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Parametric Study on Effect of Wind and Seismic Loading on Spire

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Abstract: As per CTBUH norms all Spires are counted in official height measurements of buildings. Thus most of the modern high-rise building features tall spires on top of the building to get included in super tall category. Spire has a large ratio of height (H) to least horizontal dimension (D) that makes it a more slender and wind-sensitive than any other structures. Designing the slender stack like structure is laborious procedure and it is difficult to arrive at correct size for given loading and height. Also in past several years, many accidents and much damage were caused by high wind or wind induced vibrations in such structures. Therefore purpose of this paper is to develop the wind-resistance design (WRD) procedure for the slender, tapered spires subjected to wind-induced excitations. To study the effect of wind and seismic loading on different sizes of spire, A MATHCAD program was developed. A Spire of 100m height is analyzed for all the wind speeds of 33 m/sec, 39 m/sec, 47 m/sec, 50 m/sec and highest seismic zone in India i.e. Zone IV. After this study it is concluded that High to width ratios and

1. Introduction

Spire - A spire is a structure or formation, such as a steeple, that tapers to a point at the top. It is an architectural design feature rather than functional element and thus every spire is unique. All Spires are counted in official height measurements by the Council on Tall Buildings and Urban Habitat (CTBUH).

Typically, there are usually some functional equipment on the top of the structure such as a radio wave transmitter, a radar, lamps and lanterns The combination of the slender structural and the concentrated mass at the tip makes the structure fully aero elastic and unstable. For Burj Khalifa Vanity Height is 244 meter. This vanity height will be an impressive standalone skyscraper, If build in Europe, it will become continents' 11th tallest building. Another example is of Burj Al Arab, whose architectural height is 321 m and vanity Height is124 m. Occupiable to Non- Occupiable height ratio is as high as 39 percent. Most of the vanity height is formed by providing spires. Figure 1 shows world’s top ten building with vanity heights.

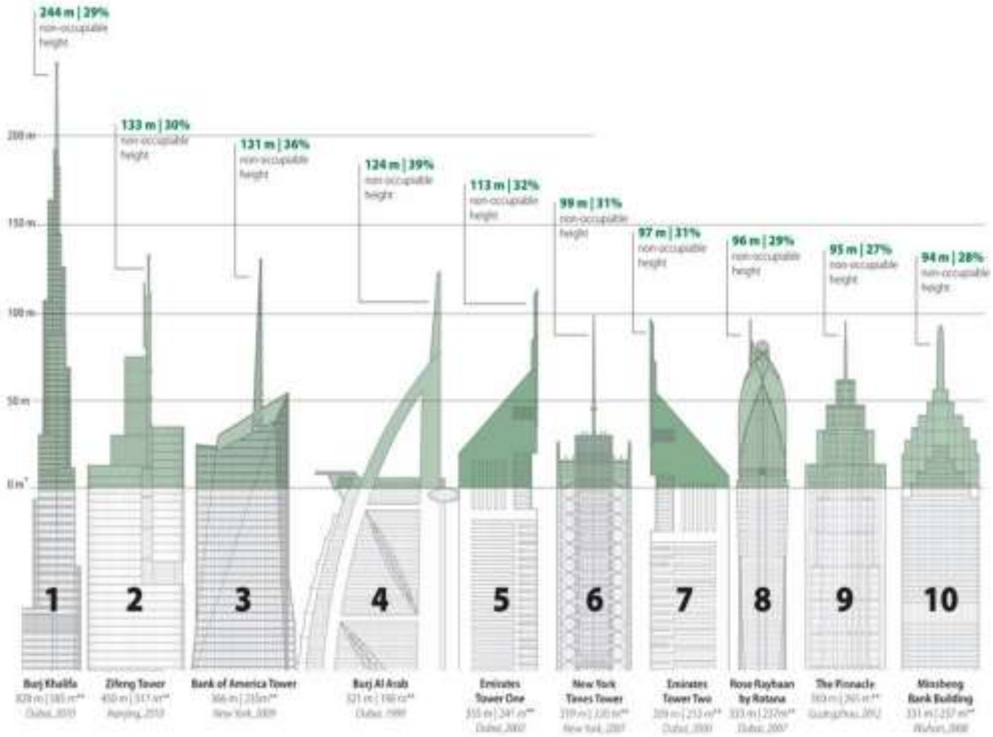


Figure 1. World Tallest Vanity Height Buildings

Self-supporting steel spires experience various loads in vertical and lateral directions. Important loads that steel spires often experiences are wind loads, earthquake loads apart from self-weight, loads from the attachments, imposed loads on the service platforms, antenna, aircraft warning lights etc. Wind effects on spires plays an important role on its safety as steel spires are generally very tall structures. The circular cross section of the spires subjects to aerodynamic lift under wind load. Again seismic load is a major consideration for spires as it is considered as natural load. This load is normally dynamic in nature. According to code provision quasi-static methods are used for evaluation of this load and recommend amplification of the normalized response of the spire with a factor that depending on the soil and intensity of earthquake.

There are many standards available for designing self-supporting industrial steel chimneys. Indian Standard IS 6533: 1989 (Part-1 and Part-2), Standards of International Committee on Industrial Chimneys CICIND 1999 (rev 1) etc. Geometry of a spire plays an important role in its structural behavior under lateral dynamic loading. This is because geometry is primarily responsible for the stiffness parameters of the chimney. However, the basic geometrical parameters of the spire (e.g., overall height, diameter at exit, etc.) are governed by architectural design.

In this study the main objective is to understand the behavior of the Spires for Various Diameter, Height, and Material and effect of wind and seismic loading on a 100m tall spire. The performance of Spire has been studied with the help of Structural Analysis Program (ETABS) models. For this Spires of different diameter, height and of different material are modelled analyzed using ETABS and MATHCAD program.

A parametric study is also performed to investigate response of 100m spire for different wind speed and seismic loading. It is observed that diameter, height and material of spire have significantly different effect of spire.

2 Numerical Data

This paper presents the analysis process and design of a steel Spire in accordance with Indian code. The finite element software ETABS which can perform non-linear analysis was used for the analysis purposes. Initially presented the assumptions used for modelling, i.e. geometry, support conditions and loading calculations. Follows the simulation methodology at the particular software package and finally are presented the results of the analysis. For the modelling, finite shell elements are used.
There are three different configuration take in this paper shown as below.

Also time period is calculated as per empirical formula in IS-1893-(part-4) and compare with time period obtained from free vibration analysis. A 3D rendered view is show in Fig. 2.

Geometry:
[A] Height considered: 100m
[B] Diameter and Thickness: as per table 1
Loading:
Four different wind speeds and one height seismic zone considered are considered in this paper shown as below,
[1] Wind Zone-1: 33 m/sec
[2] Wind Zone-2: 39 m/sec
[3] Wind Zone-3: 47 m/sec
[4] Wind Zone-4: 50 m/sec
[5] Wind Zone-4: 55 m/sec
[6] Seismic Zone: V

Spire descried in above section is analyzed and designed for all six wind zones and worst seismic zone-V. MATHCAD program is prepared to analyzed and design the Spire. Results obtained are presented in following section.

2.1 Description of Spire

The spire considered is of 100m height, single skin type with varying diameter as mentioned in table below.

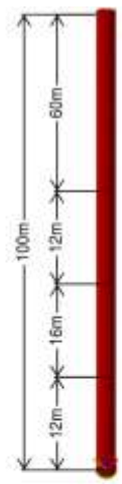


Figure 2. Spire Geometry

Table 1-Summery Spire Geometry

Part	Length (m)	Total Length (m)	Initial Thickness (mm)	Internal Model Diameter (mm)
1	18.00	0-12	18	4000 to 2000
2	14.00	12-28	14	
3	12.00	28-32	12	
4	8.00	40-100	8	

Spire consists of 4 individual pieces of cylindrical shells of different thickness. The spire will be assembled on site using the appropriate screw connections.

2.2 Software Analysis Model

In order to do dynamic wind analysis, spires time period and mode shapes needs to be calculated. Spire structure is modelled in finite element software ETABS using shell element and free vibrations analysis is carried out to obtain modal time period and mode shapes.

3. Results and Discussion

The analysis results in terms of Time period/mode shapes, moment and shear force, shale stress data is as presented below.

Table2. Time period comparison –Program calculated Vs Codal formula

Dia. (m)	Height (m)	Shell Thickness (mm)	Time Period (sec)	
			Program Calculated	Codal Formula
4	50	18	0.6	0.6
4	70	18	1.3	1.0
4	100	18	2.5	2.0
3	100	18	3.4	2.6
5	100	18	2.1	1.6

Table 3-Summery Result-Shear force and Bending Moment

Wind/Seismic Zone	Shear Force (kN)	% with V-55	Bending Moment (kN.m)	% with V-55
V-55	1583	-	398661	-
V-50	1294	81	328223	82
V-47	965	61	247926	62
V-39	731	46	189993	48
V-33	503	32	132493	33
Seismic Zone-5	0.25	2.52	964	2.5

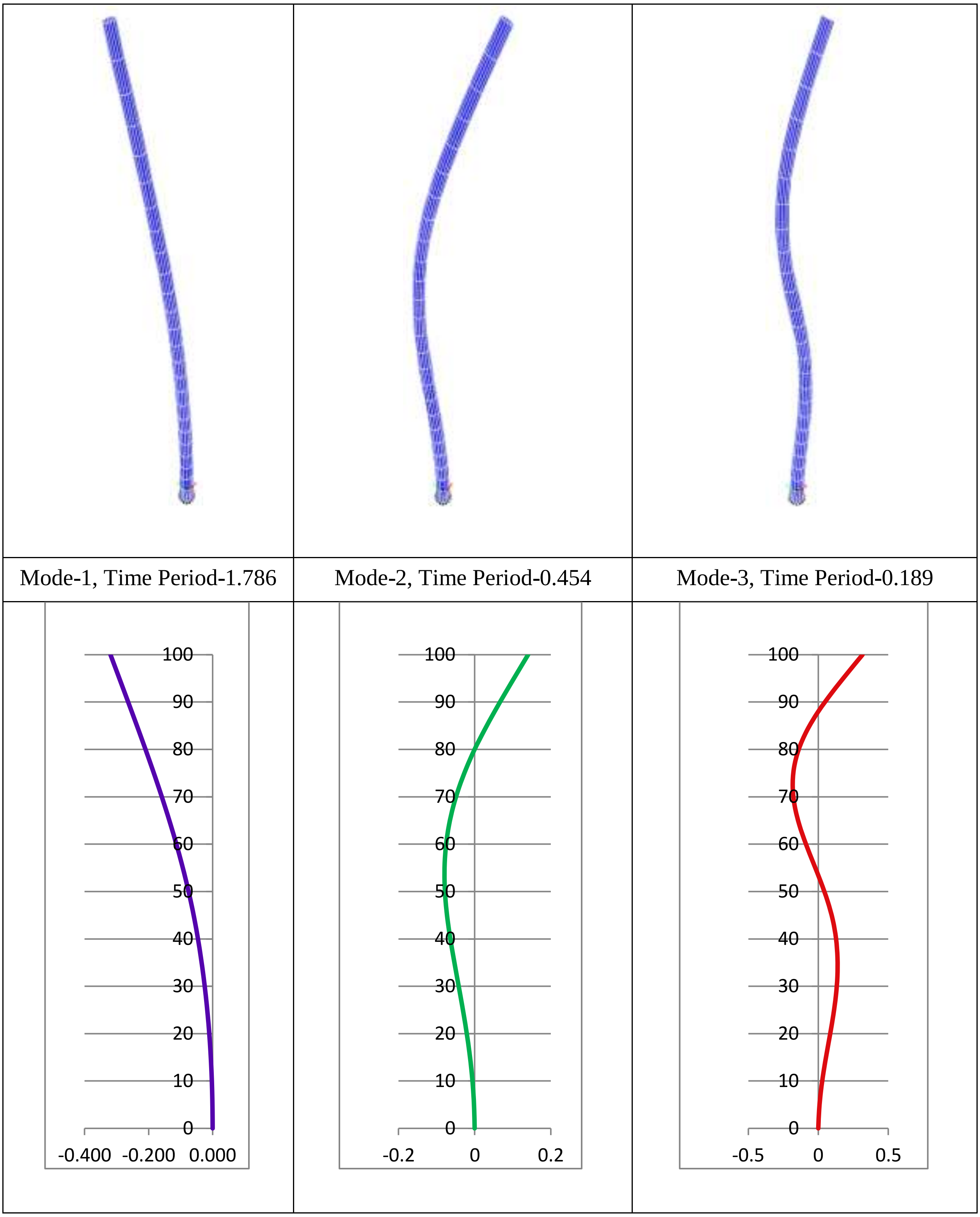


Figure3. Mode shapes and Time Period of spire from ETABS analysis

Table-4 Shear Force and Bending moment for wind speed V= 55 m/sec

Height	Static Wind Load		Dynamic Wind Load		Total	
	(P) N	M (kN.M)	(P) N	M (kN.M)	P (kN)	M (kN.M)
2	796	329440	787	69221	1583	398661
6	767	291000	661	54301	1428	345301
10	736	255690	547	42281	1283	297971
14	704	223380	443	32676	1147	256056
18	670	193950	360	25051	1031	219001
22	636	167270	295	19033	932	186303
26	601	143210	238	14327	839	157537
30	566	121620	187	10687	753	132307
34	531	102370	146	7897	676	110267
38	495	85310	113	5772	609	91082
42	460	70300	85	4165	546	74465
46	426	57200	65	2955	491	60155
50	391	45880	52	2045	444	47925
54	358	36189	41	1372	399	37561
58	324	27996	33	885	357	28881
62	291	21167	24	548	315	21715
66	259	15569	17	323	276	15892
70	228	11072	11	180	239	11252
74	197	7549	7	95	204	7644
78	167	4874	4	47	171	4921
82	137	2926	2	21	139	2947
86	108	1585	1	8	109	1593
90	80	735	1	2	81	737
94	53	261	0	0	53	261
98	26	52	0	0	26	52

Table-5 Shear Force and Bending moment for wind speed V= 50 m/sec

Height	Static Wind Load		Dynamic Wind Load		Total	
	(P) N	M (kN.M)	(P) N	M (kN.M)	P (kN)	M (kN.M)
2	658	272257	636	55965	1294	328223
6	634	240487	535	43905	1169	284393
10	608	211307	442	34185	1051	245493
14	582	184607	358	26419	940	211027
18	554	160287	291	20254	845	180542
22	526	138237	239	15388	765	153626
26	497	118347	192	11583	689	129931
30	468	100507	151	8640	619	109148
34	439	84597	118	6384	556	90982
38	409	70497	91	4666	501	75164
42	381	58097	69	3367	449	61465
46	352	47277	53	2389	405	49666
50	324	37918	42	1654	366	39572
54	295	29909	34	1109	329	31018
58	268	23138	26	716	294	23854
62	241	17494	19	443	260	17937
66	214	12867	14	261	228	13128
70	188	9150	9	146	197	9296
74	163	6238	6	77	168	6315
78	138	4028	3	38	141	4066
82	113	2418	2	17	115	2435
86	89	1310	1	6	90	1316
90	66	607	0	2	67	609
94	43	215	0	0	44	216
98	21	43	0	0	21	43

Table-6 Shear Force and Bending moment for wind speed V= 47 m/sec

Height	Static Wind Load		Dynamic Wind Load		Total	
	(P) N	M (kN.M)	(P) N	M (kN.M)	P (kN)	M (kN.M)
2	571	236142	550	47776	1121	283919
6	550	208592	464	37476	1013	246069
10	528	183282	385	29179	912	212462
14	504	160122	313	22550	817	182673
18	481	139032	256	17288	736	156321
22	456	119912	211	13135	667	133048
26	431	102662	171	9887	602	112550
30	406	87182	136	7375	542	94558
34	380	73382	108	5449	488	78832
38	355	61152	85	3983	440	65136
42	330	50392	66	2874	396	53267
46	305	41004	52	2039	357	43043
50	281	32886	43	1412	324	34298
54	256	25940	36	947	292	26887
58	232	20068	30	611	262	20679
62	209	15173	24	378	232	15551
66	186	11160	19	223	205	11383
70	163	7936	15	125	178	8061
74	141	5410	12	66	153	5476
78	119	3493	10	32	129	3525
82	98	2097	9	14	107	2112
86	78	1136	1	5	78	1142
90	57	527	0	2	58	528
94	38	187	0	0	38	187
98	19	37	0	0	19	37

Table-7 Shear Force and Bending moment for wind speed V= 44 m/sec

Height	Static Wind Load		Dynamic Wind Load		Total	
	(P) N	M (kN.M)	(P) N	M (kN.M)	P (kN)	M (kN.M)
2	500	206963	465	40963	965	247926
6	482	182813	391	32134	873	214947
10	462	160633	323	25020	786	185653
14	442	140343	262	19336	704	159679
18	421	121853	213	14824	634	136677
22	400	105093	174	11263	574	116356
26	378	89973	140	8478	518	98451
30	356	76413	110	6324	466	82737
34	333	64313	86	4673	419	68986
38	311	53593	66	3416	378	57009
42	289	44164	50	2465	339	46629
46	267	35936	38	1749	306	37685
50	246	28822	31	1210	276	30032
54	225	22734	24	812	249	23546
58	204	17587	19	524	222	18111
62	183	13297	14	324	197	13621
66	163	9780	10	191	173	9971
70	143	6955	6	107	149	7062
74	124	4742	4	56	128	4798
78	105	3062	2	28	107	3090
82	86	1838	1	12	88	1850
86	68	996	1	5	69	1000
90	50	462	0	1	51	463
94	33	164	0	0	33	164
98	16	33	0	0	16	33

Table-8 Shear Force and Bending moment for wind speed V= 39 m/sec

Height	Static Wind Load	Dynamic Wind Load	Total

	(P) N	M (kN.M)	(P) N	M (kN.M)	P (kN)	M (kN.M)
2	386	159572	346	30422	731	189993
6	371	140952	291	23865	662	164816
10	356	123852	240	18581	597	142432
14	341	108202	195	14360	536	122561
18	325	93952	158	11009	483	104960
22	308	81032	130	8364	438	89395
26	291	69372	104	6296	396	75667
30	274	58912	82	4696	356	63607
34	257	49586	64	3470	321	53055
38	240	41322	50	2536	290	43858
42	223	34052	37	1830	260	35882
46	206	27708	29	1298	235	29006
50	190	22223	23	899	213	23121
54	173	17529	18	603	191	18131
58	157	13561	14	389	171	13950
62	141	10253	11	241	152	10493
66	126	7541	8	142	133	7683
70	110	5363	5	79	115	5442
74	95	3656	3	42	98	3697
78	81	2361	2	21	82	2381
82	66	1417	1	9	67	1426
86	52	768	1	3	53	771
90	39	356	0	1	39	357
94	25	126	0	0	26	126
98	13	25	0	0	13	25

Table-9 Shear Force and Bending moment for wind speed V= 33 m/sec

Height	Static Wind Load		Dynamic Wind Load		Total	
	(P) N	M (kN.M)	(P) N	M (kN.M)	P (kN)	M (kN.M)

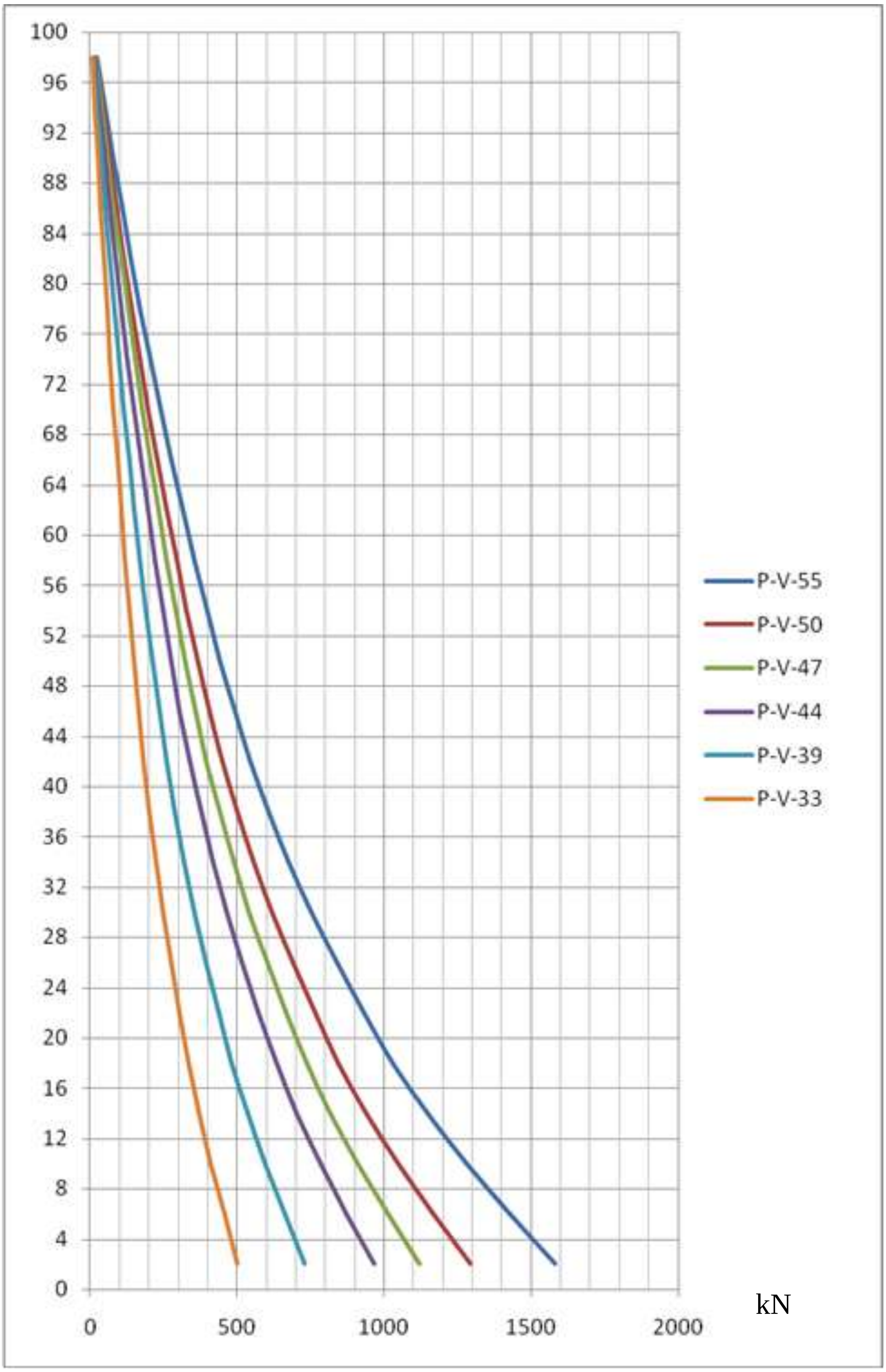
2	271	112101	232	20392	503	132493
6	261	99021	195	15997	456	115018
10	250	87001	161	12455	412	99456
14	239	76011	131	9625	370	85636
18	228	66001	106	7379	334	73380
22	216	56923	87	5606	304	62529
26	205	48734	70	4220	275	52954
30	193	41388	55	3148	248	44536
34	181	34836	43	2326	224	37162
38	169	29030	33	1700	202	30730
42	157	23923	25	1227	182	25150
46	145	19466	19	870	164	20336
50	133	15612	15	603	149	16214
54	122	12315	12	404	134	12719
58	110	9527	10	261	120	9787
62	99	7203	7	161	106	7364
66	88	5298	5	95	93	5393
70	77	3768	3	53	81	3821
74	67	2569	2	28	69	2597
78	57	1658	1	14	58	1672
82	47	996	1	6	47	1002
86	37	539	0	2	37	542
90	27	250	0	1	27	251
94	18	89	0	0	18	89
98	9	18	0	0	9	18

Table 10 Shear Force and bending moment for seismic zone -5

Height	**SEISMIC**	
	(P) N	**M (kN.M)**
2	40	964
6	40	922

10	39	881
14	38	841
18	37	802
22	36	764
26	35	727
30	34	691
34	33	655
38	32	621
42	31	587
46	29	554
50	28	521
54	26	490
58	24	458
62	23	428
66	21	397
70	19	367
74	17	336
78	15	306
82	12	274
86	10	241
90	8	206
94	5	166
98	3	116

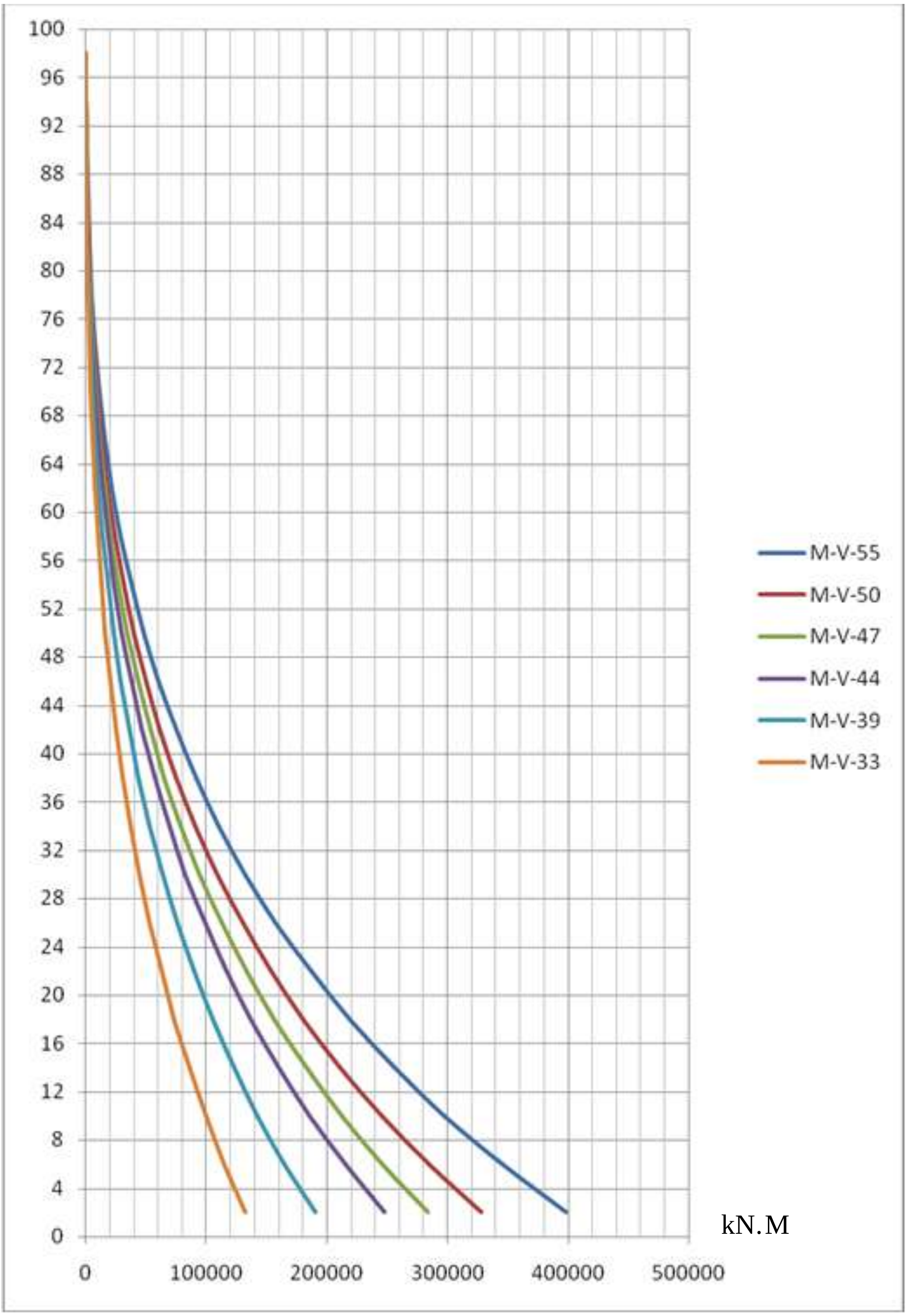
Height



Shear

Figure 4. Shear force distriution alog heigh of spire for differet loadig cases

Height



Moment

Figure. 5. Beding moment distriution alog heıgn oı spıre ıor different loading cases

Summary of permissible and actual stress along the height of the spire for different wind zones is summarise as bellow.

Table 11.Summary of Results-Permissible actual stress

Wind Speed		V-33	V-39	V-44	V-47	V-50	V-55
Height	Permissible stress	Actual Stress	Actual Stress	Actual Stress	Actual Stress	Actual Stress	Actual Stress
4	89.7	9.2	9.2	9.3	9.3	9.3	9.4
8	91.7	9.4	9.4	9.5	9.5	9.5	9.6
12	93.8	9.6	9.6	9.7	9.7	9.7	9.8
16	96	13.4	13.4	13.5	13.5	13.6	13.6
20	79.3	13.7	13.7	13.8	13.8	13.9	13.9
24	81.4	14	14	14.1	14.1	14.2	14.3
28	83.6	14.3	14.4	14.4	14.5	14.5	14.6
32	85.2	17.9	18	18.1	18.1	18.2	18.3
36	74.6	18.3	18.4	18.5	18.6	18.6	18.8
40	76	18.8	18.9	19	19	19.1	19.2
44	77.6	34.7	34.9	35.1	35.2	35.3	35.6
48	48.7	35.6	35.8	36	36.1	36.3	36.5
52	49.8	36.6	36.8	37	37.1	37.3	37.5
56	51	37.6	37.8	38	38.2	38.3	38.6
60	52.3	38.7	38.9	39.1	39.3	39.5	39.7
64	53.6	39.8	40	40.3	40.4	40.6	40.9
68	54.9	41	41.3	51.5	41.7	41.9	42.2
72	56.4	42.3	42.6	42.8	43	43.2	43.6
76	57.9	43.6	43.9	44.2	44.4	44.7	45
80	59.5	45.1	45.4	45.7	45.9	46.2	46.6
84	61.9	46.6	47	47.3	47.5	47.8	48.2
88	62.9	48.3	48.7	49	49.3	49.5	50
92	64.8	50.1	50.5	50.9	51.1	51.4	51.9
96	66.8	52	52.4	52.9	53.1	53.4	53.9
100	68.9	54.1	54.5	55	55.3	55.6	56.2

Summary and Conclusions

The economic growth, rapid urbanization and race to go high is lading to slender, tall and complex geometry of spires. The slender nature of the spire and its low level of intrinsic damping result in a structure which is susceptible to dynamic excitation from the wind. This imposes limitations on height of the spire. It has been found that, in its unmodified form – without any additional damping, the spire would be expected to vibrate excessively. These vibrations would give rise to unacceptably high fatigue stresses and structural failure could be expected. Excessive vibrations will not occur if additional damping is provided in the spire by means of damping devises.

It is found from analysis that,

1. Wind calculation is largely depends on dynamic prosperities of Spire. So study of validity of codal formulas for time period is important. From the study it found that codal formula gives leaser time period than program calculated time period. It means if codal formulas are used for wind load calculations, wind loads will be underestimated.

2. Seismic forces for most sever zone are much lower than lowest wind zone. It is is not governing the design.

3. Dynamic prosperities of spire are very sensitive to diameter of spire and thus selecting proper diameter of spire is key to optimum design.

4. This study gives guideline for choosing proper height of spire if that is choice of designer.

In past many failures of engineered stack like structure are observed because of fatigue. Some work is already done but yet a generalized well established method for wind induced fatigue design needs to be developed.

Also there is scope for further work on application of damping devices specially tuned mass dampers to avoid the fatigue failures. Also it's been observed that theoretical performance of TMD differs from actual performance and furthers work can be done to minimize this deviations.

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