<u>**The Dubai Expo Shade Structures and How to Flex with the Flow**</u>

Simple Basis, Complex Execution

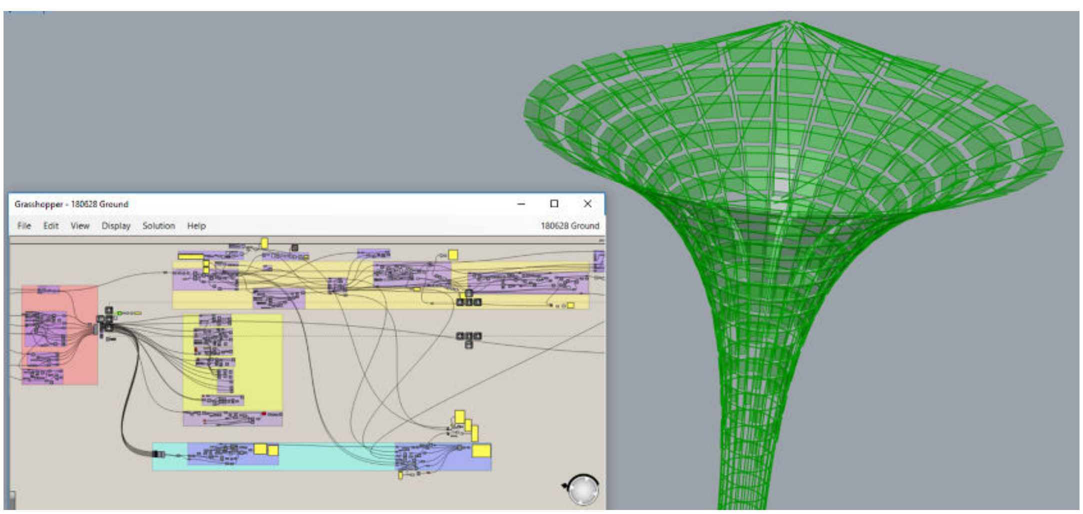
The idea behind the Dubai Expo Sunshades was a simple, if initially contradictory, one: create shade without creating a large, top heavy structure that would catch the wind . This would reduce the wind loads on the structure and therefore reduce the amount of structure needed. In a seismic zone less structure also means less mass and less horizontal acceleration loads which in turn reduces the structure further. Less structure is also less foundations, less materials, less cost, less carbon. But how do you make an effective shading canopy, with large flat surfaces to block the sun, without letting it catch the wind? The answer was right in front of us in nature: trees. The goal of trees is to collect sunlight but the leaves aren't rigid, they bend and pivot in the wind to allow air to pass through. Simple but effective.

To utilise this feature best we proposed a tensile cable net that shading panels could be hung from. The cable net would be a very thin and efficient form and the panels would be able to shed wind load by pivoting. The challenge then became working out exactly how much wind load the panels would actually shed.

In Theory

There were three aspects of the pivoting panels that would affect how much wind load they attracted: the angle of the panel, how much the panel moved in different wind speeds and the perforation pattern. All three of these interact with each other and are too complex to be covered in design standards so wind tunnel testing would be required eventually but theoretical calculations enabled us to gain an understanding of the various effects.

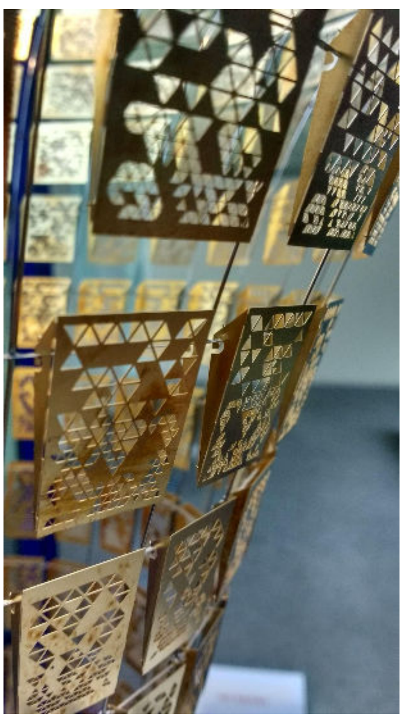
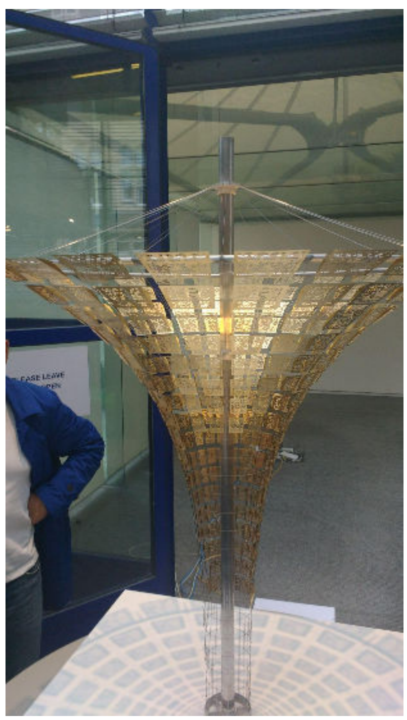
To get a better understanding of the motions of the system we turned to mechanical motion and aerodynamics to attempt to predict the panel movement for different applied wind speeds. The first step of this was to calculate both the horizontal (drag) and vertical (lift) forces on a flat plate, initially ignoring the perforation. This was done for varying angles from vertical to horizontal.



Once the static state wind load was understood the second step to consider was the dynamics of the panel and structure. The swing frequency is calculated from the mass and the distance from the pivot, which for a pendulum with a concentrated mass is straightforward but for a large distributed mass, where the majority of the geometry is significantly further from the pivot than the centre of mass, the equation is more complex, using the polar moment of inertia instead.

The dynamic nature of the panels was not just an issue for its effect on the wind load, it was also hard to design the panel pivot mechanism to resist this. The design called for an easy to install pivot that would be tolerant of repeated panel swinging and would stay in position when subjected to loads in various directions, panel flex, cable movement and wear over the structure's life. Added to this was the fact there were over 20,000 of them so some tolerance and redundancy had to be built in. A two-part steel clamp and clip-on washer was developed to attempt to address these requirements with the washer wearing down over time.Using the appropriate theoretical movement of panels subjected to different wind speeds, combined with fatigue wind load spectrums and average wind speed profiles, a best estimate was made at the sum-total angle the panel would rotate through during its life. Using this and an estimated wear rate, the washer thickness was determined in order to ensure it would last the intended 25 years.

Test, Prototype, Test Again


Wind tunnel testing was carried out on small scale models with surroundings, medium scale 'facade' models and also full-size individual panels. The small scale models gave us an understanding of how the wind load would vary across the site for different structures. The medium scale allowed us to vary the wind pressures across the height and different elements of the structure. For us the large scale was the most interesting, giving us an understanding of how the perforated and moveable panels behaved in different wind speeds and how well they shed wind load when compared to the solid, fixed surfaces in the other scale models.

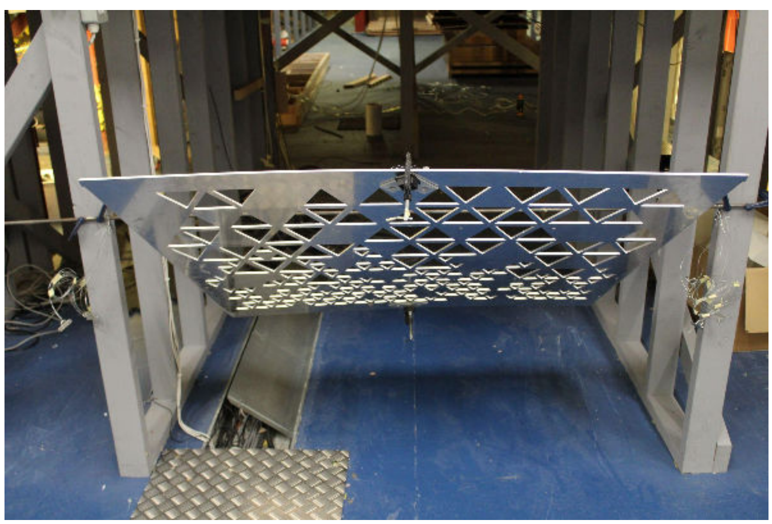
Simultaneously with the latter rounds of wind tunnel testing, various mock-ups and prototypes were built to test connections, buildability and overall aesthetics. We built a scale cable-net model to interrogate the tensioning and form, the architects built a similar scale model with all the hung panels to understand the effect of the pivoting and scale of the elements. 3D printed plastic connecting nodes and panel bearing assemblies were developed and, once the contractor was appointed, fabricated from 3D printed steel and tested to ensure they gripped the cables sufficiently and restrained the panels. All of these models were incredibly useful in understanding the complexities of the structures and discussing them with the various parties.

The testing of the bearing washers for the panels was crucial in determining the maintenance regime. Several washers were cyclically tested using a rig that emulated the motion of the panel over the course of a week but with sufficient movement to simulate 6 months of wear. Washers were tested inside as a control, outside in Dubai and also outside with water and sand poured over daily to simulate the worst case conditions. These tests showed a faster wear rate at the start as the washers "bed in" and then a reduced rate following that. The washers had originally been sized to theoretically last 25 years but the tests projected closer to 15 years due to the variable wear rate. As a result planned replacement was set at 10 years with inspections every 5.

Predicting Chaos

We were always aware that the shading structures with their pivoting panels would be a complex dynamic system but once the first structure was completed an unusual behaviour was observed. When the wind hit a particular speed the panels would swing in-sync and cause the whole structure to flex back and forth. The structure was tethered to the adjacent building and various tests were conducted to investigate the behaviour, which was due to the swing frequency of the panels matching the natural frequency of the full structure.

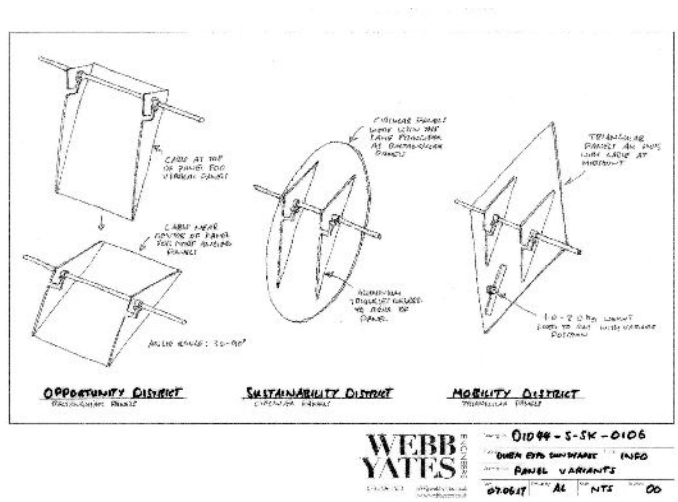
Having pivoting panels attached to a structure that itself can move and swing essentially creates a double pendulum: a classic example of a chaotic system that is almost impossible to predict. During design this potential issue had been noted and the two frequencies checked to ensure they didn't match however the slight difference in the as-built structure's frequency caused the two to become just similar enough that they linked. Once this started the two vibrations fed each other, increasing both amplitudes in a positive feedback loop until damping effects took over or the wind speed reduced.



The solution to the issue was relatively clear: change the natural frequency of the structure or the swing frequency of the panels. To adjust this frequency, we calculated that attaching steel bars to the rear of the panels would sufficiently adjust their inertia and did tests to verify this calculation. Adjustment of the frequency of the structure would already occur as the structures were tied together with additional cable nets, stiffening their movement. This proved to be sufficient for most of the structures, with only one that was not attached requiring weighted panels to avoid this effect. Construction proceeded with the amendments and further testing and observation was carried out to verify it had been successful.

Always Learning

The most successful ideas in the structure were the simplest ones: creating repeating masted structures that are tensioned by extending the mast; having the panels pivot to shed wind; and folding the plate of the panels to hang them. Keeping those ideas simple in the execution was more challenging but with a clear, simple idea kept in mind, the benefits in cost, buildability and durability really paid off.



Throughout the process we learned a lot about the complex dynamics of structures both from independent research and conversations with specialists in the field. Being surrounded by a good team that really understood the importance of the initial simple concepts enabled us to pull the right cables for a spectacular result.