Structural Design of the Tall Tower

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The challenge of building tall structures has lured people like me into the profession of structural engineering for a long time. Managing our gravitational well in order to elevate usable space above the surface of the Earth is harder than it looks. And it's not just gravity holding us down. The ebbs and flows of that thin sheet of fluid that is our atmosphere and ground shifts caused by tectonic movement create a difficult physical environment for building tall.

Despite training for the moment for my entire career, I was a bit stunned when Neal Stephenson asked me if a 20 km tall tower could be built. As a structural engineer I was still basking in the glow of the achievement of the Burj Khalifa—the current world's tallest building standing 830 m tall. The notion of creating a structure 25 times taller than the tallest structure in the world was at odds with the gradual increments that have long characterized the evolution of tall buildings and long bridges. What? Do that next?

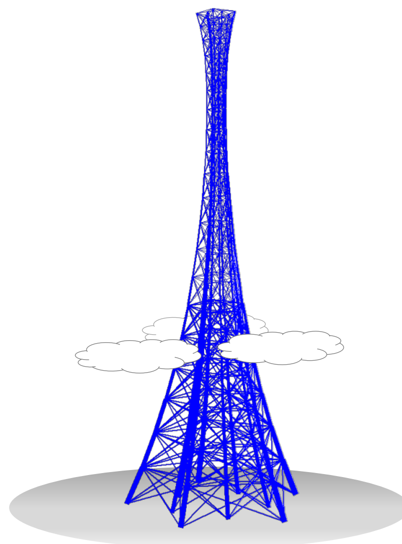
Neal had been inspired by a speculative paper from about a decade earlier—written by scientist and science fiction writer Geoffrey Landis—that claimed a tower 15 to 25 km high could be built from steel. A tower of that height could double the payload to orbit of a conventional rocket, he argued. The proposal that Landis had made appears to have been based on the assumption that, at a given level, the structure need only provide vertical resistance to the accumulated weight of the tower and payload above it. Engineers basically manage force by increase resisting area to reduce stress. In essence, Landis had proposed a vertical column with cross sectional area large enough to keep the stress below the available strength of the material. The weight of the resisting material gets to be a large part of the load. If you add material to reduce stress you also add to the cause of that stress. The result is an exponential cascade of material from top to bottom. Steel is strong, but it is also heavy. This simple model suggests that the total weight of material required is $W = P(e^{\mu} - 1)$, where P is the payload at the top and $\mu = \rho h / \sigma$ is the ratio of the density times height to the strength of the material—a sort of characteristic number of the tall tower. So the weight of material is basically the payload multiplied by a factor that gets exponentially large as the height goes up. If you want to carry no load then you need no material. One key engineering challenge is to figure out what P should be. How much does Cape Canaveral weigh? The Burj Khalifa weighs 0.5 million tonnes empty. So to put the Burj Khalifa up on top of the tower would require about 5 million tonnes of the best steel you can get. The upshot of these "back of the envelope" figures is that the 20 km tower seems very doable. That might have been the inspiration of Landis's comment that the tower would be easy to achieve with today's materials.

The simple Landis model gives us a baseline number for what it might take to realize the tower, but it ignores the lateral forces caused by wind and the possibility of the tower buckling under its own weight. To have lateral stability the tower must have bending resistance. Now, not only is the area of material important, so is its distribution. The tower needs girth.

The main design problem is to determine the shape that minimizes the weight of material while providing adequate strength. We narrowed the design space by considering symmetric towers with circular plans because we had no good reason to assume that the wind would blow in a particular direction, but we allowed for the possibility that the radius of the tower could vary with the height. The tower would need to have a wide base to resist overturning, but should be narrower in the upper reaches to project a smaller area in the most intense winds.

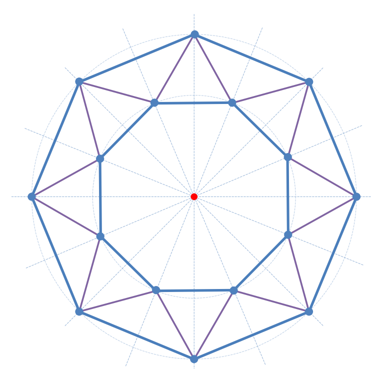
The tall tower will extend into the jet stream—a wind environment far more demanding than any we design for on the surface of the Earth. Some data indicated that the wind velocity would peak at about 90 m/s at about two thirds of the way up from the base. The wind load model we adopted was fairly primitive, but included the variation of air density with height along with the variation of wind velocity. The force on the structure is the accumulation of the forces on each member of the structure. We sought a design that would catch the least wind, narrowing the neck of the tower in the most intense portion of the jet stream.

While some data are available on winds in the troposphere, it is generally not tailored to what a structural engineer needs to know. It is a basic truth of structural engineering that the structure will be exposed to the environment all of the time and probably for hundreds of years. There is no instant in all of that time that can be passed off as insignificant. The structure will have to bear it all and while the most intense loads might be rare, the likelihood of occurrence over the lifetime is significant and the consequence of being unable to meet the demands that nature serves up are dire.



To advance the design at a more refined level, we developed a reticulated model, grafted some of the shape assumptions from the simpler models, and added a simple optimization engine to keep the stresses below allowable levels for the material for each member. Even at this more refined level the model blurs many details. Neal had always imagined that the tower would need to have a "fractal" structure (like the Eiffel Tower). What that means is that the tower would comprise mega-members that would be made of smaller members (laced together in some sort of trussed configuration) and those smaller members would be made of members smaller yet. And so on until the members that you actually build with can actually be made (and lifted). One consequence of the fractal geometry is that not all of the material can be oriented in the optimal direction (e.g., vertical for vertical loads). Some of the material must be invested in bracing—the members must be tied together to transmit the forces of wind and gravity over the structure so that it can mobilize its structural resistance.

For the reticulated model we created a design that would allow a variable number of levels (like stories in a tall building except that each "story" in the tower is about the height of the Burj Khalifa) and a variable number of primary columns. We imagined the plan as concentric circles to give the tower a "wall thickness." At each level we created a truss ring that would transfer the loads at that level across all of the primary columns. The tower radius builds from a broad base (covering about 25 km^2 in recent designs); it tapers in the region of the jet stream and blossoms at the top to provide usable real estate. With a four-sided geometry the tower looks a lot like the Eiffel Tower (except for the flair at the top)—an inevitable consequence of the forces it must resist. For a given geometry we optimized the structure with an algorithm that simply put more material in areas where stresses were high and took away material from areas where the stresses were low. Hence, for a given geometry we could find the minimum amount of material required. A recent design suggests that we are in the neighborhood of 250 million tonnes of steel—a healthy fraction of world annual steel production.



The truss geometry provided a sort of "level-zero" layout of the fractal structure, but it did not explicitly model all of the additional fractal levels. For a tower with twenty levels there are about a thousand members. In a fractal structure each member replicates the geometry of the larger structure. Therefore, modeling at the next level of the fractal geometry would have a million members. One more fractal level would give a billion members. An investigation of the fractal nature of the structure revealed an important result—as the number of fractal levels increases the wind area of the members also increases unfavorably. While the fractalization allows the wind to "blow right through the structure" it traps wind on the way in and on the way out. The fractalization thins out the members but there are more of them and member stability requirements at the smallest level determine the exposed fractal area. The implication of this observation is that the main members would likely need to be enclosed in a sheathing to reduce the wind drag. The demands of the wind have fostered interesting speculation about whether or not it is possible to use aerodynamics to help mitigate the wind induced stresses. The wind could be employed as a passive system that mobilizes uplift when needed most.

At present the tower is conceptualized only at the level of broad brush strokes. The design of the tower has opened areas of fundamental inquiry into the nature of the jet stream and the nature of air flow around and through fractal structures. Many design questions remain. A method of construction is yet to be devised—it is difficult to imagine the traditional steel worker toiling at minus 60 Celsius in air so thin that a Nepali Sherpa would be left gasping. That paradigm will need to give way to a robot-based approach (or perhaps even more clever strategies). The foundations of this enormous structure will bring unprecedented challenges to geotechnical engineers. What about transportation? Imagine a train system spiraling around the exterior of the tower. Imagine an airport two kilometers above the surface of the Earth.

It is evident that the lightest structures have the coarsest fractal geometry. But the horizontal bracing members at the first level of a twenty-level tower with five sides are longer than the longest bridge span in the world today. Each member will be a monumental record-shattering design in its own right. We still have to figure out how to do that. And the details are mind-numbingly complex. The basic geometry of how the members come together to form a structural joint capable of transmitting the huge forces is a challenge. A strategy for joining the members to form the structure is not solved and is made more complicated by the very cold temperatures in the upper reaches of the structure. And questions about the integrity of the structure in the event of an attack or natural disaster remain unresolved. The ordinary strategy of adding redundancy brings enormous additional weight.

This journey to wrap my mind around the possibility of the tall tower has caused me to recalibrate nearly everything I have ever thought about building tall. Along the way, every time my engineering sensibilities said "no" I would struggle back to "why not?" The idea is just big enough to keep you from trying to extend what has been done just a little bit further—it is an idea big enough to drive new thought.

Is the *Tall Tower* possible? Yes, theoretically. Is it feasible? Who is to say? That is more a question of human will than anything else. We still await the flood of ideas for use of the tower, and therein lies the case for building it. Oh, and by the way, if you put more stuff on the tower we will need to increase the size a bit.