerodynamic in nature and thus has a lower wind resistance. Salient features of the triangular tower are bracings required for the tower is less than 80% compared with the square tower, thereby, considerable cost savings in civil works, namely reinforcing and labour requirements, painting area required will be less when compared to the square tower. Hence a three legged lattice mast of 100m height is chosen for structural optimization in this study. The towers are analyzed and designed for Indian wind load standards confirming to IS 875 (Part 3): 2015.

3. WORKING PROCEDURE

Optimization of guyed towers depends on various parameters such as the topology of the structure, initial tension in the guy wire, guy wire levels and its spacing, guy wire orientation which makes the guyed tower optimization problem a complex case of optimization. Wind forces acting on the guyed towers and the natural frequency of the towers is dynamic in nature and it changes with the output results, making the tower optimization problem much more complex. In order for achieving the optimum design within a predetermined environment, we have followed a methodology as given in Fig.1.

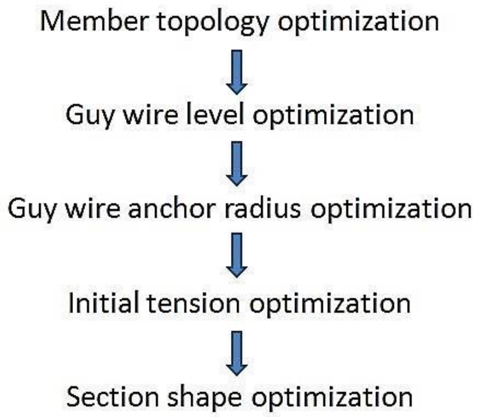

Fig. 1: Optimization flow diagram

4. RESULTS AND DISCUSSIONS:

4.1 Plan and dimension details

The following are the specifications of a 100m triangular meteorological mast. The dimensions of the tower and the boom plays a major role in understanding possible flow disturbances that may result in less accurate wind speed readings. The complete details of the structure, including modelling concepts, are given below.

Table 4.1: Details & Dimension of the met mast

Specification of 100m height met mast	
Tower height	100m
Base width of tower	0.400m
Type of bracing	X – braced frame
Conductor Material	Steel

4.2 AutoCAD Model

AutoCAD is a sophisticated CAD (Computer Aided Design) software for engineering drafting. Initially, Site was selected, the soil properties & terrain conditions of the proposed site was studied. A triangular met mast of 100m height was created using AutoCAD software which is shown in Fig.2.

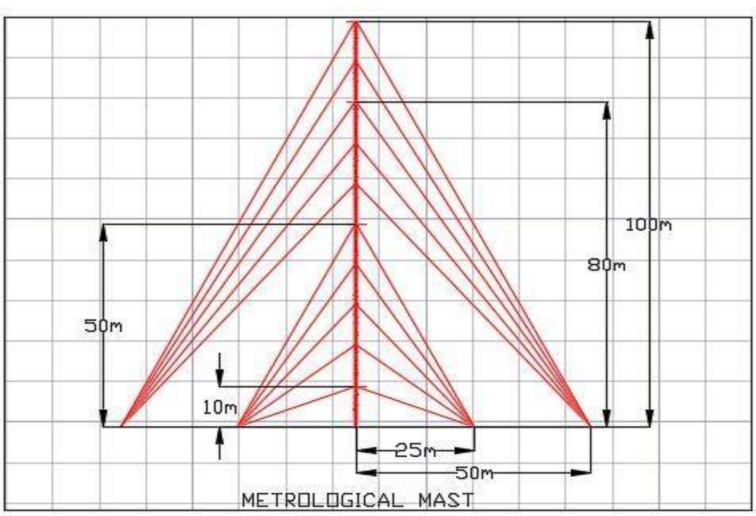

Fig. 2 :AutoCAD model

4.3 STAAD.PRO Analysis

Steel, concrete and timber design can be performed using STAAD.Pro software confirming to many international standards ailing analysis and design. The AutoCAD triangular met mast model is imported into STAAD.PRO software and the structure is analysed. The plan and elevation of the met mast depicting the X and Y direction of base width of 400mm and 100m height used for analysis are shown in Fig. 3 and Fig.4. STAAD.Pro allows only one kind of analysis at a time if different kinds of analysis viz. cable analysis, P-Δ analysis etc. are performed in a single instance only the first encountered analysis command will be considered. Owing to this reason, we have performed P-Δ analysis and cable analysis separately.

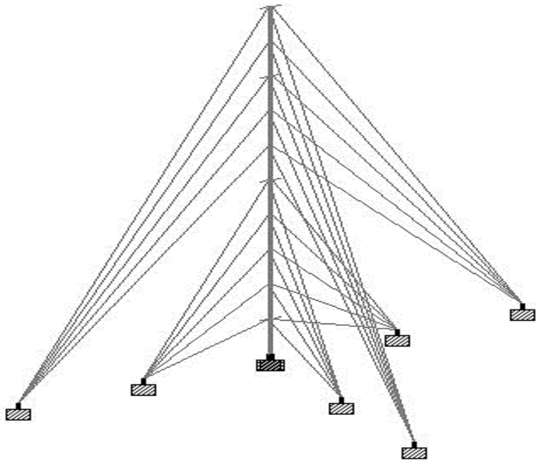

Fig. 3: Plan of the 100m met mast model

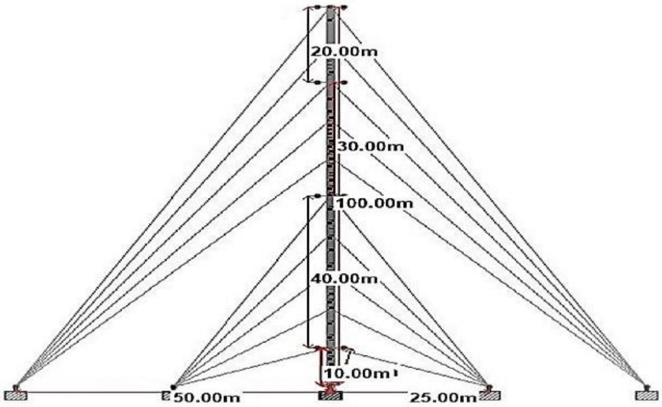

Fig. 4: Elevation of the 100m met mast model

Table 4.2: Material properties of the 100m mast

E (N/mm^2)	Poisson' s Ratio	Density (kg/m^3)	Alpha (/ºc)	Fy (kN/mm^2)	Fu (kN/mm^2)
2.0x10^5	0.3	7850	12x10^{-6}	500	545

Table 4.3: Section Property Pipe and Tube Steel

Material	Ax (cm^2)	OD (cm)	Tw (cm)	D (cm)	B (cm)
PIP3239H	62.9	32.39	0.63	-	-
TUB50252.9(1)	3.8	-	0.29	5.0	2.5
TUB25252.6(2)	2.16	-	0.29	2.5	2.5

Due to the buckling efficiency, angular members require more bracing members when compared with tubular member towers resulting in higher erection costs but have reasonable transportation costs. The smooth and curved outer surface of the tubes also contributes to better protection against corrosion hence viz. tubular section and pipe section is adopted in this study.

4.4 Assigning Support

The support provided for the met mast is fixed support and are rigidly fixed to the foundation at the three legs of the met mast.

4.5 Load Assigning

The load acting on the met mast is as follows:

- Dead load: Self-weight of the met mast and guy wires. Fig.5 shows the assigning of dead load.
- Anemometer placed at 100m, 80m, 50m and 10m levels (Weight of an anemometer sensor: 0.5kg) as described in IEC 61400-

12-1 and IEA guidelines. The boom lengths are placed as per clause G.4 as specified by IEC 61400-12-1 standards. Lightning arrestor (4.2 kg) load is provided at the top of the tower as per MEASNET guidelines.

- Guy wires are galvanized and are 7kN pre-tensioned. Fig.6 shows the assigning of Combination loads.
- Wind load on the tower body was calculated as per IS 875 (Part 3) - 1987, "Indian Standard Code of Practice for Design Loads (other than Earthquake) for Buildings and Structures".

4.6 Load Combinations

The load combinations have been created by selecting the Indian code from the combinations tool in the loading group for post-processing. The define load combinations dialog box is opened and the combination type was selected.

Table 4.4: Load Combinations

Type	L/C	Cases
Primary	1	Load Case 1 Dead Load
Primary	2	Load Case 2 Live Load
Primary	3	Load Case 3 Wind Load
Primary	4	Load Case 4 Sensor Nodal Load
Combination	5	Combination Load Case 5 DL + LL
Combination	6	Combination Load Case 6 DL + LL + WL

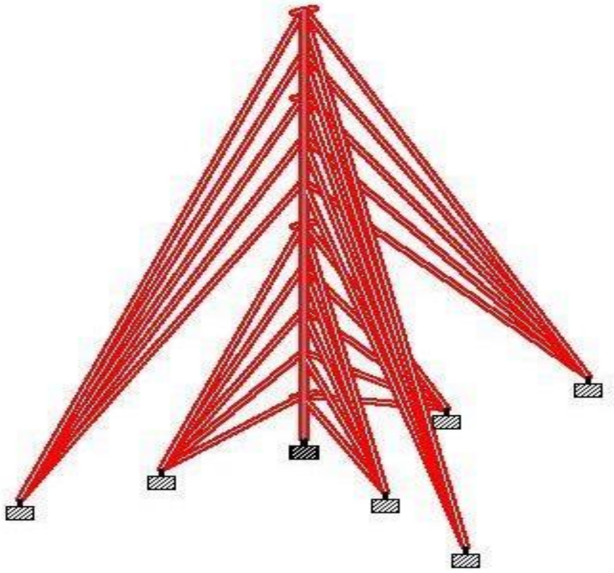

Fig. 5: Assigning dead load

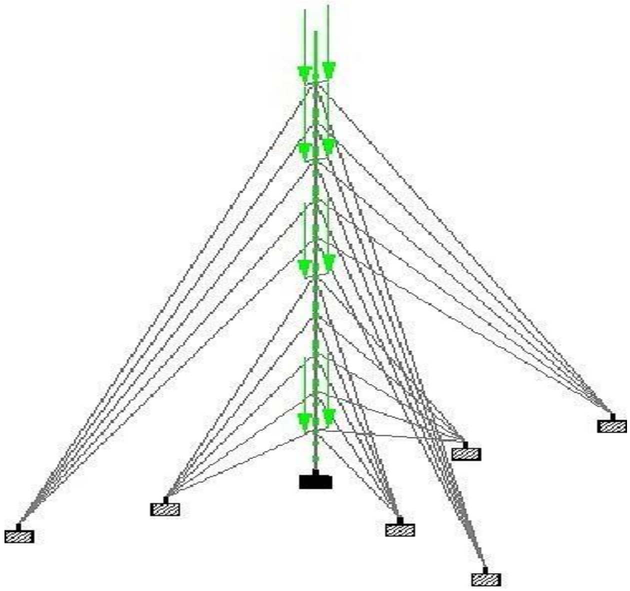

Fig. 6: Assigning Combination loads

4.7 Analysis and design

The analysis is carried out after assigning loads in the structure, to calculate the axial forces, Shear, torsion, bending, displacement and steel take-off for arriving the optimized section. The arrived tensile or compressive stress in various members is validated by checking the permissible stress limits standards as prescribed in the IS code. Thereby the design is executed in the STAAD.Pro for the Indian code. The results are summarized below.

Table 4.5: Axial Forces

S. No	Node Point	Beam No	Axial Force (kN)
1	Bottom leg	3	150.6
2	Top column	12070	118.5
3	Bottom horizontal member	35	1972
4	Top horizontal member	1527	4.2
5	Bottom bracing	617	49

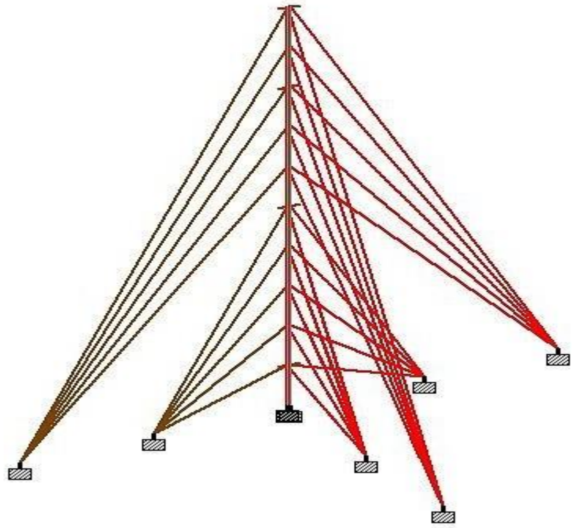

Fig. 7: Axial force diagram

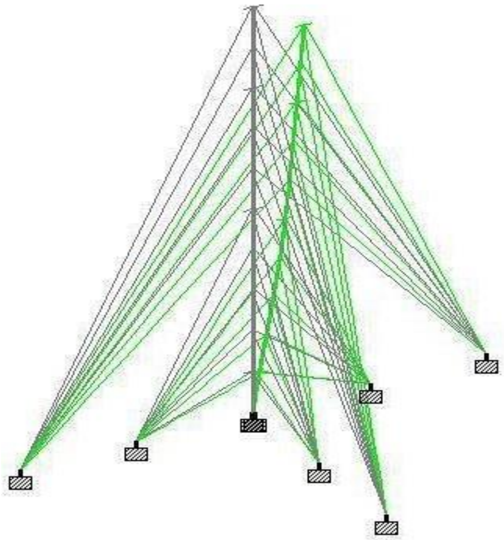

Fig.8 Displacement diagram

Reaction, Axial, Shear, Torsion and Bending results obtained from the STAAD.Pro analysis report are as follows:

Table 4.6: Statics Check Results

L/C	Type	Fx (kN)	Fy (kN)	Fz (kN)
1	Loads	3193	-8780	3189
	Reactions	-3193	8780	-3189
	Difference	-0	0	0
2	Loads	66	-85	71
	Reactions	-66	85	-71
	Difference	-0	0	0
3	Loads	22	22	22
	Reactions	-22	-22	-22
	Difference	-0	0	0

Table 4.7: Max Forces by Section Property

Section	Type	Axial	Shear		Torsion	Bending	
		Max Fx (kN)	Max Fy (kN)	Max Fz (kN)	Max Mx (kNm)	Max My (kNm)	Max Mz (kNm)
PIPE	Max +ve	120	2049	1707	926	6386	1846
	Max -ve	-115	-2732	-1313	-935	-638	-4374
TUBE1	Max +ve	6.6	0	6.6	0.16	11	0.16
	Max -ve	-6.6	-6.6	-6.6	-0.16	-12	-12
TUBE2	Max +ve	635	0.6	0	0	0	0
	Max -ve	-465	-0.6	0	0	0	0

Table 4.8: Utility Check

Beam	Actual Ratio	Allowable Ratio	Normalized Ratio	Clause
74	0.76	1.00	0.76	IS-7.1.1(B)
678	0.91	1.00	0.91	IS-7.1.1(A)
4929	0.17	1.00	0.17	IS-7.1.1(A)
12029	0.05	1.00	0.05	IS-7.1.2

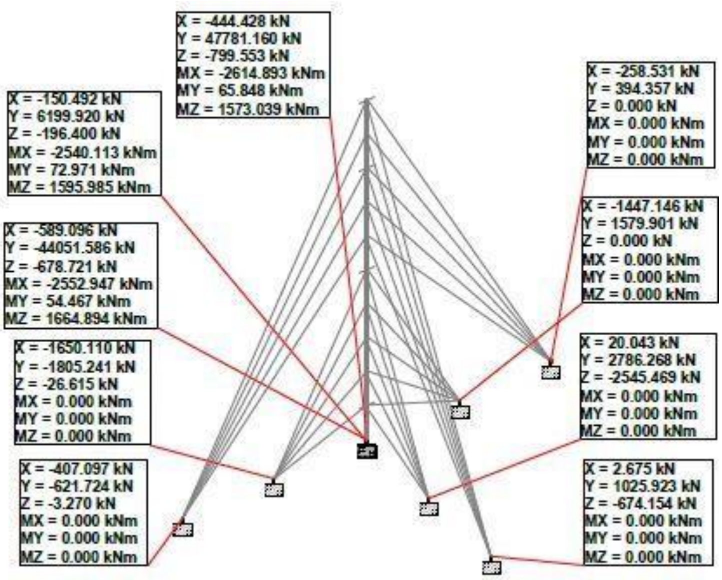

Fig. 9: Reactions

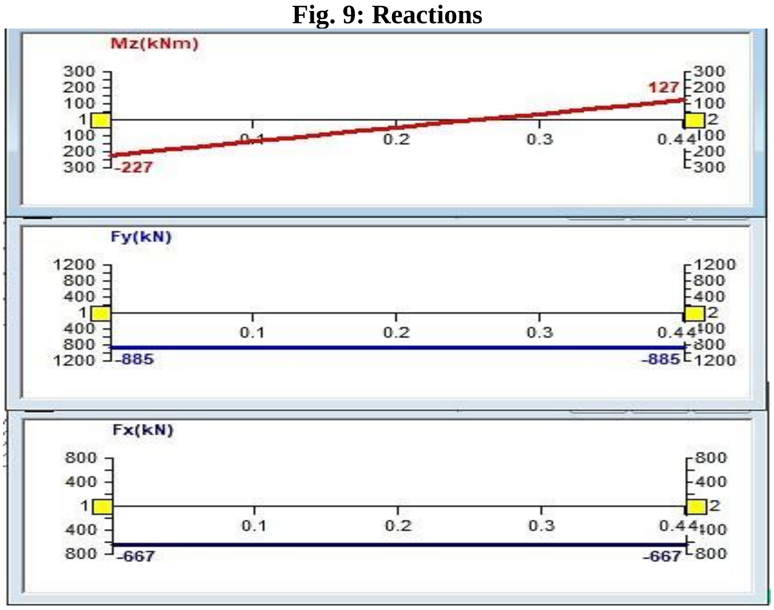

Fig. 10: Shear force and bending moment diagram

4.8 Steel take off

The following table depicts the quantity of steel required for the structurally safe and economical met mast. The structure has been member optimized, Guy-wire level optimized, Guy wire anchor optimized, the initial tension optimized and the section shape optimized.

Table 4.9: Steel Take off

S. No	Profile	Length (m)	Weight (kn)
1	PIPE	4779	2309.5
2	TUBE1	16	0.5
3	TUBE2	2029	32.2
		Total	2342.2

5. CONCLUSION

The meteorological mast of 100m height becomes necessary to study the wind characteristics for the commissioning of the wind turbine projects to a height of 100m. The major load in the design is the initial tension load coming on the structure from the guy wires. Thus the final optimum design arrived is a triangular tower of 100m height with a base width of 400mm having an X-bracing configuration. Guy wires are provided at every 10m level. The guy wire anchor radius is taken as 25m at each level. The bottom members play a major role in the performance of the tower by taking axial forces.

The optimization problem is carried out in a planned manner, thereby arriving at a wholesome optimum design. Thus the tower with X-bracing has the greatest reduction in weight after optimization. The conclusions from the design are the tower is safe against (i) static and dynamic analysis considering wind loads, (ii) self-weight of the tower, and (iii) loads of antenna arrays. All tower members are safe and meeting the requirements as per IS 800-2007. The tower is safe against deflection at maximum design wind speed and structurally optimized.

6. SCOPE FOR FUTURE WORK

Further work could be done in terms of performing vibration studies on the tower model and identifying its impact on measurement readings from the anemometer. A comparative study could be made between the self-supporting and guyed towers to find the cost-effective one for utilization. CFD modelling of the boom in the tower could be made to study the effect of flow change affecting the wind measurements from the tower. An accurate or absolute optimum result could be strived for by developing problem-specific algorithms.

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