Structural Design and Analysis of Hyperboloid with Tower Assembly of Solar-Thermal Plant

R. K. Verma, M. K. Agrawal, P. Halder, and J. Chattopadhyay

Abstract A 2MWe solar plant is proposed to be set-up. A 40.8 m diameter hyperboloid supported on three towers (60 m height), 118 heliostats of dimension 10 m × 10 m, 228 heliostats of dimension 5 m × 5 m and an 8 m diameter receiver are the major components of the proposed plant. Hyperboloid with tower assembly is one of the key components of the concentrated solar power plants based on central receiver concept. Hyperboloid reflects the reflected rays from the field heliostats to the receiver mounted at the ground. It consists of hyperboloid frame on to which aluminium-based reflector is fixed. Hyperboloid frame is made of carbon steel and aluminium tubes. Aluminium reflector (mirror) is made of 0.8 mm aluminium sheet. Hyperboloid structure along with reflectors is supported by tower structures. Towers are made of carbon steel tubes. Hyperboloid is fixed with three towers by bolting arrangement. Hyperboloid with tower assembly is designed against wind load of 39 m/s basic wind speed. Finite element analyses have been performed to optimize the design and estimate the deflections and stresses due to dead weight, imposed loads, earthquake loads and wind loads. Stresses due to various loads and their combinations have been checked against the allowable stresses as per IS 800. Buckling checks have been performed as per IS 800.

Keywords Design wind pressure · Vortex shedding frequency · Seismic zone · Response spectrum analysis

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1 Introduction

India is a tropical country where sunshine is available for longer hours per day and in great intensity. Several technologies are available for large-scale solar power deployment. Solar-thermal plant based on central receiver technology with molten salt as the working fluid is one such concept. Solar power tower type plant has been planned employing field heliostats, hyperboloid with tower, molten salt-based receiver with steam in secondary side, turbine, etc. The proposed plant uses central receiver concept wherein the incident solar radiation concentrated to heat up the molten nitrate salt in receiver. Molten salt is a mixture of KNO_3 and $NaNO_3$ in a proportion of 40:60 w/w. In the steam generating system, the heated salt transfers its energy to water to generate steam. The steam is then passed on to a steam turbine for electricity generation.

Hyperboloid with tower assembly is one of the key components of the concentrated solar power plants based on central receiver concept. Hyperboloid reflects the reflected rays from the field heliostats to the receiver mounted at the ground. Hyperboloid reflector is mounted 60 m above the ground at the top of three lattice towers. Hyperboloid is 40.8 m in diameter. It consists of hyperboloid frame on to which aluminium-based reflector is fixed. Hyperboloid frame is made of carbon steel and aluminium tubes. Aluminium reflector (mirror) is made of 0.8 mm aluminium sheet. Towers are made of carbon steel tubes. Hyperboloid is fixed with tower assembly by bolting arrangement.

Size of hyperboloid is calculated based on optimum heliostat layout for 5250 kWth power in molten salt. The area of the hyperbolic mirror is estimated to be approx. 1403 m^2 for a tower height of 60 m. The diameter and depth of the hyperboloid is 40.8 m and 6.5 m, respectively. The thermal radiation incident on the reflector is 6.46 MWth, which generates a radiant heat flux of 3.9 $kWth/m^2$. Temperature rise of secondary hyperboloid reflector due to incident solar radiation is calculated to be 55 °C. Hyperboloid with tower assembly is designed against wind load of 39 m/s basic wind speed. Approximate weight of the assembly is 220 tonnes. Figure 1 shows the hyperboloid with tower assembly.

2 Material Properties

Structural tubes are available in various grades. YSt 310 grade has been taken conforming to IS: 1161:1998 (steel tubes for structural purposes). Aluminium tubes have also been used in hyperboloid. The mechanical properties of YSt 310 grade steel and aluminium are given in Table 1 [1].

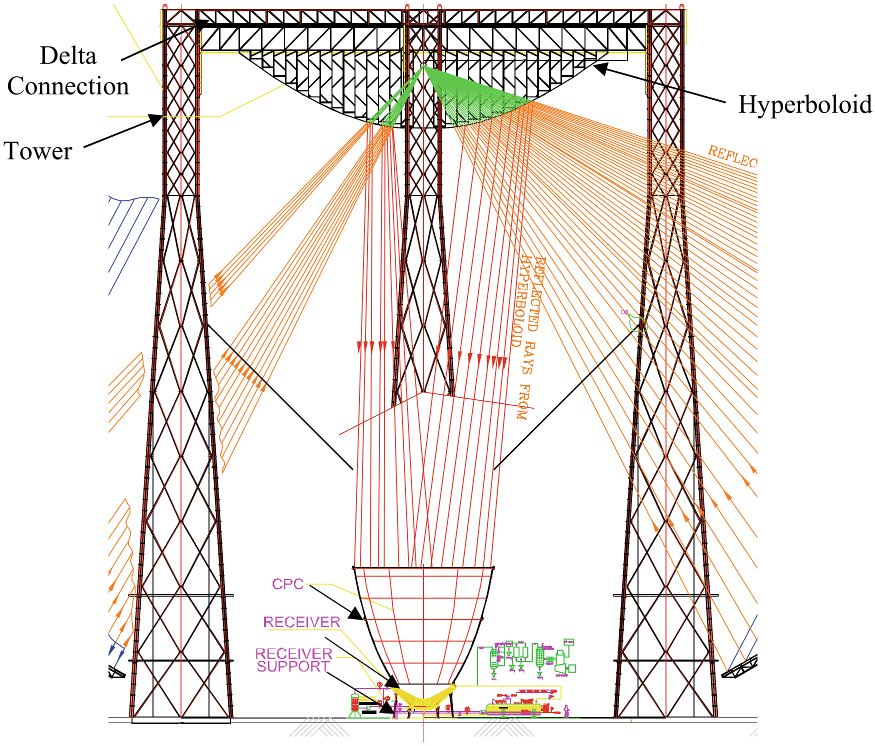

Fig. 1 Hyperboloid with tower assembly

Table 1 Mechanical properties

Properties	Carbon steel (YSt 310)	Aluminium
Tensile strength (MPa)	450	324
Yield strength (MPa)	310	276
Young's modulus (GPa)	200	68.9
Density (kg/m^3)	8000	2700

3 Design Specifications

3.1 Geometrical Specifications

1. Height of towers = 60 m
2. Diameter of hyperboloid = 40.8 m
3. Depth of the hyperboloid = 6.5 m

3.2 Types of Loads

Hyperboloid with tower assembly has been designed as a truss structure as per IS 800. Loads which need to be considered as per IS 800 are as follows [2, 3]:

1. Dead loads
2. Imposed loads
3. Wind loads (as per IS 875 Part 3)
4. Earthquake loads (as per IS 1893 Part 1).

3.3 Wind Loads and Operational Limits

1. Operating wind speed is 40 kmph (user's requirement)
2. Survival wind speed is 140.4 kmph (as per IS 875 Part 3).

4 Loads Considered in the Analysis

4.1 Wind Load on Hyperboloid Surface and Towers

Wind loads on hyperboloid and towers have been taken as per IS 875 Part 3. IS 875 Part 3 provides force coefficient for most structural shapes [4–6].

Wind load on any object is given by

$$F = C_\mathrm{f} \times A_\mathrm{e} \times p_\mathrm{d}$$

where

C_f force coefficient;
A_e effective area of the object normal to the wind direction, m^2;
p_d design wind pressure, $\mathrm{N/m}^2$.

4.1.1 Design Wind Speed

The basic wind speed for any site shall be obtained from IS 875 Part 3 and shall be modified to include the following effects to get design wind speed, V_Z at any height, Z.

Design wind speed (V_Z)

$$V_Z = V_\mathrm{b} \times k_1 \times k_2 \times k_3 \times k_4$$

Table 2 Parameters used in the calculation of design wind speed

Parameters	Value	Remarks
V_b	39 m/s	As per IS 875 wind zonal map
k_1	0.90	For 10 years design life, 100 years return period for the wind
k_2	0.99–1.152	For class A structure, terrain category 1
k_3	1.00	For plain land
k_4	1.00	More than 60 km away from coast

where

V_Z design wind speed at any height z, m/s;
V_b basic wind speed, m/s;
k_1 probability factor (risk coefficient);
k_2 terrain, height and structure size factor;
k_3 topography factor;
k_4 importance factor for the cyclonic region.

Various parameters used in the calculation of design wind speed have been listed in Table 2.

4.1.2 Design Wind Pressure

The wind pressure at any height above mean ground level shall be obtained by the following relationship between wind pressure and wind speed.

Design wind pressure (p_Z)

$$p_Z = 0.6V_Z^2$$

Table 3 gives the design wind speed and pressure at different heights of the structure.

Table 3 Design wind speed and pressure at different heights

Height (m)	Design wind speed (m/s)	Design wind pressure (N/m^2)
10.0	34.75	724.50
20.0	37.21	830.57
40.0	39.14	919.00
60.0	40.44	981.00

4.2 Earthquake Load on Hyperboloid Surface and Towers

Earthquake loads have been considered as per IS 1893 Part 1. For the purpose of determining seismic forces, the country is classified into four seismic zones. The design horizontal seismic coefficient A_{h} for a structure shall be determined by the following expression [7]:

$$A_{\mathrm{h}} = \frac{Z}{2} \times \frac{I}{R} \times \frac{S_{\mathrm{a}}}{g}$$

where

Z zone factor
R response reduction factor
I importance factor
S_a/g average response acceleration coefficient for rock or soil sites.

Site is located in seismic zone III. Hyperboloid with tower assembly is welded steel structure, damping for design basis earthquake has been considered as 2%. Response spectra used in the analysis for 2% damping is shown in Fig. 2.

5 Finite Element Analysis

Finite element analyses have been performed to optimize the design and estimate the deflections and stresses due to dead weight, imposed loads, earthquake loads and wind loads. Beam elements have been used to model the structural members. Lumped mass elements have been used to model imposed loads. Hyperboloid is connected to tower at 18 locations and to star delta at 24 locations with the help of link elements. All degrees of freedom have been fixed at the bottom nodes of the tower for analyses. Figure 3 shows the finite element model of hyperboloid with tower assembly.

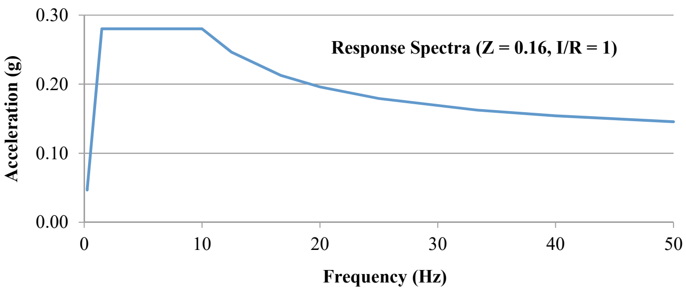

Fig. 2 Response spectra for 2% damping

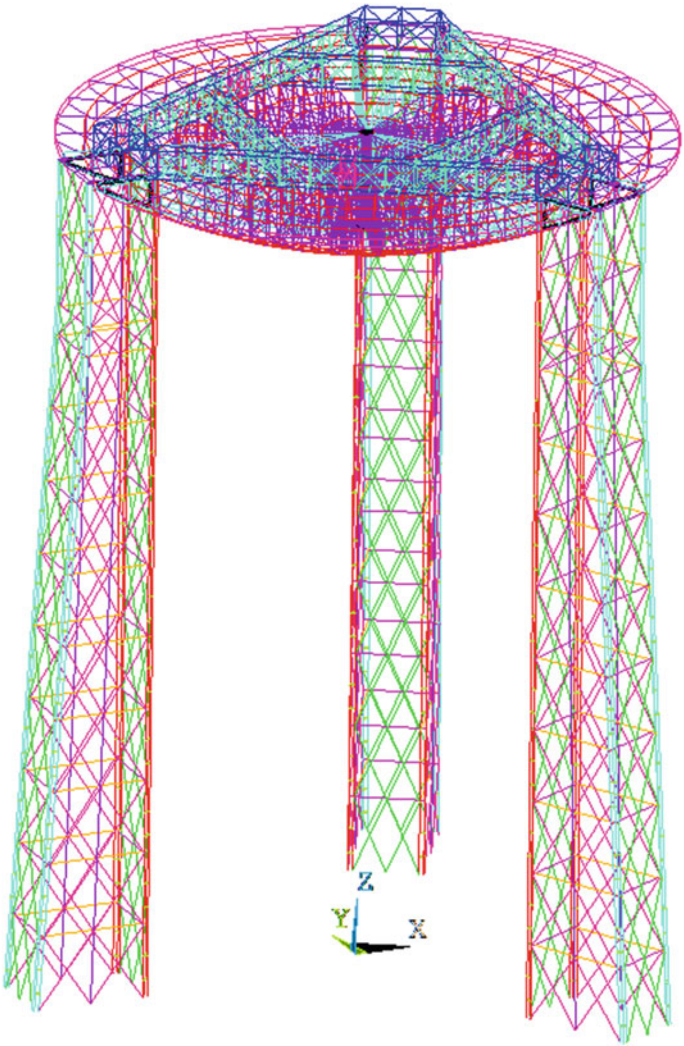

Fig. 3 Finite element model of hyperboloid with tower assembly

Static analyses have been performed to estimate the stresses and deflections due to dead weight, imposed loads and wind loads. Response spectrum analysis has been performed to estimate the stresses and deflections due to earthquake loads. The maximum deflections due to various loads and their combinations have been listed in Table 4. Deflections due to dead loads, imposed loads and operating wind loads are within the allowable limit (35 mm). Figure 4 shows the deflected shape due to dead weight and imposed loads of reflecting surface.

Table 4 Maximum deflections due to various loads and their combinations

Load combinations	Deflection (mm)
Dead loads + imposed loads	24.62
Dead loads + imposed loads + wind loads in *X* direction (operating)	26.57
Dead loads + imposed loads + wind loads in *Y* direction (operating)	26.45
Dead loads + imposed loads + wind loads in *X* direction (survival)	151.86
Dead loads + imposed loads + wind loads in *Y* direction (survival)	155.75
Dead loads + imposed loads + earthquake loads	74.71

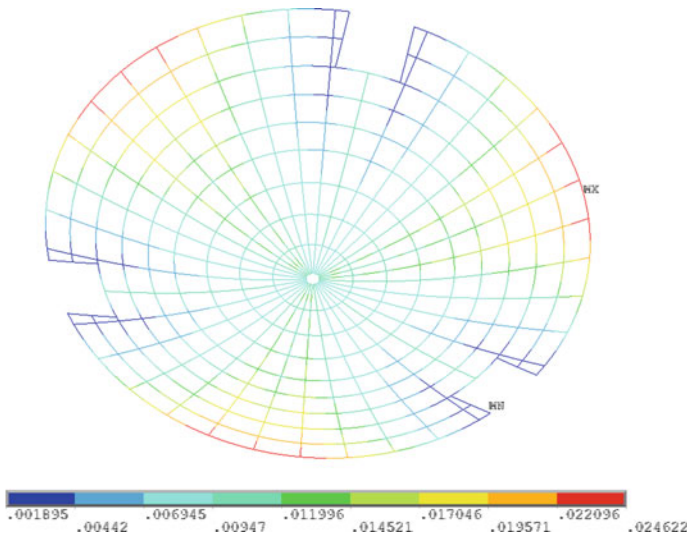

Fig. 4 Deflected shape (dead loads + imposed loads)

6 Design Checks

6.1 Permissible Stresses as Per IS 800

6.1.1 Axial Stress in Tension

The permissible stress in axial tension on the net cross-sectional area of hollow sections shall not exceed the values of σ_{at}.

$$\sigma_{at} = 0.6 f_y$$

where

f_y minimum yield stress, MPa.

6.1.2 Axial Stress in Compression

The direct stress in compression on the gross cross-sectional area of axially loaded steel hollow sections shall not exceed $0.6f_y$ nor the permissible stress σ_{ac}, calculated using the following formula:

$$\sigma_{ac} = 0.6\frac{f_{cc} \times f_y}{\left[(f_{cc})^n + \left(f_y\right)^n\right]^{1/n}}$$

where

σ_{ac} permissible stress in axial compression, MPa
f_{cc} elastic critical stress in compression $= \pi^2 E/\lambda^2$ MPa
λ l/r = ratio of the effective length of the member and the radius of gyration
f_y minimum yield stress, MPa
E modulus of elasticity, MPa
n a factor assumed as 1.4.

6.1.3 Bending Stresses

In hollow sections, the tensile bending stress and the compressive bending stress in the extreme fibres shall not exceed the values of σ_{bt}.

$$\sigma_{bt} = 0.66f_y$$

where

f_y minimum yield stress, MPa.

Table 5 gives the allowable stresses for tension and bending for structural steel and aluminium for different load combinations. Table 6 gives the permissible stresses in compression based on slenderness ratios for steel and aluminium members for different load combinations.

Table 5 Allowable stresses for tension and bending

	Dead loads + imposed loads		Dead loads + imposed loads + wind loads or earthquake loads	
	Structural steel	Aluminium	Structural steel	Aluminium
Axial tension (MPa)	186.0	165.6	248.0	220.8
Bending stress (MPa)	204.6	182.2	272.8	242.9

Table 6 Permissible stresses in axial compression in MPa

	Dead loads + imposed loads		Dead loads + imposed loads + wind loads or earthquake loads	
Slenderness ratio	Structural steel	Aluminium	Structural steel	Aluminium
25	181.0	150.2	241.3	200.3
50	156.8	100.2	209.1	133.6
75	120.3	59.7	160.4	79.6
100	87.3	37.1	116.4	49.5
125	63.4	24.8	84.5	33.1
150	47.0	17.6	62.7	23.5
175	35.9	13.1	47.9	17.5
200	28.1	10.1	37.5	13.5

6.1.4 Combined Stresses

Combined stresses in axial compression and bending should satisfy Eq. (1).

$$\frac{\sigma_{ac}\text{, cal.}}{\sigma_{ac}} + \frac{C_{mx} \times \sigma_{bcx}\text{, cal.}}{\left\{1 - \frac{\sigma_{ac}\text{,cal.}}{0.60 f_{ccx}}\right\}\sigma_{bcx}} + \frac{C_{my} \times \sigma_{bcy}\text{, cal.}}{\left\{1 - \frac{\sigma_{ac}\text{,cal.}}{0.60 f_{ccy}}\right\}\sigma_{bcy}} \le 1.0 \quad (1)$$

Similarly combined stresses in axial tension and bending should satisfy the Eq. (2).

$$\frac{\sigma_{at}\text{, cal.}}{0.60 f_y} + \frac{\sigma_{btx}\text{, cal.}}{0.66 f_y} + \frac{\sigma_{bty}\text{, cal.}}{0.66 f_y} \le 1.0 \quad (2)$$

where

- σ_{ac}, cal. calculated average axial compressive stress
- σ_{at}, cal. calculated average axial tensile stress
- σ_{bc}, cal. calculated bending compressive stress in extreme fibre
- σ_{bt}, cal. calculated bending tensile stress in extreme fibre
- σ_{ac} permissible axial comp. stress in the member subject to axial comp. load only
- σ_{at} permissible axial tensile stress in the member subject to axial tensile load only
- σ_{bc} permissible bending compressive stress in extreme fibre
- σ_{bt} permissible bending tensile stress in extreme fibre
- f_{cc} elastic critical stress in compression
- C_m a coefficient.

Table 7 Dead loads + imposed loads

Tubular sections size	Axial tension stress (MPa)	Axial compression stress (MPa)	Bending stress (MPa)
Tower			
200 NB 5.6 mm thk	3.73	12.7	12.5
150 NB 4.8 mm thk	5.07	6.94	9.13
Connecting members			
150 NB 4.5 mm thk	4.99	1.51	41.0
100 NB 4.5 mm thk	7.55	4.43	4.20
Delta connection			
150 NB 4.5 mm thk	17.0	28.6	17.6
100 NB 4.5 mm thk	14.2	22.5	32.7
50 NB 2.9 mm thk	32.6	33.0	29.1
Hyperboloid			
100 NB 4.5 mm thk	9.99	0.47	22.6
65 NB 3.2 mm thk	33.6	30.2	28.3
50 NB 2.9 mm thk	15.8	10.1	46.0
50 NB 2.5 mm thk	18.7	18.5	31.6

6.2 Maximum Stresses in Structural Tubes Due to Various Loadings

Structural tubes of different sizes have been used in the design of hyperboloid with tower assembly. Stresses in axial tension, axial compression and bending are listed in Tables 7, 8, 9 and 10 for different load combinations.

The stresses listed in the above tables for various loads and their combinations have been checked against the allowable stresses as per IS 800 and are found within the allowable limit. Considering as fixed–fixed end conditions, buckling checks have been performed as per IS 800 and found safe.

Table 8 Dead loads + imposed loads + wind loads in *X* direction (survival)

Tubular sections size	Axial tension stress (MPa)	Axial compression stress (MPa)	Bending stress (MPa)
Tower			
200 NB 5.6 mm thk	93.0	107	62.2
150 NB 4.8 mm thk	49.4	45.8	39.0
Connecting members			
150 NB 4.5 mm thk	7.41	8.05	180
100 NB 4.5 mm thk	14.9	39.2	21.2
Delta connection			
150 NB 4.5 mm thk	80.4	91.2	66.2
100 NB 4.5 mm thk	111	72.5	129
50 NB 2.9 mm thk	90.0	90.7	89.0
Hyperboloid			
100 NB 4.5 mm thk	8.82	21.0	42.2
65 NB 3.2 mm thk	170	126	123
50 NB 2.9 mm thk	31.4	36.9	160
50 NB 2.5 mm thk	59.3	62.8	117

Combined stresses in axial compression and bending, and axial tension and bending are listed in Tables 11, 12, 13 and 14 for different load combinations. The stress ratios listed in Tables 11, 12, 13 and 14 are less than 1, hence the structure is safe.

7 Vortex Shedding Frequency

Vortex shedding frequency of a structure is determined by the following formula:

$$f_s = \frac{S_t \times \overline{V}_{z,H}}{b} = \frac{0.25 \times 40.44}{40.8} = 0.25\,\text{Hz}$$

Table 9 Dead loads + imposed loads + wind loads in Y direction (survival)

Tubular sections size	Axial tension stress (MPa)	Axial compression stress (MPa)	Bending stress (MPa)
Tower			
200 NB 5.6 mm thk	104	114	68.4
150 NB 4.8 mm thk	42.6	44.1	37.3
Connecting members			
150 NB 4.5 mm thk	8.10	8.74	166
100 NB 4.5 mm thk	19.3	34.1	22.2
Delta connection			
150 NB 4.5 mm thk	77.5	86.0	68.0
100 NB 4.5 mm thk	113	74.1	123
50 NB 2.9 mm thk	85.4	88.5	89.6
Hyperboloid			
100 NB 4.5 mm thk	10.3	22.8	55.8
65 NB 3.2 mm thk	144	138	123
50 NB 2.9 mm thk	36.6	37.1	165
50 NB 2.5 mm thk	55.8	60.0	108

where

S_t Strouhal number;
$\overline{V}_{z,H}$ hourly mean wind speed at height z;
b breadth of structure normal to the wind direction in the horizontal plane.

Vortex shedding frequency of the hyperboloid with tower assembly is 0.25 Hz which is lesser than the fundamental frequency (1.1 Hz) obtained from modal analysis of the structure. Frequencies and mass participations obtained from modal analysis of the structure have been listed in Table 15.

Table 10 Dead loads + imposed loads + earthquake loads

Tubular sections size	Axial tension stress (MPa)	Axial compression stress (MPa)	Bending stress (MPa)
Tower			
200 NB 5.6 mm thk	44.5	53.5	36.8
150 NB 4.8 mm thk	21.6	23.4	23.3
Connecting members			
150 NB 4.5 mm thk	14.8	11.3	49.9
100 NB 4.5 mm thk	10.1	7.0	70.7
Delta connection			
150 NB 4.5 mm thk	43.1	54.7	36.8
100 NB 4.5 mm thk	48.2	56.5	43.1
50 NB 2.9 mm thk	49.1	49.5	43.1
Hyperboloid			
100 NB 4.5 mm thk	14.4	4.9	32.3
65 NB 3.2 mm thk	86.1	82.7	71.8
50 NB 2.9 mm thk	23.5	17.8	86.8
50 NB 2.5 mm thk	26.1	25.9	42.3

8 Conclusions

Hyperboloid with tower assembly has been analyzed and design checks have been performed as per IS 800. Based on the above analyses, following conclusions can be made:

1. Hyperboloid with tower assembly has been analyzed to estimate the stresses due to dead weight, imposed loads, wind loads and earthquake loads.
2. Wind loads on hyperboloid with tower assembly have been considered as per IS 875 and earthquake loads as per IS 1893.
3. Fundamental frequency of the structure is 1.1 Hz. IS 875 recommends frequency more than 1.0 Hz to avoid wind oscillations.
4. Deflections due to dead loads and operating wind loads are within the allowable limit (35 mm).

Table 11 Dead loads + imposed loads

Tubular sections size	Axial compression and bending	Axial tension and bending
Tower		
200 NB 5.6 mm thk	0.08 + 0.05 + 0.05 = 0.18	0.02 + 0.06 + 0.06 = 0.14
150 NB 4.8 mm thk	0.06 + 0.01 + 0.04 = 0.11	0.03 + 0.01 + 0.04 = 0.09
Connecting members		
150 NB 4.5 mm thk	0.01 + 0.17 + 0.08 = 0.26	0.03 + 0.20 + 0.10 = 0.33
100 NB 4.5 mm thk	0.03 + 0.02 + 0.01 = 0.06	0.04 + 0.02 + 0.01 = 0.08
Delta connection		
150 NB 4.5 mm thk	0.16 + 0.05 + 0.07 = 0.28	0.09 + 0.05 + 0.09 = 0.23
100 NB 4.5 mm thk	0.13 + 0.04 + 0.14 = 0.31	0.08 + 0.05 + 0.16 = 0.28
50 NB 2.9 mm thk	0.33 + 0.01 + 0.02 = 0.36	0.18 + 0.11 + 0.14 = 0.43
Hyperboloid		
100 NB 4.5 mm thk	0.01 + 0.08 + 0.09 = 0.18	0.05 + 0.09 + 0.11 = 0.25
65 NB 3.2 mm thk	0.26 + 0.07 + 0.14 = 0.47	0.18 + 0.07 + 0.14 = 0.39
50 NB 2.9 mm thk	0.09 + 0.15 + 0.20 = 0.44	0.08 + 0.16 + 0.22 = 0.47
50 NB 2.5 mm thk	0.36 + 0.00 + 0.06 = 0.41	0.11 + 0.08 + 0.17 = 0.36

Table 12 Dead loads + imposed loads + wind loads in *X* direction (survival)

Tubular sections size	Axial compression and bending	Axial tension and bending
Tower		
200 NB 5.6 mm thk	0.49 + 0.23 + 0.18 = 0.90	0.38 + 0.23 + 0.17 = 0.78
150 NB 4.8 mm thk	0.28 + 0.09 + 0.15 = 0.51	0.20 + 0.08 + 0.14 = 0.42
Connecting members		
150 NB 4.5 mm thk	0.03 + 0.56 + 0.28 = 0.88	0.01 + 0.66 + 0.24 = 0.91
100 NB 4.5 mm thk	0.17 + 0.07 + 0.03 = 0.27	0.06 + 0.08 + 0.03 = 0.17
Delta connection		
150 NB 4.5 mm thk	0.38 + 0.15 + 0.22 = 0.75	0.33 + 0.16 + 0.24 = 0.73
100 NB 4.5 mm thk	0.32 + 0.13 + 0.44 = 0.89	0.12 + 0.14 + 0.47 = 0.74
50 NB 2.9 mm thk	0.69 + 0.07 + 0.16 = 0.91	0.01 + 0.27 + 0.33 = 0.61
Hyperboloid		
100 NB 4.5 mm thk	0.11 + 0.13 + 0.14 = 0.38	0.04 + 0.15 + 0.16 = 0.34
65 NB 3.2 mm thk	0.61 + 0.13 + 0.21 = 0.94	0.69 + 0.13 + 0.05 = 0.86
50 NB 2.9 mm thk	0.14 + 0.21 + 0.54 = 0.90	0.13 + 0.41 + 0.27 = 0.81
50 NB 2.5 mm thk	0.52 + 0.08 + 0.04 = 0.64	0.27 + 0.18 + 0.48 = 0.93

Table 13 Dead loads + imposed loads + wind loads in *Y* direction (survival)

Tubular sections size	Axial compression and bending	Axial tension and bending
Tower		
200 NB 5.6 mm thk	0.52 + 0.26 + 0.20 = 0.98	0.42 + 0.25 + 0.19 = 0.87
150 NB 4.8 mm thk	0.27 + 0.08 + 0.14 = 0.49	0.17 + 0.07 + 0.14 = 0.38
Connecting members		
150 NB 4.5 mm thk	0.04 + 0.52 + 0.24 = 0.79	0.03 + 0.61 + 0.28 = 0.92
100 NB 4.5 mm thk	0.15 + 0.07 + 0.03 = 0.25	0.08 + 0.08 + 0.03 = 0.19
Delta connection		
150 NB 4.5 mm thk	0.36 + 0.16 + 0.23 = 0.75	0.31 + 0.18 + 0.25 = 0.75
100 NB 4.5 mm thk	0.32 + 0.13 + 0.42 = 0.87	0.21 + 0.14 + 0.45 = 0.80
50 NB 2.9 mm thk	0.67 + 0.05 + 0.15 = 0.88	0.35 + 0.23 + 0.33 = 0.91
Hyperboloid		
100 NB 4.5 mm thk	0.12 + 0.15 + 0.19 = 0.45	0.04 + 0.16 + 0.21 = 0.41
65 NB 3.2 mm thk	0.70 + 0.12 + 0.15 = 0.96	0.58 + 0.11 + 0.13 = 0.83
50 NB 2.9 mm thk	0.13 + 0.21 + 0.58 = 0.91	0.15 + 0.49 + 0.32 = 0.96
50 NB 2.5 mm thk	0.62 + 0.01 + 0.22 = 0.85	0.25 + 0.19 + 0.45 = 0.88

Table 14 Dead loads + imposed loads + earthquake loads

Tubular sections size	Axial compression and bending	Axial tension and bending
Tower		
200 NB 5.6 mm thk	0.24 + 0.13 + 0.13 = 0.49	0.18 + 0.14 + 0.14 = 0.45
150 NB 4.8 mm thk	0.14 + 0.08 + 0.08 = 0.30	0.09 + 0.09 + 0.09 = 0.26
Connecting members		
150 NB 4.5 mm thk	0.05 + 0.16 + 0.16 = 0.36	0.06 + 0.18 + 0.18 = 0.43
100 NB 4.5 mm thk	0.03 + 0.22 + 0.22 = 0.48	0.04 + 0.26 + 0.26 = 0.56
Delta connection		
150 NB 4.5 mm thk	0.23 + 0.12 + 0.12 = 0.47	0.17 + 0.14 + 0.14 = 0.44
100 NB 4.5 mm thk	0.25 + 0.14 + 0.14 = 0.54	0.19 + 0.16 + 0.16 = 0.51
50 NB 2.9 mm thk	0.38 + 0.20 + 0.20 = 0.79	0.20 + 0.16 + 0.16 = 0.52
Hyperboloid		
100 NB 4.5 mm thk	0.03 + 0.10 + 0.10 = 0.23	0.06 + 0.12 + 0.12 = 0.30
65 NB 3.2 mm thk	0.40 + 0.27 + 0.27 = 0.94	0.35 + 0.26 + 0.26 = 0.88
50 NB 2.9 mm thk	0.12 + 0.30 + 0.30 = 0.72	0.09 + 0.32 + 0.32 = 0.73
50 NB 2.5 mm thk	0.28 + 0.19 + 0.19 = 0.65	0.12 + 0.17 + 0.17 = 0.47

Table 15 Frequencies and percentage mass participations

Frequency (Hz)	%Mass participation (*X*)	%Mass participation (*Y*)	%Mass participation (*Z*)
1.1	61.68	7.11	0.00
1.1	7.11	61.68	0.00
4.0	0.30	3.78	0.00
4.0	3.78	0.30	0.00
4.3	0.00	0.00	12.16

5. Stresses due to various loads and their combinations have been checked against the allowable stresses as per IS 800 and are found within the allowable limits.
6. Buckling checks have been performed as per IS 800 and found safe.

References

1. IS 1161 (1998) Steel tubes for structural purposes
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