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Solar updraft tower – structural optimisation under dynamic wind action

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Abstract

A solar updraft tower is a type of power plant which uses solar irradiation to generate electricity. It consists of three elements: a solar air collector, wind turbines and a chimney. The proposed concepts for this chimney schematise it as a 1-km-tall reinforced concrete shell, which are vulnerable to resonance induced by storm actions.

This paper presents a method to optimise the pre-existing designs for the chimney of a solar updraft tower. A finite element model has been created and analysed to find out which key problem areas can benefit from improvement. A design tool, based on this finite element model, is presented which enables the user to analyse multiple chimney configurations at once. A multi-objective optimisation process reveals that the key problem areas can be optimised as follows: changing the aspect ratio of the rings ensures that the chimney is fully loaded in compression. An increase in the throat height further improves the reduction of tension and the first eigenfrequency. A reduction in wall thickness at the top of the chimney improves the first eigenfrequency while also reducing material use. Finally, the stiffening rings at the bottom serve little to no purpose. Removing those rings leads to a reduction in material use while some of the material gained can be used to increase the dimensions of the top rings, consequently improving the second eigenfrequency and reducing tension.

Keywords: Structural optimisation, solar updraft tower, finite element analysis, dynamic wind actions, concrete shell

1. Introduction

A solar updraft tower (SUT) is a type of power plant which uses solar irradiation to generate electricity. Its source of energy – solar irradiation – is practically limitless and it can be constructed using conventional construction materials such as concrete, glass and steel; materials which readily available in developing countries (Schlaich *et al.* [1]). The power plant consists of three key elements:

1. Solar air collector: A large circular transparent roof functions as the collector area. The collector area is open at the perimeter so that cold air can enter. The transparent roof allows solar radiation to heat up the air underneath the roof and trap it there, functioning like a greenhouse.

2. Chimney/Tower: The heated air exits the solar air collector through the chimney as a result of air buoyancy. The taller the chimney, the greater the thermal difference and thus the greater the buoyancy force.

3. Turbines: The airflow caused by the air collector and chimney drives pressure-staged turbines at the base of the chimney. The mechanical energy in the turbines is then converted into electrical energy by conventional generators.

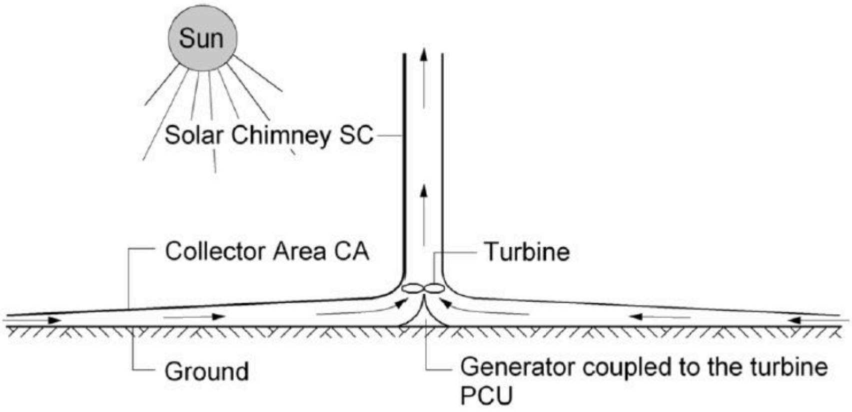


Figure 1: Working principle of a solar updraft tower (courtesy of Krätzig & Partner, Bochum) (Niemann *et al.* [2])

The taller the chimney, the larger the stack effect and thus the more energy can be generated by the turbines. Chimneys as tall as 1000 meters have been proposed, which, naturally, come with a range of structural issues. The proposed concepts for this chimney schematise it as a reinforced concrete cylindrical shell, with the bottom half shaped like a hyperboloid and the top half as a flared cylinder. Wind is the dominant action for such a tall and relatively slender structure and since a structure of such height has never been executed before there are no simplified load assumptions available which lead to a safe design (Niemann *et al.* [2]). Furthermore, most wind design profiles are only valid for altitudes up to 200m since there is a lack of meteorological data for wind speeds above 300m (Harte and Van Zijl [3]).

Previous studies have shown that the eigenfrequencies of such a tall chimney are very low and come very close to the peak of the wind power spectrum (Harte and Krätzig [4]). This makes these chimneys extremely vulnerable to resonance induced by storm actions. Not only that, dynamic loading causes fatigue which can become troublesome in a structure with a design working life of 100 years. It has to be noted that the eigenfrequencies are too low to fall into the range of the earthquake power spectrum.

2. Actions

The chimney of a solar updraft tower is exposed to various actions. Typical load actions working on the chimney are (Borri *et al.* [5]):

- Dead loads D
- Wind loads W (consisting of external pressure and suction W_e, and internal suction W_i)
- Shrinkage effects S
- Temperature effects T
- Soil settlements B
- Seismic loads E
- Construction loads M

By avoiding seismic regions, earthquake loads will not affect the chimney's design. Furthermore, the chimney is not very susceptible to seismic actions since the first natural frequency of the chimney is very low (Krätzig *et al.* [6]). Temperature effects on the chimney are relatively small compared to dead loads and wind loads and can be therefore be neglected (Dyk [7]). Unlike natural draught cooling towers, solar updraft towers have no neighbouring buildings which could cause differences in soil settlements. Construction loads are not included in the model as there is still very little known about the construction process and therefore would warrant a research of its own. Therefore, the load model for the chimney will be simplified as to only include dead loads D and wind loads W.

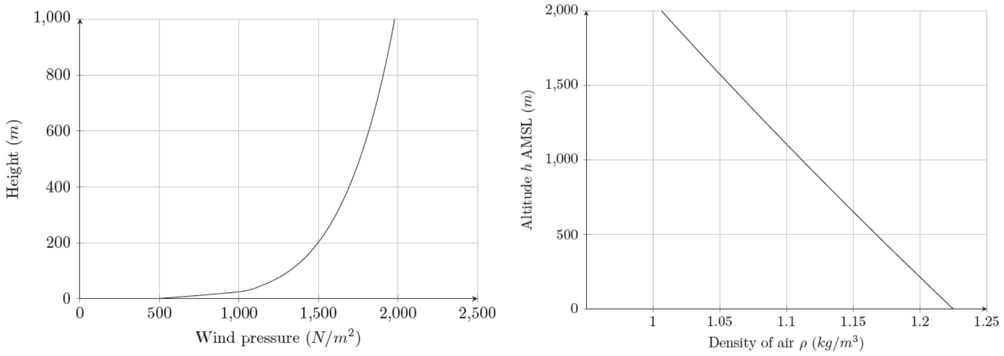


Figure 2: Free stream velocity pressure (left) and air density (right) over the height of the chimney

The corrected logarithmic profile (see Figure 2, left), developed by Harris and Deaves, has been used in this research as, unlike other wind profiles, it takes into account the Coriolis effect which influences wind speeds at high altitudes. In addition, the density of air also varies based on the altitude, which, given the height of a SUT, is not to be neglected (see Figure 2, right). Lastly, the pressure distribution for the SUT is derived from the codes of natural draft cooling towers (NDCTs) (see Figure 3).

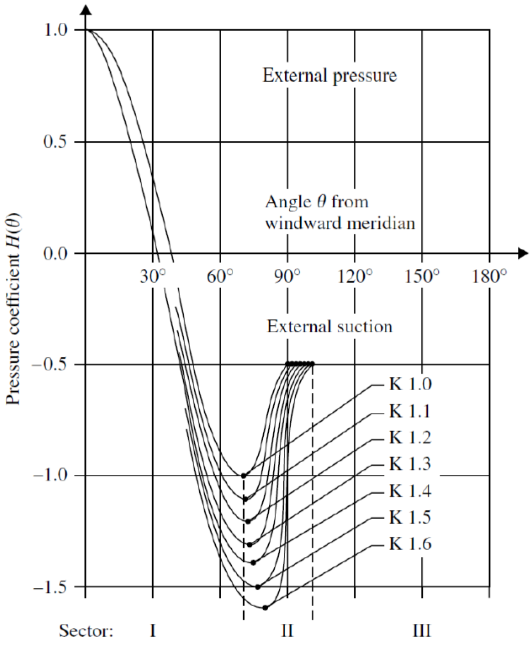


Figure 3: Pressure distributions for the design of NDCTs (Gould [8])

3. Creating a base model

In order to optimise the structure of existing designs for SUTs, a finite element model is created based on one of these designs. From here on out, this model will be referred to as the “base model”.

The geometry of the base model is based on a design by Krätzig & Partners (see Figure 4, left). The design schematises the chimney as a 1000m tall concrete shell, which starts off as a hyperboloid at the bottom and then gradually transforms into a flared cylinder (see Figure 4, right). The large base of the hyperboloid shape will help with resisting the base overturning moment caused by the wind load over the height of the chimney. The reason for implementing a flared cylinder has to do with the flow characteristics of the chimney. Over the height of the chimney, the density of the air flowing through it decreases, which causes the air to expand. If the diameter of the chimney stays constant, the airflow has to accelerate which subsequently leads to a drop in pressure and therefore losses in the energy conversion process. By enlarging the cross-sectional area of the top of the chimney by around 14% (Backström and Gannon [9]), this effect can be mitigated.

Additionally, the chimney has a relatively thin wall thickness profile, causing it to require stiffening rings which stabilise the structure. For the base model, nine intermediate stiffening rings and a top ring are applied, spaced 100 meters apart from one another.

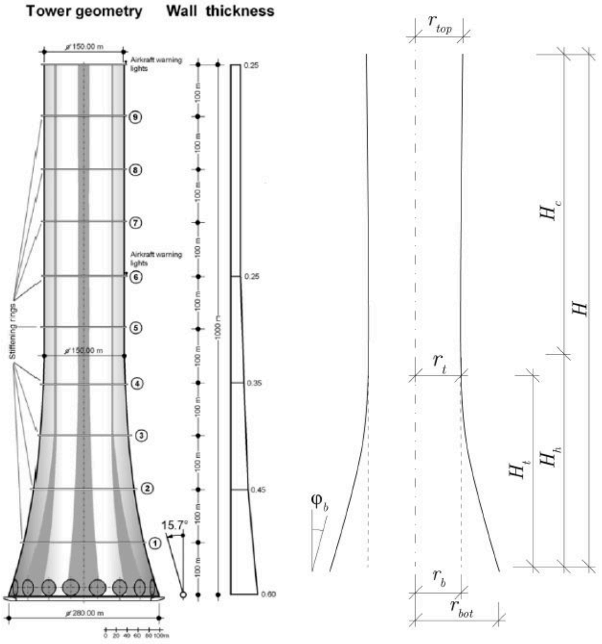


Figure 4: Pre-existing design for a 1000m tall SUT (courtesy of Krätzig & Partner, Bochum) (Niemann *et al.* [2])

4. Meshing & Calibration

To speed up calculations, various optimisations are introduced in the meshing process. Some areas of the chimney require more elements than others. Increasing the global mesh density would increase computation time significantly. Therefore, the mesh density is only increased locally, near the stiffening elements, where the largest rotations occur.

Furthermore, by modelling only half of the chimney and applying symmetry boundary conditions, the number of FE elements required can be cut in half without sacrificing accuracy (see Figure 5). The only downside to this method is that torsional eigenmodes cannot not be computed. These, however, are not found to be governing since the first torsional eigenfrequency of the base model occurs at 0,73Hz, well outside of the range of the wind power spectrum.

The created model is then further calibrated by carefully adjusting the parameters and subsequently comparing the results of the static and modal analysis with those of the existing design (see Table 1) Minor differences in the analysis results are tolerated as the goal is to optimise the existing design, not to emulate it. The corresponding eigenmodes (Figure 6) of the base model are similar to those of the existing design.

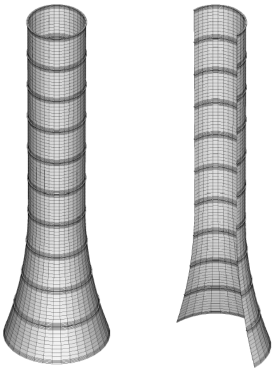


Figure 5: Full chimney (left) and half chimney with symmetry boundary conditions (right)

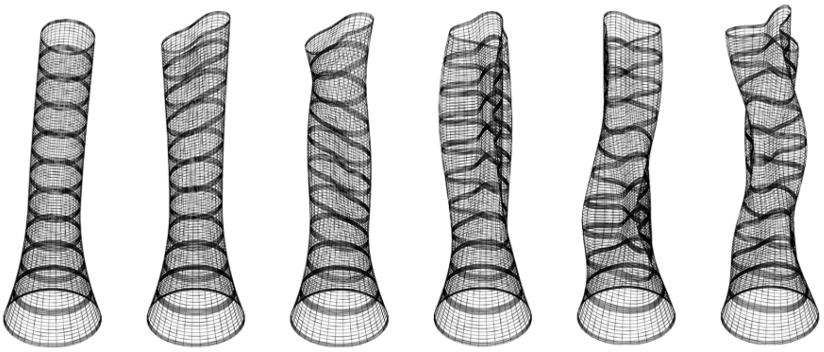


Figure 6: First six eigenmodes of the base model

Table 1: First six eigenfrequencies of the base model compared to the existing design

	Frequency		
Mode	Existing design [Hz]	Base model [Hz]	Error [%]
1	0.17	0.1715	0.9
2	0.21	0.2068	-1.5
3	0.30	0.3537	17.9
4	0.46	0.5170	12.4
5	0.56	0.5345	-4.6
6	0.63	0.5936	-5.8

5. Initial analyses

Analyses of the base model reveal four key problem areas which require attention in the optimisation process. To avoid cracks in the shell and in the rings, tension on the windward side of the chimney has to be reduced. If the rings crack then the eigenfrequencies will decrease which in turn will further increase the danger of along- and across-wind oscillations. Additionally, the first and second eigenfrequency should be improved in order to mitigate the effects of dynamic wind loading. Furthermore, it appears that the second eigenfrequency has an even greater dynamic response than the first eigenfrequency which can be seen in the spectral density of the system response in Figure 7. Lastly, the material use of the chimney should decrease for the sake of lowering costs.

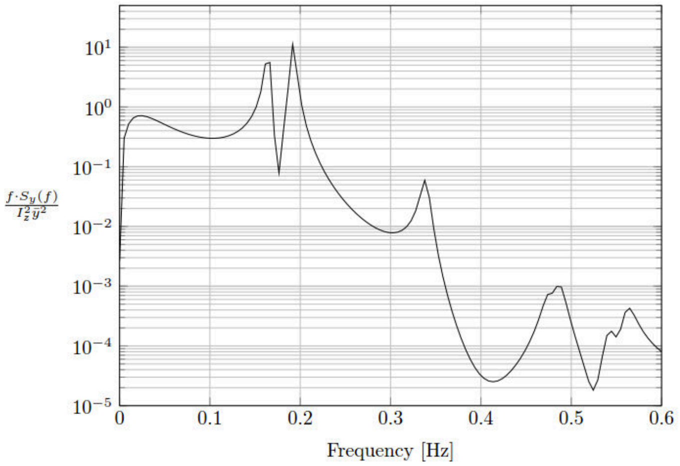
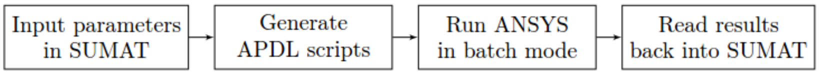
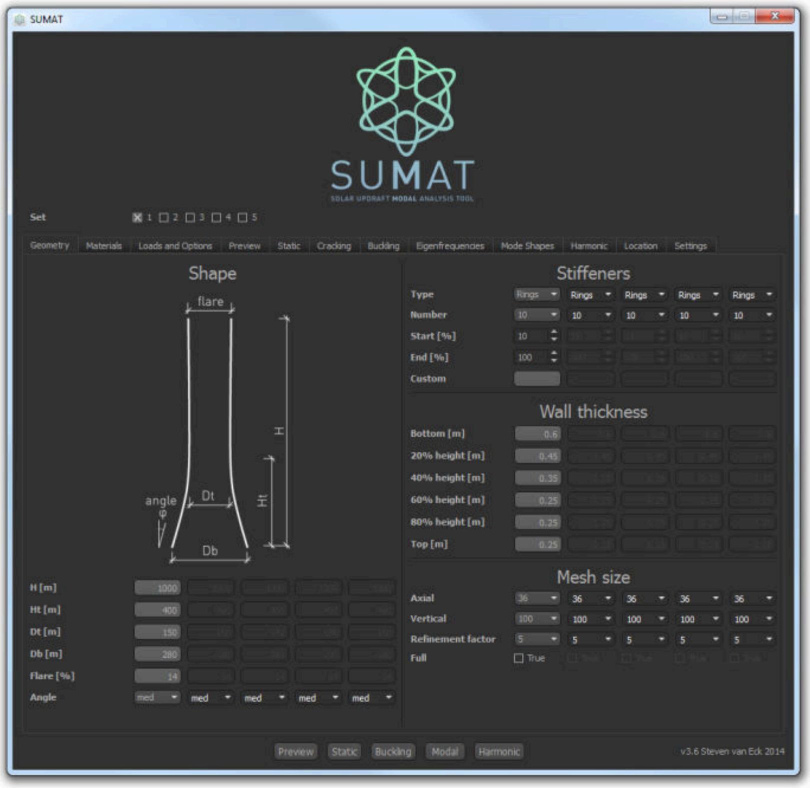


Figure 7: Spectral density of system response of the base model

6. SUMAT: a design tool for analyzing chimneys

The goal of this research is to optimise the structure of the chimney. In order to do that, a great amount of chimneys with different parameter sets have to be studied and compared. It would take too long to model all of these chimneys by hand; a different solution has to be found to quickly model and compare results. Hence the creation of the design tool SUMAT (Solar Updraft Modal Analysis Tool). The way SUMAT works is as follows: first the user can tweak the parameters of up to five chimneys in a user interface. These parameters describe every structural aspect of the chimney, ranging from geometrical shape and placement of the stiffening rings to material properties and wind loads. The user can then run one of the following analysis tasks: static analysis, modal analysis and harmonic analysis. The user interface reads all of the parameters defined by the user and starts writing APDL (ANSYS Programmable Design Language) scripts for the five cases. ANSYS then runs these scripts in batch mode in the background. Once the analysis tasks are completed, ANSYS stores the results in .txt- and .png-files which are then being read back into the UI, displaying the results to the user.





Set ☒ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

H [m]	1000				
Ht [m]	400				
Dt [m]	150				
Db [m]	280				
Flare [%]	14				
Angle	med	med	med	med	med

Type	Rings	Rings	Rings	Rings	Rings
Number	10	10	10	10	10
Start [%]	10				
End [%]	100				
Custom					

Bottom [m]	0.6				
20% height [m]	0.45				
40% height [m]	0.35				
60% height [m]	0.25				
80% height [m]	0.25				
Top [m]	0.25				

Axial	36	36	36	36	36
Vertical	100	100	100	100	100
Refinement factor	5	5	5	5	5
Full	☐ True				

Figure 8: SUMAT user interface

While it costs a lot more effort to program and calibrate the design tool, it allows for many more configurations to be studied and ultimately provides more insight than could be amassed by using traditional modelling methods.

7. Optimisation process

Various sensitivity analyses are conducted as part of the (manual) optimisation process. Each sensitivity analysis studies the influence of a single parameter on the four key problem areas. Afterwards, the results can be used to optimise the structure. This will be done in two steps. Step one consists of dividing all of the researched parameters into four categories, based on their usefulness in optimising the four key problem areas. The categories are: primary parameters, secondary parameters, teriatiry parameters and residual parameters. Primary parameters only bring about positive change in all of the key problem areas. Secondary parameters bring about mostly positive change. Tertiary parameters function as a last resort measure. If one of the objective functions is found to be lacking in terms of optimisation, then gains from other objective functions can be sacrificed by introducing these parameter changes; this is to make sure that all four objective functions show improvement when compared to the base model. Lastly, residual parameters should not be tampered with, since they only negatively influence the four objective functions or because they come with unacceptable side-effects.

The studied parameters and the categories in which they are placed are as follows:

Primary parameters

- Increasing the aspect ratio of the stiffening rings
- Lowering the number of stiffening rings

Secondary parameters

- Throat height
- Increasing the cross-sectional area of the stiffening rings

Tertiary parameters

- Redistributing the wall thickness
- Increasing the radius at the base of the chimney

Residual parameters

- Adjusting the radius of the throat of the chimney
- Adjusting the angle of inclination at the base of the chimney
- Changing the density of the concrete used
- Improving the concrete quality of the chimney
- Improving the concrete quality of the stiffening rings

The second step consists of gradually introducing the primary, secondary and tertiary parameter changes into the base model by hand to find a solution which improves all of the four key problem areas. This leads to the optimised model, of which the results are compared to those of the original base model, to verify if indeed an optimisation has taken place.

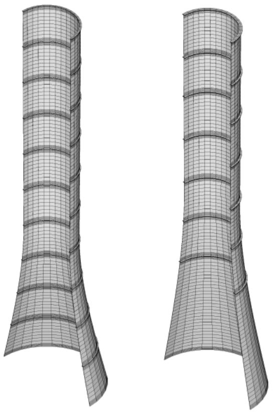


Figure 9: FE mesh of the base model (left) and the optimised model (right)

8. Conclusions

The sensitivity analyses and optimisation steps reveal that the key problem areas can be improved as follows:

- Increasing the moment of inertia of the rings by changing their aspect ratio ensures that the chimney is fully loaded in compression while also improving the second eigenfrequency.
- An increase in the throat height further improves the reduction of tension on the windward side and improves the first eigenfrequency.
- A reduction in wall thickness at the top of the chimney also improves the first eigenfrequency while simultaneously reducing material use.
- The stiffening rings at the bottom of the chimney serve little to no purpose. Removing them leads to another reduction in material use while some of the material gained can be used to improve the second eigenfrequency by increasing the dimensions of the top rings, consequently reducing tension even further.

The results of the optimisation process are displayed in the Kiviat diagram in Figure 10.

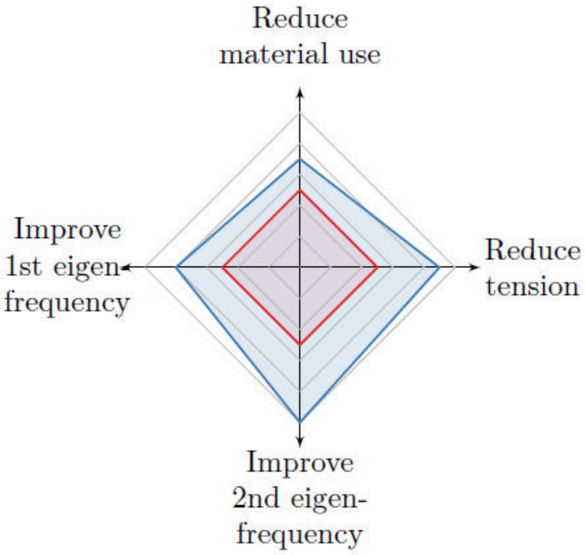


Figure 10: Kiviat diagram comparing the base model (red) with the optimised model (blue)

More thorough analyses of the optimised model reveal that:

- Along-wind resonance does not pose as great a threat as was initially assumed, due to the effect of aerodynamic admittance. The results do show, however, that the improved eigenfrequencies led to a smaller increase in deflection as a result of dynamic wind action.
- Vortex shedding also no longer poses a threat as the improved second eigenfrequency results in critical wind speeds which are much larger than could ever occur at the chosen reference location.
- Contrary to what was expected, the second eigenfrequency, associated with a shell bending mode shape, is more critical than the first, associated with a beam bending mode shape, in terms of dynamic response.
- Geometric and material parameter optimisations can lead to such a reduction in tension that the minimum reinforcement percentages, according to VGB guidelines for NDCTs, are deemed sufficient (see Figure 11).
- Optimisations of the four key problem areas also lead to a reduction in the static deflection and a minor improvement of the buckling safety factors. As is often the case, shape optimisations which benefit the eigenfrequencies often also benefit the buckling stability.

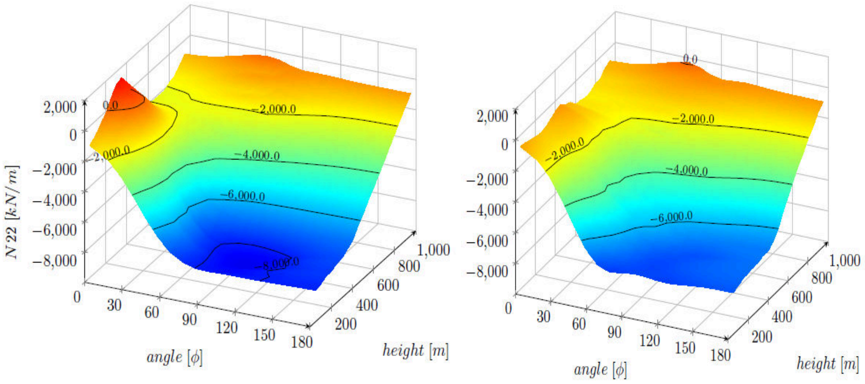


Figure 11: In-plane forces N22 in the base model (left) and the optimised model (right)

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