Computational Optimization of Steel Lattice Tower

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***Abstract*— Nowadays, there are many software available in market which can able to optimize a given structure considering its weight. Most of this software includes size optimization feature in which repetitive analysis and design part is automated. Limitation of this software is to do shape optimization, which requires successive model generation for analysis and design. Shape optimization needs comparison of results obtained from different alternatives, which is very ponderous.**

In the present study, size and shape optimization process is implemented for 3D steel lattice tower. The present study is aimed at design optimization of steel lattice tower considering its weight with satisfying stress constraints based on IS:800-2007, thus resulting in reduction of overall project cost using a self-guided strategy. The algorithm can select Indian Standard Pipe sections based on structural requirements. Shape optimization is achieved as per given constraints for changing the geometrical dimensions. Geometrical dimensions are decided for each alternate is based on Self-Guided Strategy. The process of size and shape optimization is automated using "Visual Basic for Applications" in Microsoft Excel environment using "STAAD.Pro" for analysis. The interface runs in background for both the softwares and is developed using OpenSTAAD library. The main reason for choosing STAAD.Pro and Microsoft Excel is, both are familiar to users. The process and technique used in the present study are used to provide optimized solution for steel lattice towers. Results of size and shape optimization are compared and tabulated.

***Index Terms*— Size optimization, shape optimization, lattice tower, OpenSTAAD, Visual Basic for Applications, Self-Guided Strategy**

I. INTRODUCTION

Main focus of any steel structure engineer is to optimize the weight or volume of a structure. The reason behind that is if weight of structure is less than the cost of fabrication, galvanizing, transportation will be reduced. Thus, will lead to reduction in overall cost of project.

Most of the structure design software includes size optimization feature in which repetitive analysis and design part in automated. Limitation of this software is to do shape optimization, which requires successive model generation for analysis and design. Shape optimization needs comparison of results obtained from different alternatives. In the present study, size and shape optimization process is implemented for 3D steel lattice tower. The process of size and shape optimization is automated using "Visual Basic for Applications" in Microsoft Excel environment using "STAAD.Pro" for analysis. For designing purpose IS:800-2007 is used. The interface runs in background for both the software and is developed using OpenSTAAD library. The optimization method generates random points in initial stage. And moves possible nearest point after sequential alternates. Algorithm will stop when convergence criteria is satisfied.

II. EXCEL INPUT INTERFACE

Fig.1 shows the Excel input interface for optimization of steel lattice tower. There are some blank boxes in the interface. The user has to fill geometry data, material data and shape optimization constraints.

A. Geometry Data

Geometry data contains overall height of steel lattice tower, number of panels in lattice tower and height of each panel, bottom and top width of lattice tower. Here, the program restricted to maximum 20 number of panels. After changing top and bottom width of lattice tower all the intermediate nodes will be automatically created and new coordinate system is generated. This data is used by STAAD.Pro software to create member connectivity.

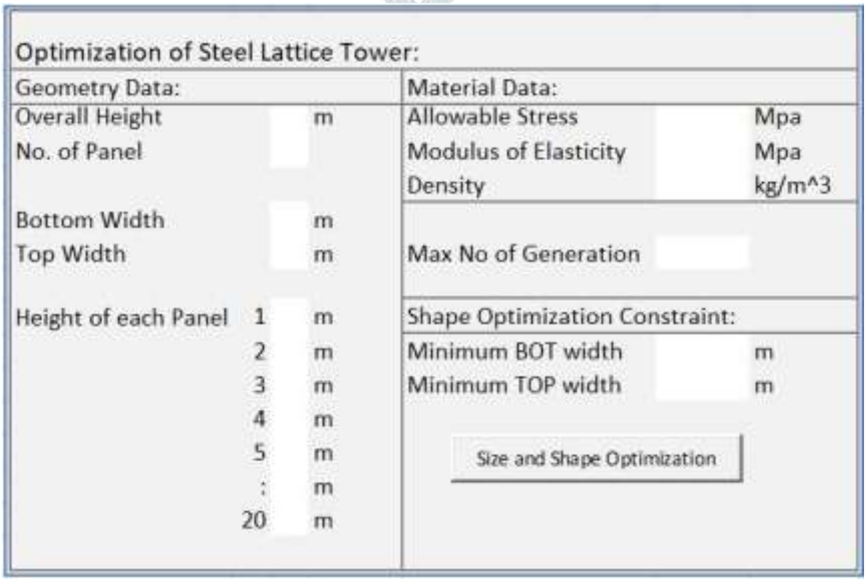

Fig. 1 Excel Input Interface

B. Material Data

Material data contains allowable stress, modulus of elasticity and density of steel. This data is shared by STAAD.Pro. Allowable stress of steel is used for design calculation of members in excel. Density is used for weight calculation of structure. Both parameters are used at each iteration.

C. Shape Optimization Constraint

Shape optimization constraint gives two blank boxes. Here, user can limit the minimum dimensions i.e. bottom and top width of lattice tower.

D. "Size and Shape Optimization" Button

The tasks performed can be summarized as follows:

Step 1: starts selecting random sections for each member. Then STAAD.Pro environment invokes and geometry creation, assignment of support, load, material, random sections will be automated.

Step 2: After analysis is done forces are dumped in predefined excel sheet and design module is carried out automatically. Where capacity, factor of safety and required new section is calculated for each member.

Step 3: After getting the new section assignment of section is done and will execute step 2 again till convergence criteria is satisfied or maximum no of generation is reached.

Step 4: Now, new dimensions are adopted to change shape of lattice tower and algorithm will get back to step 1 to step 3. Algorithm will keep on changing the dimensions of lattice tower till shape optimization constraint is reached or convergence criteria is satisfied.

E. Documentation

A well documentation of result is much needed for easy understanding and for submission purpose. Fig.2 shows design file of 40-bar lattice tower. In the present work, user can get design file of each shape alternate as shown in fig.2

Member	Name	Length (m)	Force	Area Provided (mm2)	Actual Stress (Mpa)	KL/R	fcd (in case of compression	comp/ tension Capcity	FOS	Comment	Weight of Member (kg)
1	PIP603L	1.782	-112.5	523	215.19	88	155.24	118.86	1.06	SAFE	7.303
2	PIP889L	1.782	155.4	862	180.27	59	197.37	170.14	1.09	SAFE	12.036
3	PIP889L	1.782	155.4	862	180.27	59	197.37	170.14	1.09	SAFE	12.036
4	PIP603L	1.782	-112.5	523	215.19	88	155.24	118.86	1.06	SAFE	7.303
5	PIP337M	1.528	-59.8	307	194.72	141	78.41	69.77	1.17	SAFE	3.674
6	PIP603M	1.528	101.0	641	157.63	76	174.79	112.04	1.11	SAFE	7.672
7	PIP603M	1.528	101.0	641	157.63	76	174.79	112.04	1.11	SAFE	7.672
:	:	:	:	:	:	:	:	:	:	:	:
40	PIP213L	0.500	6.3	121	51.89	73	179.56	21.73	3.46	SAFE	0.474

Fig. 2 Documentation of Design File

III. TECHNIQUES FOR SHAPE OPTIMIZATION

In steel lattice tower shape optimization is a key technique to optimize weight. Shape optimization needs number of different alternates. This, alternates are in the form of various bottom and top width of steel lattice tower. In the present study, lower limit and upper limit of both the top and bottom width of tower is pre-decided. To cover the most values between the limits in limited alternates here two methods are developed. Shape alternatives are denoted as A1, A2, A3,..An. Upper limit of bottom and top width are denoted as B_{UL} and T_{UL}. Lower limit of bottom and top width are denoted as B_{LL} and $T_{LL.}$

Method 1:

In this method for initial alternate is a combination of upper limit of bottom and top width. Then top width is gradually decreased with specified interval till the weight is decreasing. If there isn't any further reduction in weight then bottom width is decreased and top width is taken similar to the last optimal alternate. This process is carried out till the algorithm reaches the lower limit of bottom width.

Method 2:

In this method six alternatives are used to get optimal weight of tower. Below method is developed to choose top and bottom width for alternatives.

No. of Alternates	Bottom Width		Top Width	
A1	B1 = B_{UL}		T1 = T_{UL}	
A2	B2 = B_{LL}		T2 = T_{LL}	
A3	B3 = $\frac{B_{UL}+B_{LL}}{2}$		T3 = $\frac{T_{UL}+T_{LL}}{2}$	
A4	A3<A1	A3>A1	A3<A1	A3>A1
	B4 = $\frac{B_{AVG}+B_{LL}}{2}$	B4 = $\frac{B_{AVG}+B_{UL}}{2}$	T4 = $\frac{T_{AVG}+T_{LL}}{2}$	T4 = $\frac{T_{AVG}+T_{UL}}{2}$
A5	A4<A2	A4>A2	A4<A2	A4>A2

	B5 = $\frac{B_{AVG}+B_{UL}}{2}$	B5 = $\frac{B_{LL}+B_{UL}}{2}$	T5 = $\frac{T_{AVG}+T_{LL}}{2}$	T5 = $\frac{T_{LL}+T_{UL}}{2}$
A6	A5<A2	A5>A2	A5<A2	A5>A2
	B6 = $\frac{B_{AVG}+B_{UL}}{2}$	B6 = $\frac{B_{LL}+B_{UL}}{2}$	T6 = $\frac{T_{AVG}+T_{LL}}{2}$	T6 = $\frac{T_{LL}+T_{UL}}{2}$

For 40-bar and 148-bar steel lattice tower both the shape optimization methods are implemented along with size optimization and comparison between two methods is carries out. Based on results, method-2 is chosen from two methods for optimization of 196-bar steel lattice tower.

IV. Numerical examples

Material property and section database is kept same for all examples.

A) 40-Bar steel lattice tower

A 40-bar truss structure is shown in Fig. 3 with node numbers, member numbers and initial dimensions of the truss structure. Here, the cross-sectional areas of each members are considered as 40 sizing design variables, for which the STAAD database is used. Indian pipe sections are used for design variable.

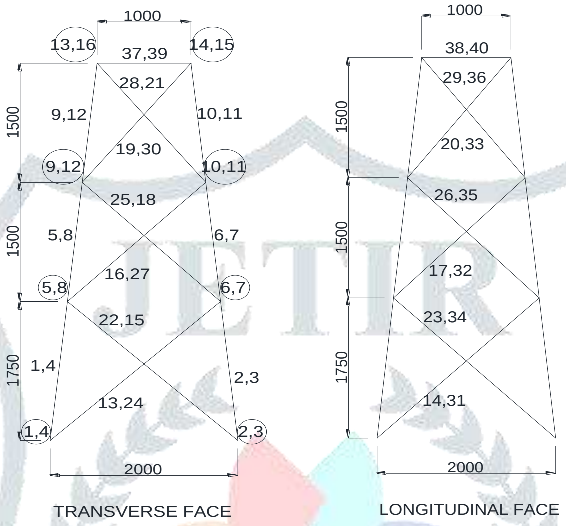

Fig. 3 A 40-bar steel lattice tower

For shape optimization top width and bottom width are considered as design variable. For all examples steel lattice tower is assumed to be symmetric. The data assumed are: modulus of elasticity, E = 205000 MPa, density, ρ = 7833 kg/m^3, yield stress, σ_{max} = 250 MPa. Loading details are given in Table 1. Fig. 4 shows excel input interface. For shape optimization minimum bottom and top width are restricted to 1.5m and 0.5m respectively.

Table 1 Loads on 40-bar steel lattice tower

Node No.	X-dir(kN)	Y-dir(kN)	Z-dir(kN)
13	0	-30	0
14	0	-30	0
15	0	-30	0
16	0	-30	0
5	30	0	0
8	30	0	0
9	30	0	0
12	30	0	0
13	30	0	0
16	30	0	0

Table 2 Results from method-1 for 40-bar steel lattice tower

RESULTS OBTAINED FOR 40-BAR STEEL LATTICE TOWER (SHAPE OPTIMIZATION METHOD 1)			
Shape Alternate	Bot width (m)	Top width (m)	Optimized Weight(kg)
1	2	1	181
2	2	0.9	174
3	2	0.8	174
4	1.9	0.9	175
5	1.9	0.8	174
6	1.9	0.7	172
7	1.9	0.6	166
8	1.9	0.5	165
9	1.8	0.5	167
10	1.7	0.5	166

11	1.6	0.5	167
12	1.5	0.5	173

Table 3 Results from method-2 for 40-bar steel lattice tower

RESULTS OBTAINED FOR 40-BAR STEEL LATTICE TOWER (SHAPE OPTIMIZATION METHOD 2)			
Shape Alternate	Bot width (m)	Top width (m)	Optimized Weight(kg)
1	2.00	1.00	181
2	1.50	0.50	173
3	1.75	0.75	175
4	1.63	0.63	170
5	1.69	0.69	173
6	1.59	0.59	171

Table 2 shows that alternative 8 with TW=0.5 and BW=1.9 gives the most optimized weight of 165 kg. There is a 9.7% saving in weight compare to initial design or alternate 1. Table 3 shows that alternative 4 with TW=0.63 and BW=1.63 gives the most optimized weight of 170 kg. There is a 6.5% saving in weight compare to initial design or alternate 1. There is not much difference between both the methods.

B) 148-Bar steel lattice tower

A 148-bar truss structure, shown in Fig.3.

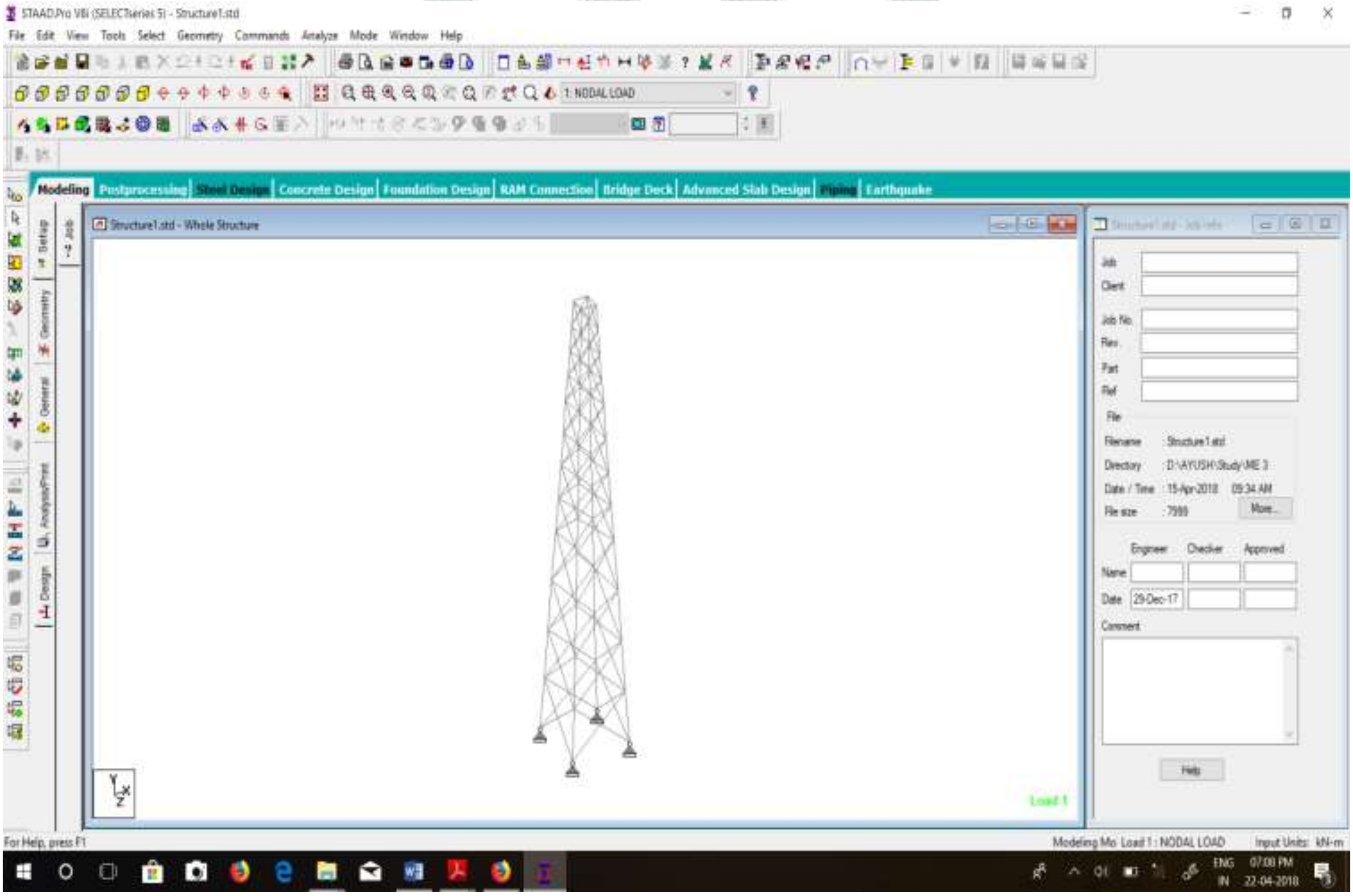

Fig. 3 3D view of 148-bar steel lattice tower

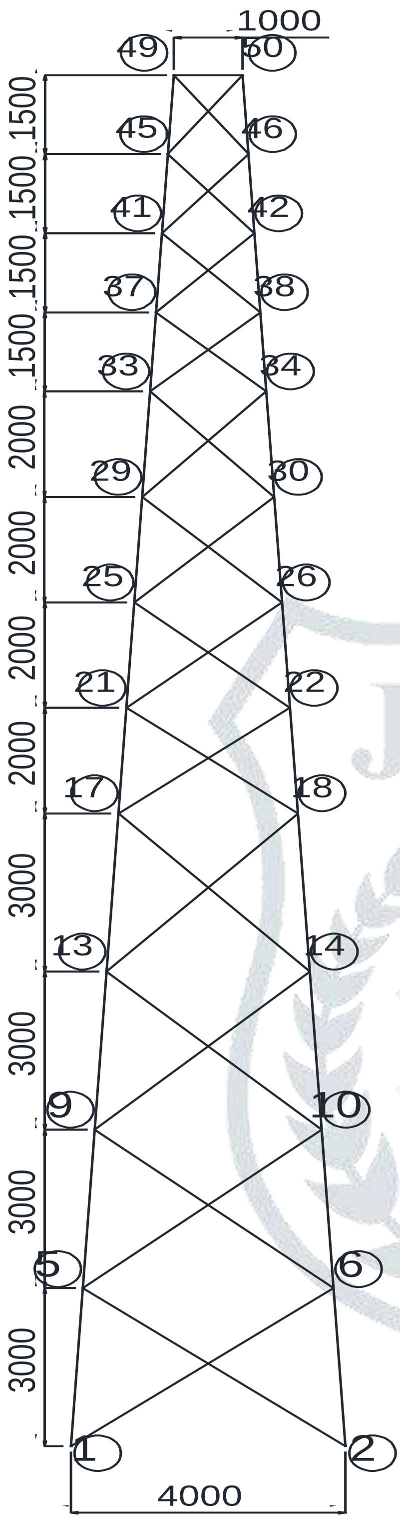

Fig. 4 Details of 148-bar steel lattice tower

Table 4 Loads on 148-bar steel lattice tower

Node No.	X-dir(kN)	Y-dir(kN)	Z-dir(kN)
52	0.294	0.000	-0.294
51	0.294	0.000	-0.294
50	0.294	0.000	-0.294
49	0.294	0.000	-0.294
48	1.618	-1.324	-1.618
47	1.618	-1.324	-1.618
46	1.618	-1.324	-1.618
45	1.618	-1.324	-1.618
44	0.686	-0.441	-0.686
43	0.686	-0.441	-0.686
42	0.686	-0.441	-0.686
41	0.686	-0.441	-0.686
40	0.735	-0.441	-0.735
39	0.735	-0.441	-0.735
38	0.735	-0.441	-0.735
37	0.735	-0.441	-0.735
36	0.932	-0.539	-0.932
35	0.932	-0.539	-0.932
34	0.932	-0.539	-0.932
33	0.932	-0.539	-0.932
32	1.128	-0.686	-1.128
31	1.128	-0.686	-1.128
30	1.128	-0.686	-1.128
29	1.128	-0.686	-1.128
28	1.226	-0.785	-1.226
27	1.226	-0.785	-1.226
26	1.226	-0.785	-1.226
25	1.226	-0.785	-1.226
24	1.324	-0.854	-1.324
23	1.324	-0.854	-1.324
22	1.324	-0.854	-1.324
21	1.324	-0.854	-1.324
20	1.618	-0.981	-1.618
19	1.618	-0.981	-1.618
18	1.618	-0.981	-1.618
17	1.618	-0.981	-1.618
16	1.961	-1.275	-1.961
15	1.961	-1.275	-1.961
14	1.961	-1.275	-1.961
13	1.961	-1.275	-1.961
12	2.157	-1.422	-2.157
11	2.157	-1.422	-2.157
10	2.157	-1.422	-2.157
9	2.157	-1.422	-2.157
8	2.354	-1.569	-2.354
7	2.354	-1.569	-2.354
6	2.354	-1.569	-2.354
5	2.354	-1.569	-2.354

For shape optimization minimum bottom and top width are restricted to 1.8m and 0.5m respectively.

Table 5 Results from method-1 for 148-bar steel lattice tower

Shape Alternate	Bot width (m)	Top width (m)	Optimized Weight(kg)
1	4.0	1.0	1326
2	4.0	0.9	1323
3	4.0	0.8	1313
4	4.0	0.7	1304
5	4.0	0.6	1280
6	4.0	0.5	1274
7	3.8	0.5	1253
8	3.6	0.5	1212

9	3.4	0.5	1199
10	3.2	0.5	1175
11	3.0	0.5	1141
12	2.8	0.5	1143
13	2.6	0.5	1104
14	2.4	0.5	1091
15	2.2	0.5	1097
16	2.0	0.5	1098
17	1.8	0.5	1098

Table 6 Results from method-2 for 148 bar steel lattice tower

Shape Alternate	Bot width (m)	Top width (m)	Optimized Weight(kg)
1	4.00	1.00	1326
2	1.80	0.50	1098
3	2.90	0.75	1156
4	2.35	0.63	1092
5	2.63	0.69	1118
6	2.21	0.59	1089

Table 5 shows that alternative 14 with TW=0.5 and BW=2.4 gives the most optimized weight of 1091 kg. There is a 21.5% saving in weight compare to initial design or alternate 1. Table 6 shows that alternative 6 with TW=0.59 and BW=2.21 gives the most optimized weight of 1089 kg. There is a 21.7% saving in weight compare to initial design or alternate 1. So, method-2 gives optimized weight, though there isn't much difference between both the methods. But method-2 takes 6 alternatives and method-1 takes 14.

C) 196-Bar steel lattice tower

A 196-bar truss structure, shown in Fig.5.

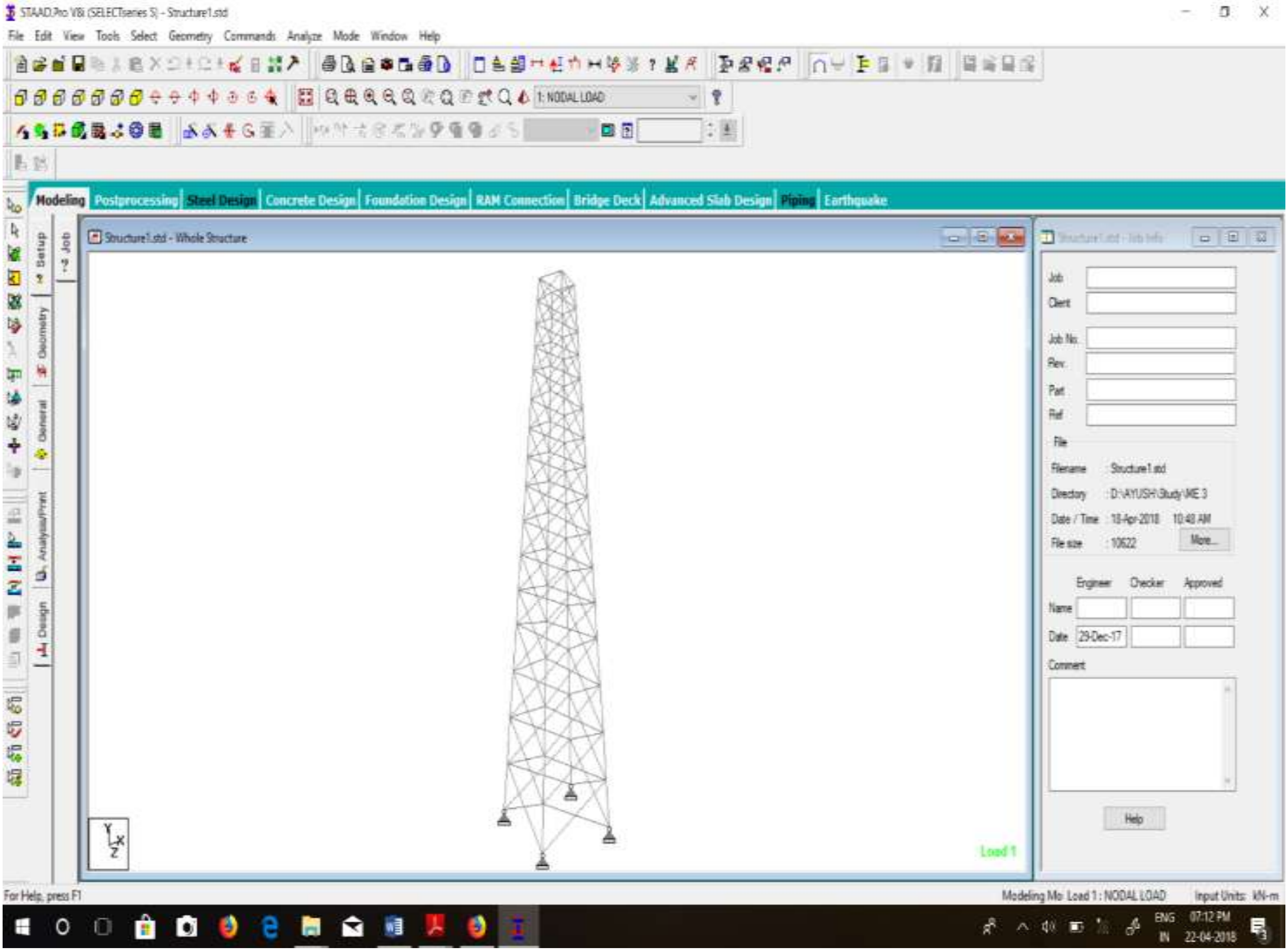

Fig. 5 3D view of 196-bar steel lattice tower

Calculation of Wind Load on Equipment: (IS 875(Part 3):2015)

Basic Wind Speed	V_b=	39.00	m/sec
Coefficients	K_1= K_2= K_3=	1.06 1.16 1.20	
Design Wind Speed Design Wind Pressure	$Vd=V_r*k_1*k_2*k_3$ $P_d=0.6*V_d^2$	57.42 1978.3	 N/m^2
Diameter of dish Exposed area of dish Co-efficient for wind from front	D= A_e= C_f=	2.0 3.14 1.4	m m^2
Wind load on dish front face	$Fwt=C_f*Ae*P_d$	8.7	KN acting on nodes 61,62,63,64 equally.

Calculation of wind load distribution on tower nodes: (IS 802(Part 1/Sec 1):1995)

Reference Wind Speed	$V_r=V_b/K_0$	28.36	
Coefficients	K_1=	1.00	
	K_2=	1.00	
Design Wind Speed	$V_d=V_r*k_1*k_2$	28.36	
Design Wind Pressure	$P_d=0.6*V_d^2$	482.7	N/m^2

Loading Point	Panels	Height	Exposed Area m2	Circumscribed Area m2	Exposed/ Circumscribed Area	Drag Coefficient	Gust Factor	Load, Fwt N	Distribution of load	Load on Each Node N
1,2,3,4									396.70	0.397
	1	4	1.07	29.13	0.04	3.6	1.7	3174		
5,6,7,8									759.04	0.759
	2	8	0.98	27.39	0.04	3.6	1.7	2899		
9,10,11,12									703.63	0.704
	3	12	0.91	25.65	0.04	3.6	1.73	2730		
13,14,15,16									675.58	0.676
	4	16	0.86	23.04	0.04	3.6	1.79	2674		
17,18,19,20									580.42	0.580
	5	19	0.62	16.79	0.04	3.6	1.82	1969		
21,22,23,24									481.46	0.481
	6	22	0.58	15.81	0.04	3.6	1.872	1883		
25,26,27,28									460.81	0.461
	7	25	0.55	14.83	0.04	3.6	1.894	1804		
29,30,31,32									435.57	0.436
	8	28	0.50	13.85	0.04	3.6	1.916	1681		
33,34,35,36									379.32	0.379
	9	30.5	0.40	10.80	0.04	3.6	1.96	1354		
37,38,39,40									332.27	0.332
	10	33	0.38	10.12	0.04	3.6	1.99	1304		
41,42,43,44									312.66	0.313
	11	35.5	0.34	9.44	0.04	3.6	2.015	1197		
45,46,47,48									287.37	0.287
	12	38	0.31	8.76	0.04	3.6	2.048	1102		
49,50,51,52									253.93	0.254
	13	40	0.26	6.52	0.04	3.6	2.07	929		

53,54,55,56									218.04	0.218
	14	42	0.23	6.08	0.04	3.6	2.082	815		
57,58,59,60									196.12	0.196
	15	44	0.21	5.65	0.04	3.6	2.094	754		
61,62,63,64									186.31	0.186
	16	46	0.20	5.21	0.04	3.6	2.118	736		
65,66,67,68									92.05	0.092

Fig. 6 Excel input interface for 196-bar steel lattice tower

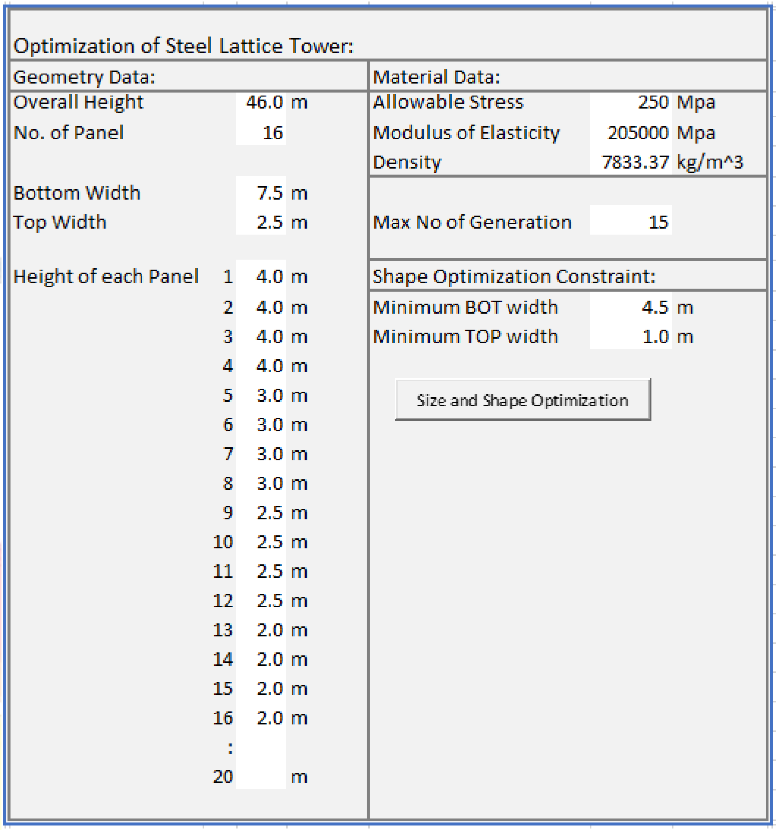

Table 7 Loads on 196-bar steel lattice tower

Node No.	X-dir(kN)	Y-dir(kN)	Z-dir(kN)
68	0.092	0.000	-0.092
67	0.092	0.000	-0.092
66	0.092	0.000	-0.092
65	0.092	0.000	-0.092
64	0.186	-3.972	-0.186
63	0.186	-3.972	-0.186
62	0.186	-3.972	-0.186
61	0.186	-3.972	-0.186
60	0.196	-1.323	-0.196
59	0.196	-1.323	-0.196
58	0.196	-1.323	-0.196
57	0.196	-1.323	-0.196
56	0.218	-1.323	-0.218
55	0.218	-1.323	-0.218
54	0.218	-1.323	-0.218
53	0.218	-1.323	-0.218
52	0.254	-1.617	-0.254
51	0.254	-1.617	-0.254
50	0.254	-1.617	-0.254
49	0.254	-1.617	-0.254
48	0.287	-2.058	-0.287
47	0.287	-2.058	-0.287
46	0.287	-2.058	-0.287
45	0.287	-2.058	-0.287
44	0.313	-2.355	-0.313
43	0.313	-2.355	-0.313
42	0.313	-2.355	-0.313
41	0.313	-2.355	-0.313
40	0.332	-2.562	-0.332
39	0.332	-2.562	-0.332
38	0.332	-2.562	-0.332
37	0.332	-2.562	-0.332
36	0.379	-2.943	-0.379
35	0.379	-2.943	-0.379
34	0.379	-2.943	-0.379
33	0.379	-2.943	-0.379
32	0.436	-3.825	-0.436
31	0.436	-3.825	-0.436
30	0.436	-3.825	-0.436
29	0.436	-3.825	-0.436
28	0.461	-4.266	-0.461
27	0.461	-4.266	-0.461
26	0.461	-4.266	-0.461
25	0.461	-4.266	-0.461
24	0.481	-4.707	-0.481
23	0.481	-4.707	-0.481
22	0.481	-4.707	-0.481
21	0.481	-4.707	-0.481
20	0.580	-4.707	-0.580
19	0.580	-4.707	-0.580
18	0.580	-4.707	-0.580
17	0.580	-4.707	-0.580
16	0.676	-4.707	-0.676
15	0.676	-4.707	-0.676
14	0.676	-4.707	-0.676
13	0.676	-4.707	-0.676
12	0.704	-4.707	0.704
11	0.704	-4.707	0.704
10	0.704	-4.707	0.704
9	0.704	-4.707	0.704
8	0.759	-4.707	0.759
7	0.759	-4.707	0.759
6	0.759	-4.707	0.759
5	0.759	-4.707	0.759

Table 8 Results from method-2 for 196-bar steel lattice tower

Shape Alternate	Bot width (m)	Top width (m)	Optimized Weight(kg)
1	7.5	2.5	5230
2	4.5	1.0	2671
3	6.0	1.8	3692

4	5.3	1.4	3088
5	4.9	1.2	2841
6	4.7	1.1	2722

Table 8 shows that alternative 4 with TW=1.0 and BW=4.5 gives the most optimized weight of 2671 kg. There is a 51.1% saving in weight compare to initial design or alternate 1.

V. CONCLUSION

Shape optimization is a very efficient technique to determine optimal weight of steel lattice tower. Proposed work shows that by decreasing top and bottom width of tower to certain level helps in reducing the tower weight. As the bottom width decreases the force in member increases and capacity of member also increases. But after certain level, capacity will not increase dominantly as the forces and because of that more reduction in width leads to increasing in weight.

The conclusions achieved from present work are:

1. Integration with STAAD.Pro software to overcome its limitation of shape optimization leads to remarkable percentage of saving in weight.
2. The excel input interface is user friendly and customized to handle both size and shape of steel lattice tower in a smooth and continuous environment.
3. This seamless procedure reduces the post processing time and dumps all the results for user verification in a single file with well documented format.

In the present work, two methods are developed for shape optimization to cover the most values between the upper and lower limits in limited alternates. There isn't much difference in optimized weight between two methods. But method-2 takes only 6 alternates to get optimized weight.

VI. ACKNOWLEDGMENT

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