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THE UNIVERSITY OF ALABAMA

PRELIMINARY DESIGN, FEASIBILITY AND COST EVALUATION OF 1 TO 15-KILOMETER HEIGHT STEEL TOWERS

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Introduction

Design and construction of tall towers is an on-going research program of NASA. The agency has already done preliminary review in this area and has determined that multi-kilometer height towers are technically and economically feasible. The proposed towers will provide high altitude launch platforms reaching above eighty percent of Earth's atmosphere and provide tremendous gains in the potential energy as well as substantial reduction in aerodynamic drag. NASA has also determined that a 15-KM tower will have many useful applications in: (i)Meteorology,(ii)Oceanography, (iii)Astronomy, (iv)High Altitude Launch, (v)Physics Drop Tower, (vi) Biosphere Research, (vii) Nanotechnology, (viii) Energy/Power, (ix)Broadband Wireless Technology, (x)Space Transportation and (xi)Space Tourism.

Research Plan and Findings

In order to determine structural feasibility of constructing a 15-Km tall tower, it was decided to use the following twelve-step design process: (i)select appropriate software, (ii)develop trial model, select materials, (iii)preliminary design and weight calculations for all members, (iv)revise member sizes, if needed, (v)check structural stability for self weight, (vi)revise model, if needed, (vii)check stability for self weight, (viii)detailed design of each component, (ix)check for wind loads, (x)check for earthquake loads, (xi)check for equipment vibrations and (xii)check for temperature variations.

This process first starts with a design that is just sufficient to support its own weight. The process allows for revision of design for all natural hazards and other loads in a sequential order. It may be noted that response of a tower to wind, earthquake, equipment thrust etc., can only be calculated if all individual components of tower are completely designed. This approach for designing a tower first for own self weight and subsequently strengthening for all external loads allows for a least weight design that can be accomplished using structural design software. SAP2000 structural design software was used for constructing the model. SAP 2000 has been used for designing many important structures, e.g., Petronas Towers, Malaysia, Eiffel Tower-II, Nevada, Las Vegas and Safeco field, Seattle, Washington and many other structures throughout the world. This software can generate extremely large structures having millions of members.

A 50mx50mx200m module (Figure1) was used to develop a 15-KM tall steel tower. The module is comprised of eight beams each 50m long, four columns each 200m long, four horizontal braces each 31m long and twelve diagonal braces each 61m long. Structural members of such lengths are not uncommon and can be easily constructed in the form of a 2D or 3D truss using existing steel sections produced by the steel industry. The module has an internal spatial node that connects twelve braces to four 200m long columns (Figure1). This 3D bracing allows for increased shear strength in all three axes and also braces 200m long columns at every 50m. In order to reduce steel weight of beams and braces, it is recommended that trusses be used for construction. Calculations were made to find number of modules needed in each kilometer and then module was replicated in fifteen different files; one for each kilometer of tower. The replication process allows tall 200m meter sides of the module to be supported by four braces at 90 degrees to each other at every 50 meters (Figure 2). Such a bracing system for columns will substantially reduce buckling effects.

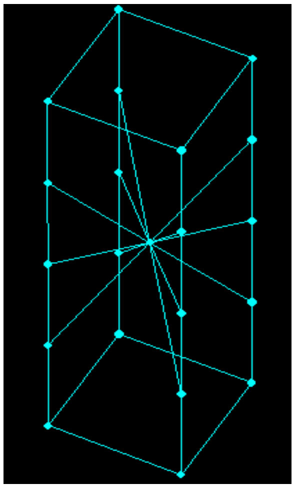


Figure 1

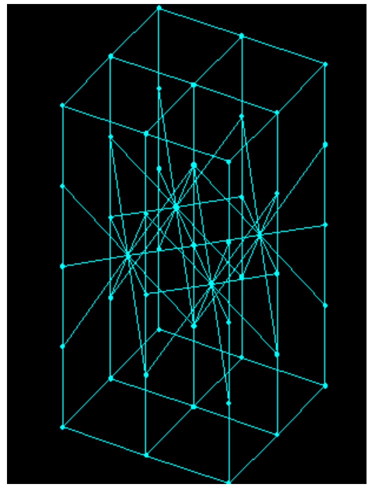
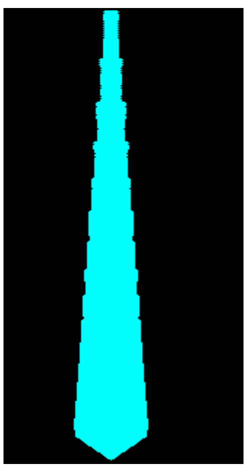
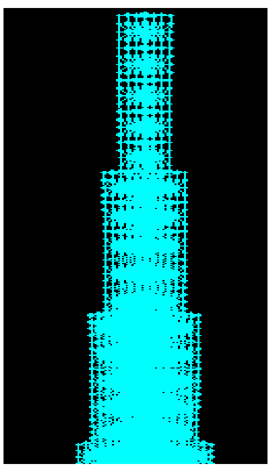


Figure 2

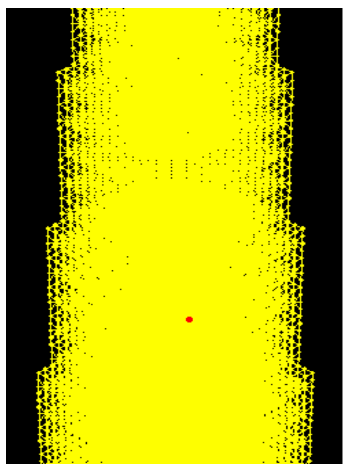
All fifteen files were then combined and a 3D view of the resulting tower is shown in Figure 3. Figures 4-6 show 3D views of particular parts of tower for visual comparison. It was noted that lowest kilometer has same amount of steel that is used in top eleven kilometers combined. This tower has 147,899 joints and 505,984 members.



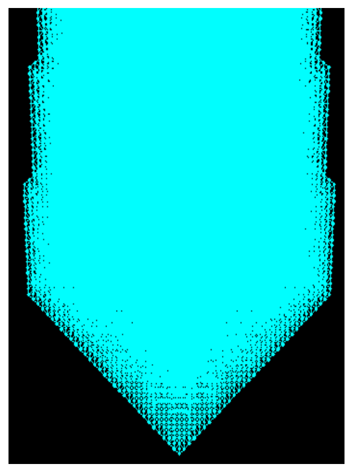
KM1-15
Figure 3



KM1-4
Figure 4



KM 7-10
Figure 5



KM13-15
Figure 6

The structural data from the software was included in the basic analysis of the tower (Table 1). Self weight of Individual braces and beam elements were assumed as follows: 50kg/m for a 50-long beam, 30kg/m for a 31m long horizontal brace, and 60 kg/m for a 61m long diagonal brace. These self weights are quite comparable to self weights of similar trusses used in the steel industry for 2D or 3D trusses as per Steel Joist Institute data.

No	Km	Col. Grid Size	No. of Cols.	Total Col. Length ms	No. of Beams	Total Beam Length ms.	No. of Bracing Nodes	Total Beam wt. kg.	No. of Hoz. Braces	No. of Diag. Braces	Total Hoz. Brace Length(ms.)	Total Diag. Brace Length	Total Wt. of Hoz. Braces
1	14-15	4x4	16	16,000	120	6,000	45	300,000	180	360	6,363	22,043	190,890
2	13-14	6x6	36	36,000	300	15,000	125	750,000	500	1,000	17,675	61,230	530,250
3	12-13	8x8	64	64,000	560	28,000	245	1,400,000	980	1,960	34,643	120,011	1,039,290
4	11-12	10x10	100	100,000	900	45,000	405	2,250,000	1,620	3,240	57,267	198,385	1,718,010
5	10-11	12x12	144	144,000	1,320	66,000	605	3,300,000	2,420	4,840	85,547	296,353	2,566,410
6	9-10	14x14	196	196,000	1,820	91,000	845	4,550,000	3,380	6,760	119,483	413,915	3,584,490
7	8-9	16x16	256	256,000	2,400	120,000	1,125	6,000,000	4,500	9,000	159,075	551,070	4,772,250
8	7-8	18x18	324	324,000	3,060	153,000	1,445	7,650,000	5,780	11,560	204,323	707,819	6,129,690
9	6-7	20x20	400	400,000	3,800	190,000	1,805	9,500,000	7,220	14,440	255,227	884,161	7,656,810
10	5-6	22x22	484	484,000	4,620	231,000	2,205	11,550,000	8,820	17,640	311,787	1,080,097	9,353,610
11	4-5	24x24	576	576,000	5,520	276,000	2,645	13,800,000	10,580	21,160	374,003	1,295,627	11,220,090
12	3-4	26x26	676	676,000	6,500	325,000	3,125	16,250,000	12,500	25,000	441,875	1,530,750	13,256,250
13	2-3	28x28	784	784,000	7,560	378,000	3,645	18,900,000	14,580	29,160	515,403	1,785,467	15,462,090
14	1-2	30x30	900	900,000	8,700	435,000	4,205	21,750,000	16,820	33,640	594,587	2,059,777	17,837,610
15	0-1	32x32	1,024	1,024,000	9,920	496,000	4,805	24,800,000	19,220	38,440	679,427	2,353,681	20,382,810

Table 1

No	Total Wt. Of Diag. Braces	Total Col. Wt. Prov.	Total Steel Wt/ Km.	Cum. Total Steel Wt.	Factored Total Steel Wt./ Km.	Cost of Structural Steel ($)	Col. X-Area Needed m2	Col. Wt. Needed Kg.	Col. X-area Needed in2	X-Area per Col. in2
1	1,322,568	635,401	2,448,859	2,448,859	3,428,403	1,346,872	0.08	643,201	126.92	7.93
2	3,673,800	2,715,808	7,669,858	10,118,717	14,166,204	5,565,294	0.34	2,657,715	524.42	14.57
3	7,200,648	7,103,114	16,743,052	26,861,769	37,606,477	14,773,973	0.90	7,055,334	1,392.16	21.75
4	11,903,112	15,875,104	31,746,226	58,607,995	82,051,193	32,234,397	1.96	15,393,588	3,037.47	30.37
5	17,781,192	29,667,569	53,315,171	111,923,166	156,692,432	61,557,741	3.74	29,396,997	5,800.63	40.28
6	24,834,888	52,356,071	85,325,449	197,248,615	276,148,061	108,486,738	6.59	51,808,015	10,222.78	52.16
7	33,064,200	86,170,096	130,006,546	327,255,161	458,157,225	179,990,339	10.94	85,954,673	16,960.62	66.25
8	42,469,128	138,132,347	194,381,165	521,636,326	730,290,856	286,899,979	17.44	137,009,542	27,034.79	83.44
9	53,049,672	211,472,644	281,679,126	803,315,452	1,124,641,633	441,823,499	26.86	210,993,516	41,633.35	104.08
10	64,805,832	318,554,080	404,263,522	1,207,578,974	1,690,610,564	664,168,436	40.37	317,174,694	62,585.08	129.31
11	77,737,608	468,987,896	571,745,594	1,779,324,568	2,491,054,395	978,628,512	59.49	467,345,605	92,216.88	160.10
12	91,845,000	680,804,567	802,155,817	2,581,480,385	3,614,072,539	1,419,814,212	86.31	678,034,538	133,790.13	197.91
13	107,128,008	970,488,900	1,111,978,998	3,693,459,383	5,170,843,136	2,031,402,661	123.49	970,099,576	191,420.55	244.16
14	123,586,632	1,392,213,960	1,555,388,202	5,248,847,585	7,348,386,619	2,886,866,172	175.49	1,378,627,539	272,031.50	302.26
15	141,220,872	1,942,258,987	2,128,662,669	7,377,510,254	10,328,514,356	4,057,630,640	246.66	1,937,727,975	382,353.49	373.39

Table 2

The data presented in Table1 and Table2 is based on use of A913 high strength low alloy steel with a density of 7856kg/m^3, Load Factor of 1.4 and Resistance Factor of 0.85. It may be noted that most of the steel columns will need special fabrication and therefore can be designed and built for slenderness ratio of less than 20. AISC permits 85% of yield stress as critical failure stress for columns with slenderness ration of less than 20. Therefore buckling of columns was excluded in this preliminary analysis. The analysis indicates that for a 15-KM tower we need 7,377,510,254 KG of steel. This amount of steel would cost $4,057,630,640 at the current market rate of $0.55 per KG. It may also be noted that steel requirement increase exponentially and the requirements for a 5-KM Tower are substantially lower (Figure 7 and 8).

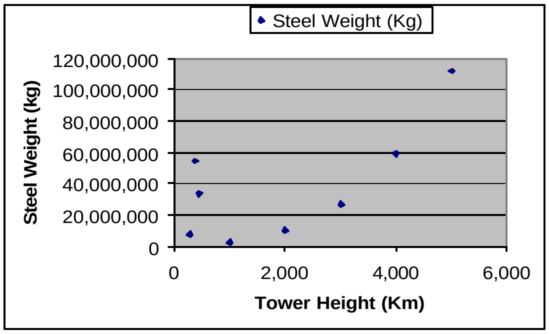


Figure 7

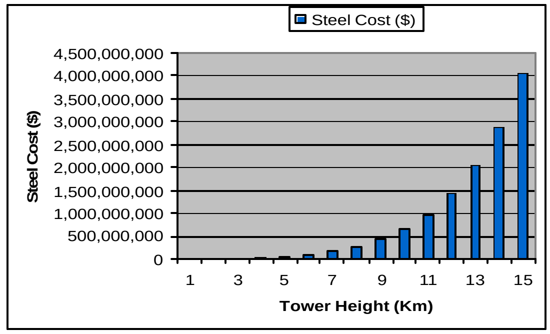


Figure 8

Conclusions

Based on the tower geometry and other assumptions, it is concluded that construction of a 15-KM self supporting steel tower is possible. The material costs, however, may exceed four billion dollars. The cost of substructure and labor involved are extremely difficult to estimate but will definitely add additional 4 billion dollars. These calculations indicate that a 15-KM tower may be cost prohibitive. As columns in lower stories become extremely large special design and fabrication techniques may have to be explored. However, a 4 to 5-KM tall tower appears to be cost effective and can be built using existing material sizes with little or no need for specialized design and fabrication. The design considered in this analysis did not increase the number of columns for subsequent lower stories and it is suggested that alternate designs with a higher rate of increase of column should be explored. NASA may want to limit future research on tall towers to be preferably within 1-5 KM range and definitely not more than 10-Kilometers.
Please send your input to author at shankerajay@hotmail.com.

Recommendation for Future Research

This research is the first attempt to approximately quantify the steel requirements of 1-15KM tall steel towers. Future research should address labor and installation costs that include advanced robotic construction techniques. Materials, e.g., composites, aluminum and concrete should also be explored for reducing cost. A triangulated form of construction should also be explored as it may reduce steel requirements. As the tower files become extremely large (54MB for this example) a faster computer with 3-4MB of RAM should be used to do analysis. Number of columns should be increased as a faster rate as we approach lower parts of the tower. Effects of wind, earthquake, temperature changes and equipment thrust and vibrations should be included to modify the structure. Carbon nanotube materials and other forms of construction, e.g., inflatable structures should also be explored

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