Dyson Bursary Project Summary

Solar Updraft Towers for Greenhouse Gas Removal

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Introduction

Global warming poses a considerable threat to mankind, making removal of greenhouse gases from the atmosphere a desirable goal. Solar updraft towers (consisting of a greenhouse collector area and tall chimney) make use of natural convection to help drive considerable air flow and could form part of a greenhouse gas removal system.

The focus of this project was the modelling of a pre-stressed hyperboloid cable-net tower that could form the tower part of the solar updraft tower. This consists of a central mast and exterior cable-net formed of straight "generator" cables, possibly connected where they intersect, which delineate the hyperboloid form. The cables are suspended from a "bicycle wheel" that forms the top rim and pre-stressed against the central mast to prevent them going slack as the tower displaces, preserving the stiffness. It is likely the cables would be made of Kevlar or steel. The cable-net will be connected to the central mast via multiple other bicycle wheels up its height to brace the mast against buckling. This structural form is well suited to use as a solar updraft tower as the exterior cables (with a non-structural fabric covering) naturally form the chimney wall, and the hyperboloid shape helps accelerate the airflow as occurs in cooling towers. An example of a similar hyperboloid tower in Germany is shown in Figure 1.

Approach

Various structural models were developed, both computational and analytical, in order to gain an understanding of the structural behaviour. A rough estimate of the cable and the central mast sizing could then be made, a construction sequence suggested, and an assessment of the overall feasibility made.

Figure 1: A similar cooling tower in Germany, but with vertical and horizontal instead of inclined cables.

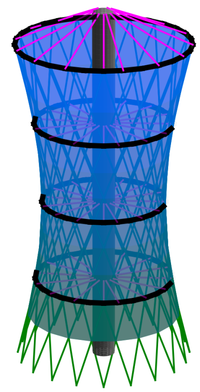

Figure 2: An impression of the finished structure.

For understanding the structural behaviour a multi-pronged approach was conceived, consisting of algebraic analysis, computational modelling, and laboratory testing. Each branch provides an opportunity to validate the results from the other two branches. Covid-19 prevented any laboratory testing, so further computational modelling was performed instead. Dynamic relaxation was chosen as the primary method of computational modelling. It involves simulating dynamics to allow the structure to "relax" to the equilibrium configuration. It is explicit, thus easily code-able, easily implemented for novel situations, and is well suited for tension structures where form-finding is typically required. It can also be used to model beams/columns and so was used investigate the buckling behaviour of the central mast of the tower in addition to the lateral stiffness of the tower as a whole. Additionally, matrix methods were used to provide a secondary approach for modelling the lateral stiffness.

Main results

Lateral stiffness

An algebraic analysis gave the equation governing the lateral stiffness of a pre-stressed hyperboloid tower, with cables not connected at intersections and the top ring free to rotate, as

$$\frac{P}{EAN} = \sin^2(\beta Q)\left(\frac{R_b}{H}\right)^2 \frac{u}{H}$$

where P is a horizontal load applied to the top of the tower, EA is the cable axial stiffness, N is the number of cables in one direction, βQ is the angular offset of a cable, R_b is the tower bottom radius, H is the tower height and u is the tip displacement. This agreed very well with both DR and matrix computational modelling, as illustrated by the overlapping lines in Figure 3.

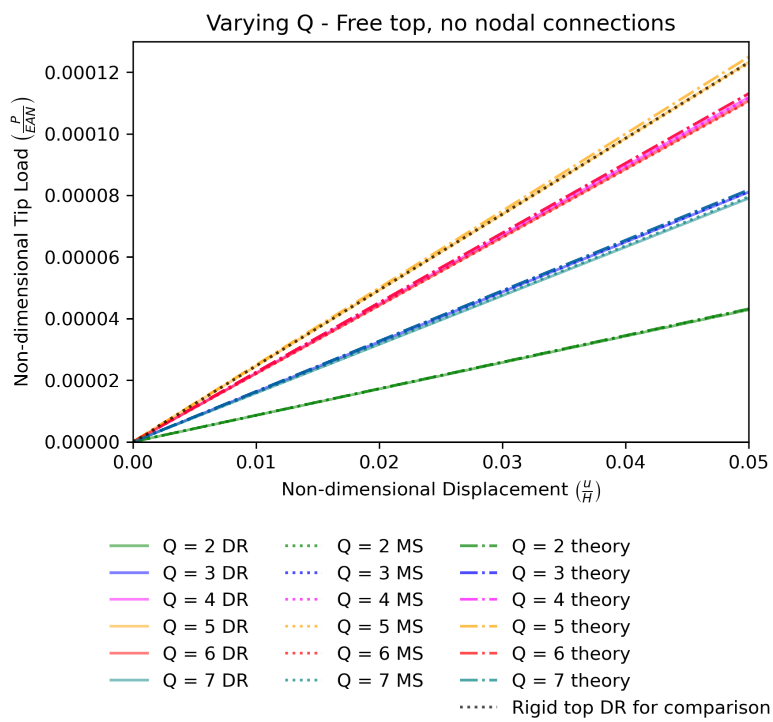

Figure 3: Comparing the stiffness for a free top with no nodal connections as predicted by different methods.

Buckling

An algebraic analysis for a global buckling mode, with the tower and cables bowing out in a sinusoid, gave the critical buckling load of the mast as

$$P_{crit} = P_E + \lambda P_{pre-stress} + \mu EAN \tan^2 \Theta$$

where P_E is the Euler buckling load of the mast, $P_{pre-stress}$ is the total pre-stress force in the cables, EA is the cable axial stiffness, N is the number of cables in one direction, Θ is the inclination of the cables to the vertical, and λ and μ are factors to account for the discreteness of the bracing rings. This suggested that the pre-stressed cables provide adequate bracing such that local buckling of the mast in-between the bracing rings is the critical buckling mode. A DR buckling test was performed to validate this result, with a fourier analysis extracting each buckling mode from the mast. There was very close agreement between the analytic solution and DR results.

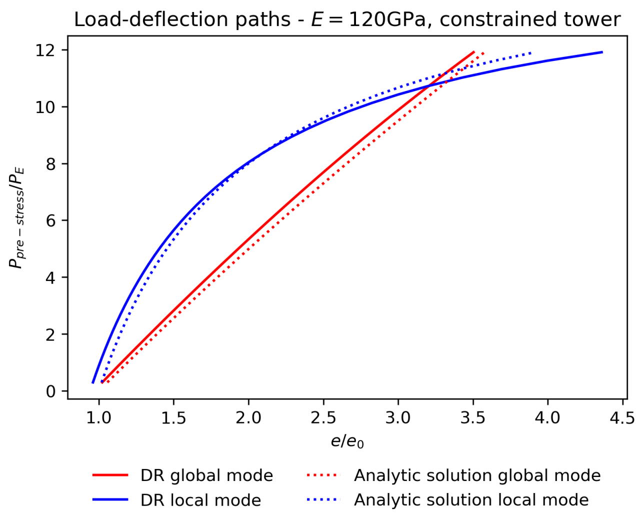

Figure 4: DR tower buckling results showing the amplitude of each buckling mode as they grow with increasing pre-stress load

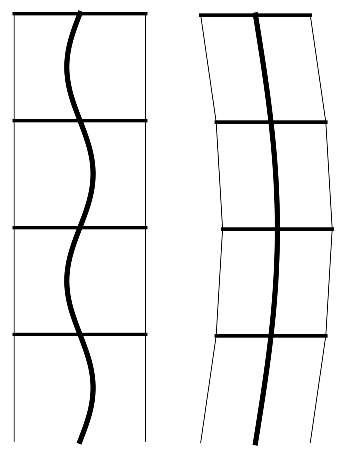

Figure 5: The local and global buckling modes

Conclusions

Computational modelling and algebraic analysis were used to gain an understanding of the structural behaviour of the tower, both regarding the lateral stiffness of the tower and the buckling of the central mast. These results were then used to make a preliminary estimate of the volume of material required for both the cables and the mast, which suggested the hyperboloid tower was competitive with a "traditional" reinforced concrete tube design.