solar chimney concept. The vast flat, unoccupied semi-desert regions make South Africa an ideal country for large solar energy plar
e diminishing source of fossil fuel, the shortage of water for more hydro-electricity plants, the abandonment of wave-generated electric
e to high cost and public resistance to nuclear energy motivate such a research program towards sustainable energy sources. In paral
h heat and mass flow analyses and computational fluid dynamics analyses to derive the optimal geometry, the conceptual designs o
ge solar collector structure, as well as a chimney are prepared and studied. In this paper the research towards the realisation of the chimr
ucture of extraordinary dimension, i.e. 1500m high, internal diameter 160m, is reported. The main actions of self-weight and wi
citation are studied through finite element analyses and a stiffening strategy to prevent ovalling is proposed. Linear buckling is perforn
study buckling under these loads in an approximate way. Aerodynamic stability is addressed through eigenvalue and eigenmode extracti
comparison with the frequency of vortex shedding.

Key words: solar, chimney, stiffeners, wind forces, aerodynamic stability

RODUCTION

s always been in search of energy. To keep him warm during
ghts, to provide that edge in the Olympic Games and nowadays
old his standards of living. Today electricity is a primal
ty in everyday life, something we cannot live without.

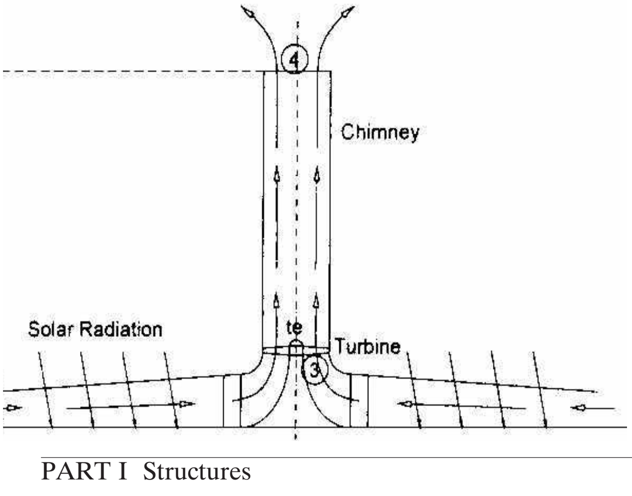
arch for energy converting mechanisms has far reaching
. The earth provides many resources, once thought of as
stible. Recently, however, mankind has had to start facing the
uences of his selfish consummation of the very resources that
im alive. The fact is the waning coal and oil deposits in the
vill soon have to be replaced by an alternative energy source.

ar chimney has proved itself as one of the main contenders in
e toward finding an alternative energy source in the twenty first
. Although the initial cost is high, the low maintenance costs
h, continuous energy output rates prove it as both an effective
sible solution.

ackground information and basic working

-three years ago a German engineer, Jörg Schlaich, came up
e idea of a solar chimney – a device that uses the sun's energy
verting heat energy into kinetic energy, and kinetic into electric
The solar chimney works on the principle that hot air rises,
t if these considerable volumes of hot air can be canalised it
ome a potential energy source.

sential elements of the solar chimney (Fig 1) are: a chimney
e, one or several turbines and a glass roof collector.



Solar radiation heats up the earth underneath the roof and the
moves along the slightly inclined glass roof towards the centre
collector, where it is canalised into the chimney, passing the tur

Several experiments have been done since the conception of th
A prototype with a height of 250 metres was built in Manz
Spain in 1980. This project proved to be the start of many r
projects, capturing the basic concepts and theory and proving th
chimney to be a prime candidate for the solution to the future
source problem.

1.2 Dimensions and materials

The development of the solar chimney as an effective
electricity generation is still only in its middle phase. Basic sha
material analysis on all three of the parts had been done but
still much room for innovation and improvement and refining
concepts.

The choice of dimensions is also under constant change, and is
to the specific site it is designed for. For instance, one of th
variables, wind velocity, is subject to the global position
proposed site. Altitude and surroundings, like buildings or mou
have a significant effect on these velocities and changes will r
adaptations to elements in size of the design.

Output demand determines the size of the different parts of th
chimney. Several combinations of chimney height, chimney
collector diameter and amount of turbines have been investigate
A demand of 200 MW output of was put forward for the design
solar chimney. Recently, the idea arose to exploit the se
climate and available space in the Northern Cape, South Af
solar chimney generation. This has led to an investigation
University of Stellenbosch, South Africa.. Proposed dimensi
the chimney structure investigated in this paper follow:

Chimney height: 1500 m, measured from ground level
Wall thickness, t_{bottom}: 2.19 m
Wall thickness, t_{top}: 0.25
Diameter, $D_{bottom,inner}$: 160 m
Diameter, $D_{top,inner}$: 170.5 m
Collector diameter: 6.9 km

The heart of the solar chimney lies at the bottom of the chimne
Here is where the turbine rests on a cone. The cone directs the
air, coming from outside through the collector, upwards. T
with the cone, the inlet guide vanes (IGV's), deflects the air b
hits the blades of the turbine, already giving it a rotation.

equals 2.190 metres. It decreases linearly up to the height of 1000 metres where the thickness is 0.250 metres. From this height, for the remaining 500 metres, a constant 0.250 metres is used.

Flaring. As air moves through the chimney, the exit air density is considerably lower than the inlet density. In previous research, a one dimensional compressible flow approach was done, accommodating variables dependent on height, wall friction, additional losses, internal drag and area change. The pressure drop associated with vertical acceleration of the air is approximately four times that of the effect of wall friction. Flaring the chimney by 14 percent to keep the through-flow Mach number constant eliminates vertical acceleration pressure drop [9]. A 14 percent increase in area is equivalent to a 13 metre increase in diameter for a 160 metre chimney.

Ring stiffeners. The basic steel ring stiffener proposed by Jörg Schlaich [4] for use on this chimney consists of an inside and outside ring, connected radially by 72 spokes. See Fig 2.

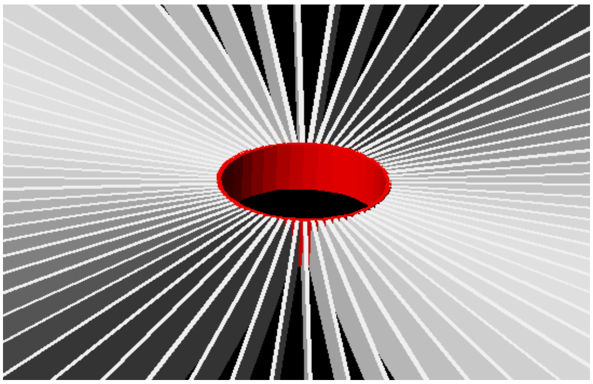


Fig. 2

The steel elements of the stiffener have been assigned a depth of 0.630 metres and a width of 60 millimetres. The width has to be kept as small as possible because of the negative effect that an increase in area, especially at the top, has on the pressure drop.

The inside ring of radius 1 metre must serve as a fitting for the stiffeners and provide stability in the structure in that it upholds the circular form of the chimney.

The stiffeners are placed in 220 metre intervals, with the intervals starting from the top edge. In the initial configuration six stiffeners are used, at heights of 1280, 1060, 840, 620, 400 and 180 metres. This positioning of the rings gives the chimney behaviour significant improvement but optimum placement is still to be determined.

Own weight. The force at the foundation of the structure due to own weight is roughly 8.549×10^9 kN. This force needs to be distributed between all the foundational elements (presumably the IGV's).

Materials. Although alternative materials such as steel frames suspending a membrane had been proposed for this extreme structure, a paper by Schlaich [5] recommends the use of concrete only.

2. WIND FORCE CHARACTERISATION

2.1 Wind action characterisation

The extraordinary height, at 1500m, of the solar chimney makes its design unique and revolutionary. Wind speeds at these heights are generally not recorded – it has never been necessary to use for structural design purposes. The only way of estimating the wind speed is to extrapolate the average wind speed, as given at a height of 10 meters, with given formulas.

Three theories was taken into account in the determination of the maximum design wind speed. They are: SABS 0160-1989 [7], Simiu and Scanlan [6] and the common formula [3] that follows:

$$\left(\frac{V_z}{V_{10} \times k_r}\right) = \left(\frac{z}{10}\right)^{\alpha} \qquad (1)$$

Where V_z = wind speed at a height of z meter, m/s
V_{10} = average wind speed at a height of 10 meters, m/s
k_r = return period adjusting factor
α = terrain factor, varies between 0.16 (open country) and 0.21 (city centres).[7]

The most conservative estimate for the extrapolation of wind speed, at a height of 1500 m, is given by Eqn 1 as V_{max} = 107.783 m/s.

2.2 Wind effects – theoretical background

A study of the theory of main wind effects on tall structures and chimneys follows [2]. The relevance of such information to this particular structure, 1500m high, lies in the fact that not much research into this area has been done. The extreme size of the structure makes it necessary to check every possible facet of wind load design.

Response to static wind forces is determined by use of Eqn 2:

$$F = C_f \times q_z \times A_e \qquad (2)$$

where C_f = force coefficient due to the pressure distribution
q_z = free stream velocity pressure (N/m^2) at height z
A_e = effective frontal area of the building (m^2), normal to the wind direction

Hoop stress. The effect on horizontal hoop stress in the shell due to the variation of wind pressure on the circumference of the shell on every height is the most important aspect. The effect of this phenomenon will be treated extensively later in this paper.

Vortex shedding-induced oscillation. Winds with low speed yield a very low Reynolds number. Airflow is entirely laminar. As the velocity, hence the Reynolds number increases the laminar flow breaks down at some point (point of separation) on the surface of the structure.

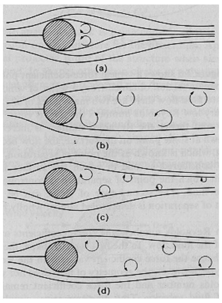


Fig. 3 (a to d)

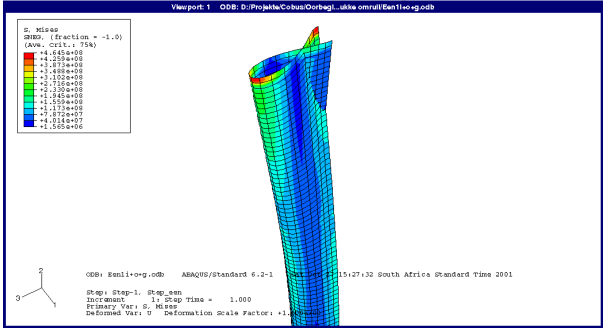
At a low Reynolds number two stationary vortices form immediately behind the section. As the air speed increases the vortices detach alternately, forming a vortex sheet behind the section. At the critical Reynolds number the point of separation moves back and the vortex sheet becomes narrower. Fig 3 (a to d) visualises this behaviour.

3. STATIC GEOMETRICAL LINEAR APPROXIMATION

3.1 Introducing ring stiffeners

Without stiffeners. In general, ovalling of circular shells is a secondary effect and the problem is limited to one of checking and proportioning the reinforcement to cater for the bending, rather than to design for such influences or regard it as your limit state.

With the solar chimney, however, this is not the case, as is shown in Fig 3, from a deformation procedure in ABAQUS software. (In order to execute finite element analysis on the structure an approximate model was created. This model could then be optimised at will.)



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Step: Step-1, Step_een
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Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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Fig. 4

The above figure (actual deformation) clearly shows the ovalling of the chimney shell. Maximum deformations here amounts to approximately 144 metres.

Ovalling happens when an along wind causes a non-uniform pressure distribution around the perimeter of the shell. Figure 5 visualises this distribution for rough edged and smooth chimneys.

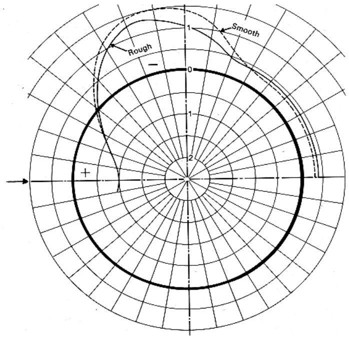


Fig. 5

On first contact the shell is pressed inward because of a positive wind pressure. The sides are sucked outwards as the pressure force there is negative. In the lee of the shell negative pressure occurs, that is, negative with regards to the wind direction. The result is the bean shaped tendency.

Once an irregularity occurs in the structure the dead weight of the concrete structure and the flaring effect makes the chimney very susceptible to buckling. With its massive diameter and exposure to each element in nature, designing the chimney so that the shell stays circular is the greatest challenge.

Gravity. From a quick investigation on the effect of gravitational force on the structure the compressive stress in the shell reaches 17 MPa. Consequently this is not a limiting factor in design. The maximum vertical deformation at the top of the structure is 0.480 meter.

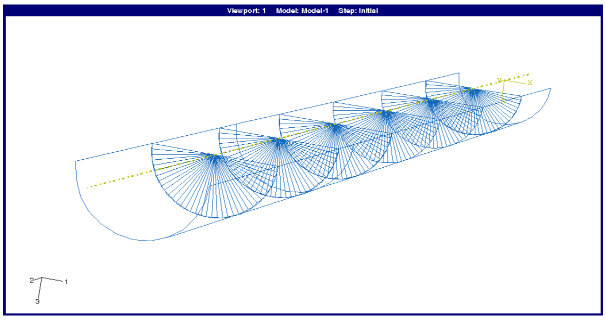


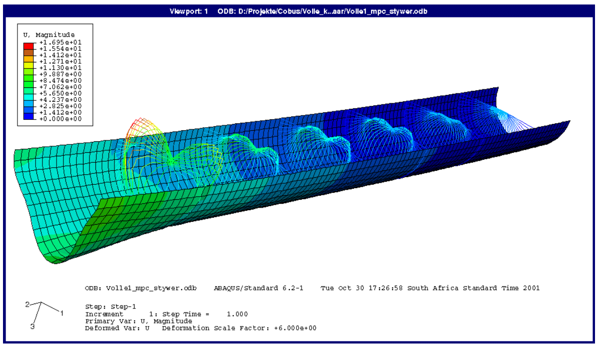
Fig. 6

Stiffener application. A cool drink can without any irregularities is very strong in axial compression but as soon as there is one dent in its surface it buckles easily. The chimney will fail in the same way and if no precaution against shape deformation is taken it will be a worthless structure. Figure 6 shows the assembly and relative position of the ring stiffeners in the chimney.

On analysis, it is seen that the addition of the stiffeners immediately reduces the structure's deformation. Deformation is minimized from 144 metres to a maximum of less than 5 metre generally and 10.4 metres at the very top, where there is, for now, no stiffener in position. This yields an improvement in deformational performance of more than 25 times!

3.2 Improving ring stiffener effectivity

Figure 7 visualises two areas where there is space for much improvement:



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Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +6.000e+00
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Fig. 7

Top ring stiffener. Firstly, deformation of the chimney at the top edge can clearly be seen. Also, it seems that the effect of the bottom stiffener, at a height of 180 metres, on the global behaviour, is trivial. A different configuration (Fig 8) – the lower stiffener shifted to the upper edge – was chosen.

The focus here is on deformational behaviour, with no consideration of material non-linearity. Therefore, the stresses are merely an indication of deformation gradients. The improvement by the new stiffener layout is evident from the principal stress lowering from 77.38 MPa to 39.68 MPa. Deformation in the shell is nearly halved as well, with a decrease from 10.4 metres to 6.5 metres. The maximum stiffener deformation doubled, though.

Stiffener deformation. This last fact calls for some attention to the stiffener deformation, especially since the shell deformation and stress values seem to be on the safe side.

Due to the slight compression action of the chimney shell on them and under their own weight, the stiffeners bend outwards, as seen in Fig 7.

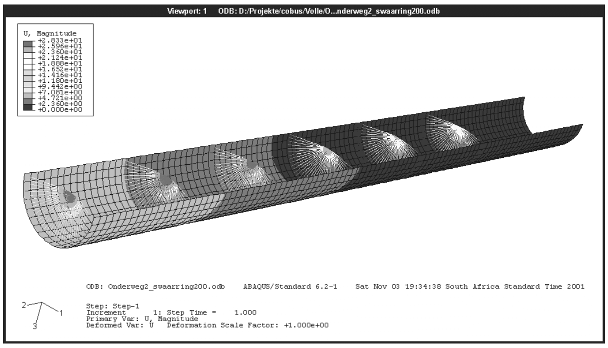
The buckled shape of the beams is caused by the ovalling of the inner and outer rings. Thereby, the windward and leeway spokes undergo end rotations and shortening, leading to the strange deformation pattern.

Solution to stiffener deformation. The problem can solved in two ways:

Firstly, enlarging the inner rings of the structure, the dead weight of the inner ring increases, pulling down the stiffeners and helping them to keep their position in the chimney. Through a greater lateral stiffness they are also more effective in resisting ovalling.

Secondly, using beam materials with higher elastic modulus will increase the stiffness and reduce deformation accordingly. Analyses with alternative materials are discussed later in this section. Such a possibility will depend on the availability of such materials and their economy.

On applying these two solutions an increase in the ring size and weight results in a more desirable maximum sagging of 22.5 meters in the vertical direction. Also, the sideways bending of the spokes of up to 35 meters seen in the previous results is prevented. Figure 8 shows the result with the stiffener positioning adjusted and the heavier inner ring employed.



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Increment      1: Step Time =    1.000
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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Fig. 8

Results with optimisation. Several models were prepared and analysed yielding the following results (the numerical values can be seen in [8]):

The heavier the inner ring the better the results. The 0.2 width ring-beam resulted in 17 percent less shell deformation and a eleven percent decrease in the stiffener deformation.

The stiffer the beam stiffeners the better the performance. An analysis with virtual 300 GPa stiffeners and an increased inner ring width of 0.1 metres yields a significant improvement in the stiffener performance.

These stiffeners brought the stiffener deformation down with twenty percent. A disadvantage of such higher elasticity materials is that they are expensive.

Summarising, the application and relative optimisation of the ring stiffeners yields positive results, firstly in the upholding of the circular shape of the chimney.

A different approach: more inner rings. It becomes apparent from initial analysis that the stiffeners deform severely under the force that the chimney shell is exerting on it. Buckling/bending may take place and decreases the effectivity of the stiffeners.

Adding more inner rings to the stiffener structure can rectify this problem. These rings will keep the individual spokes in place. The buckling/bending danger will decrease because the effective length of the spokes is shortened.

An advantage is that without changing material properties the rings act much more as a stronger unit.

Fig 9 gives a visual representation of the concept – with one ring added at 20 metre radius:

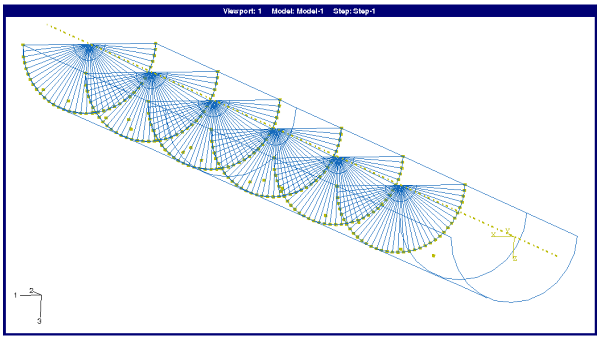

Fig. 9

2.5 General remarks

Discontinuity. In Fig 10 some of the principal stresses are shown. It is clear that the largest stresses exist around the area of the stiffener constraints.

Some of these appear in the form of a stress discontinuity. The discontinuities are due to the localised constraint of the shell to the stiffeners, causing the chimney shell to bend with the ring stiffeners, creating a local deformation in the shell.

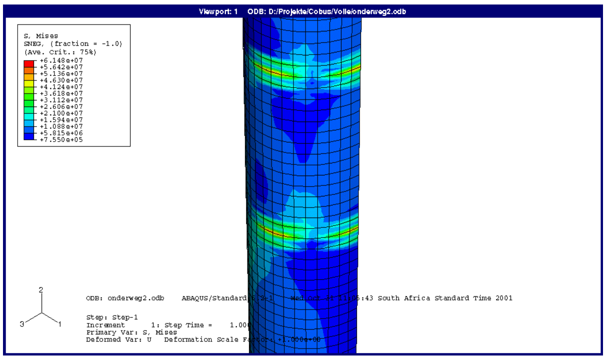

Fig. 10

Better modelling of the stiffener-shell connection will give a better prediction of the stresses. Nevertheless, it is foreseen that stress concentrations will remain. To counteract this phenomenon the shell thickness at the constraining points must be designed thicker, with higher ratios of reinforcement steel in the concrete.

Alternative material. The possibility of using lightweight composite materials was investigated:

A material such as CFRP (Composite Fibre Reinforced Plastic) has a density of 1500 kg/m^3, Poisson ratio of 0,3 and a very high elasticity modulus of 127 GPa. It is a very stiff material deforming no more than 1.21 percent. Table 1 compares CFRP's performance with the earlier steel results:

Investigating material change for stiffener optimisation

	Deformation		Principal
Material	Shell (m)	Stiffeners (m)	Stress (MPa)
200_0.1	6.4	31.15	54.82
CFRP	8.2	40.8	54.37

Table 1

While the principal stress values remain the same, CFRP does not live up to steel in this regard, due to the low stiffness. CFRP does lower the discontinuities along the constraining points on the chimney shell because of a smaller bending moment about the shells.

Cable stays. The use of cable stays on a structure as large as the proposed 1500 metre solar chimney deems to be an unpractical, unfeasible means to stability of the global structure.

At heights of 1000 metres the cables will have such great self weight that the effect of it on the chimney will much rather be one of destabilizing the structure.

It is preferable to seek global stability through the upholding of the geometrical form itself. Also, this eliminates the possibility of oscillating cable stays, which could cause great problems or even damage to the global structure.

3. GEOMETRICAL NON-LINEAR APPROXIMATION

3.1 Initial problems and overcoming it.

On application of non-linear geometrical analysis on the chimney model, numerical problems where encountered. An analysis could not be completed meaningfully. These problems confirmed, as were predicted, the discrepancies in the analysis caused by excessive local buckling. Large deformation of the stiffeners, at loads lower than the bifurcation load of the global structure, implied an unstable structure.

To study the global deformation patterns, the large local deformations of the stiffener beams were suppressed by employing artificially high moments of inertia of the beams. This procedure was followed to enable solution of the buckling analysis to study trends in global buckling. With these adjustments an analysis could be successfully completed. The local buckling must, however, be addressed.

3.2 Linear buckling analysis.

In a linear buckling analysis, as implemented in the ABAQUS finite element program the following problem is solved:

$$[K_{mat} + \lambda K_{\sigma}]u = 0 \qquad (3)$$

where K_{mat} = stiffness matrix of the material
K_{σ} = stress stiffness matrix
λ = load factor
u = displacement, m

The critical load factors for the global structure was calculated of which the results follow:

Critical load factors where found for λ = 0.76377 and λ = 0.93107. This implies an unstable structure under design wind load. Figure 11 visualises for λ = 0.76377:

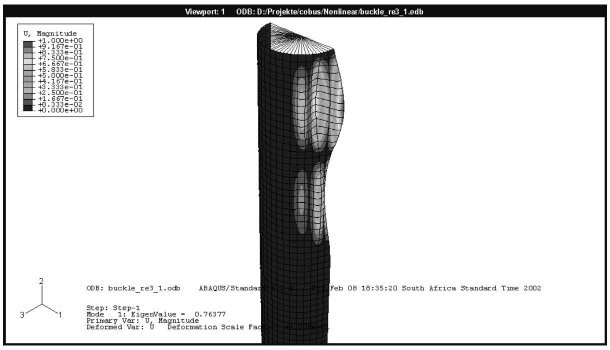

Fig. 11

It has to be mentioned, however, that deformation because of these modes, as can clearly be seen in the figures, are only present in the top 500 metres of the chimney, which has a constant shell thickness of 0.250 metres.

An interesting phenomenon was the presence of negative load factors in the analysis results. The visualisation corresponding to eigenvalues of –1.1934 and –2.0155 can be seen in Fig 12.

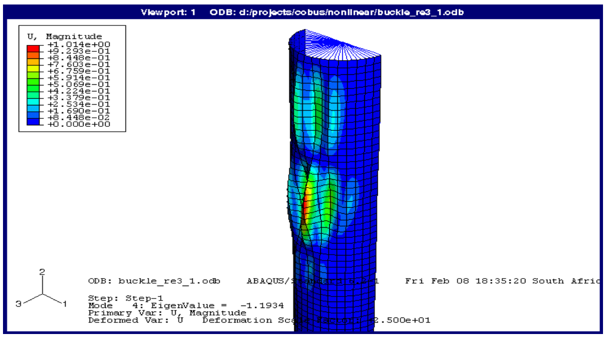

Fig 12

To understand this response – the so-called "negative eigenvalue" – one must grasp that a negative load factor implies, not a wind load from an opposite direction, but a "negative" (and in this case, virtual) force.

3.3 Furthering the study – current status.

Due to initial problems in the second order calculations on the global chimney structure the model had to be adapted, for instance by increasing the moments of inertia of the stiffener beams. This was a local adaptation to make global analysis possible. The direct effect of stiffening these beams could not be determined.

The next step in the study would be to optimise the contribution of each component of the structure and the interaction between them in order to establish a configuration complying to all and limit states.

Such a model will lend itself to further non-linear analysis.

Alternatively one would look at a complete different structure for the upholding of the circular shape of the chimney, in order to bypass the great stiffener beam deformation.

4. FREQUENCY ANALYSIS

In order to estimate vibrational behaviour in the structure of the solar chimney a frequency analysis was done. Eigenvalues were determined in order to predict critical wind speeds causing aerodynamic instability. The design was then refined to counteract destructive structural response at these wind speeds. The necessity of ring stiffeners in the structure was once again made clear by the success following its application.

4.1 Supporting theory.

A basic background study on frequency analysis for circular chimneys was done [1].

Frequency analysis-theory. For general guidance on masonry chimney vibration for frequencies corresponding to the first bending mode, which is the most likely in the range under consideration, the following should be adequate:

$$N = \frac{3}{\pi H^2}\sqrt{\frac{2EI}{5m}} \qquad (4)$$

where N = natural frequency, Hz
H = height, m
E = modulus of elasticity, Pa
m = mass per unit height, N
I = moment of inertia, m^4

The important aspect of this formula is that it shows the role of the elasticity modulus and the moment of inertia in determining the natural frequencies. At a later stage these parameters will be changed in order to study the sensitivity.

Having established the natural frequency for the type of construction under consideration, the wind speed that would match this frequency and hence cause oscillation, can be found from the following equation:

$$V = \frac{ND}{S} \qquad (5)$$

where V = critical corresponding velocity, m/s
S = Strouhal number, which for general chimneys may be taken as 0.2

The Strouhal number can range from 0.15 for square chimneys to 0.23 for circular chimneys. In the event of a critical result being calculated wind tunnel tests should be considered.

As mentioned the natural frequencies referred to correspond to the first bending mode and determine the sway of the structure. For approximate second- and third-mode frequencies, N should be multiplied by 6.26 and 17.6 respectively.

Application of theory on solar chimney structure. A few assumptions have to be made and mentioned before the theory can be applied with confidence:

- The formulas were designed for towers/chimneys with varying diameter. This implies that the formulas are not necessarily applicable on the solar chimney.

  Fortunately, these formulas can be applied with confidence because, firstly, the diameter of the solar chimney does not decrease with increase in height. Secondly, the wall thickness decreases with height, from 2.190 metres at foundation level, to a constant 0.250 metres at the top 500 metres of the chimney. There is therefore a local tapering in the wall thickness, while the diameter in the global structure stays more or less constant. This simulates conditions as seen in the examples in the literature [5].

- From Eqn 4, the natural frequency is a function of the height of the structure, as well as the mass per unit height.

  The taller the structure, the smaller the natural frequency occurs. A structure three times taller than the tallest skyscrapers in the world would possibly be outside of the range of structures the formula was designed for and has to be refined.

- As deterioration takes place in the concrete structure the elasticity modulus, and overall stiffness, decreases. Practically, using lower elasticity modulus values in the analyses can represent this. Again this influences the calculation of natural frequencies, as can be seen in Eqn 4. This adaptation to serviceability applies to the whole paper.

It must be mentioned that physical non-linearities, like cracking and creep, were not considered in this first appraisal of the solar chimney structure.

4.2 Results

Equation 5 can be simplified, using for S = 0.2 and D = 160 metres to:

$$V = 800N \qquad (6)$$

Chimney alone. At a frequency of 0.101 Hz the first global mode is present as can be seen in Fig 13. This frequency, using Eqn 6, corresponds to a wind speed of 80.8 m/s.

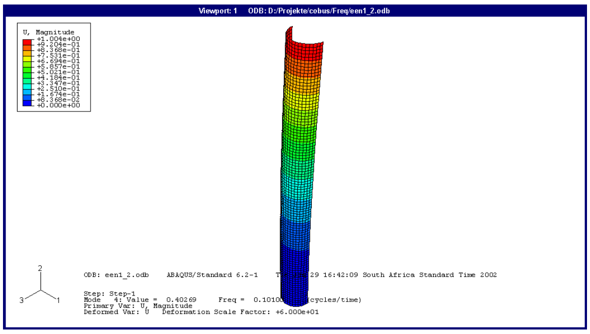

Fig. 13

Chimney with stiffeners. On initial analysis it was seen that at lower wind speeds, starting from 21.2 m/s, corresponding frequencies (lowest frequency was 0.027 Hz) only have effect on localized structures, such as the stiffener beams. This information is very useful since it illustrates a problem of bending in the stiffener beams – a problem that remains unaddressed. Figure 14 shows the excitation of a particular stiffener.

It was therefore necessary to shift the for eigenvalue extraction to 0.1 Hz in order to determine modes forms in global behaviour.

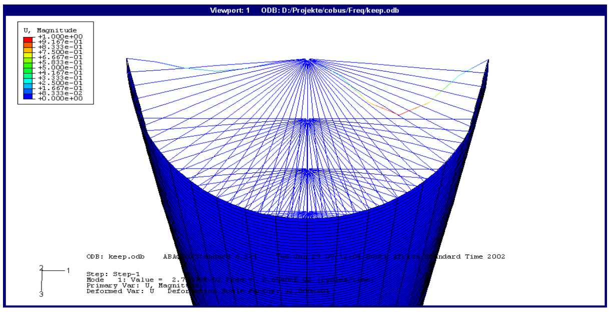

Fig. 14

The first global mode forms at a frequency of 0.3133 Hz, which corresponds to a wind speed of 250,632 m/s. See Fig 15 for visualisation.

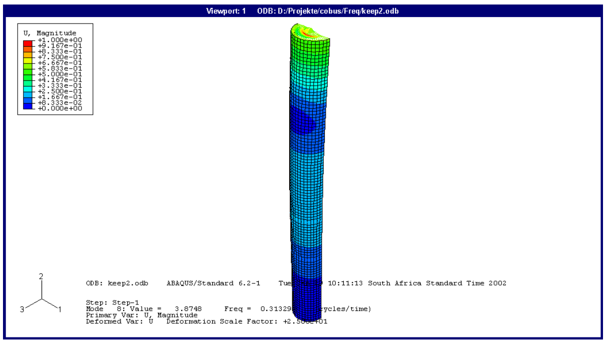

Fig. 15

These results are satisfying, firstly because it shows, once again, the significant effect the adding of the six stiffeners have on the performance of the global structure – the critical wind speed for the global structure corresponding with the first modes has increased from 80.8 m/s to 250.632 m/s.

Secondly the corresponding wind speed is more than double the maximum expected wind speed for a period of up to 100 years, for the height of 1600 metres, of 107.783 m/s [4].

It can be assumed that for wind speeds of up to 250.632 m/s the stiffener beams will absorb the forces in local buckling.

4.3 Further information.

The occurrence of typical folding, buckling shapes seen in cylindrical structures of this nature, as often found in cooling tower design. These occur, in the unstiffened chimney, at higher frequencies than that corresponding to the first mode. Fig 16 shows some of these modes.

Global action such as is shown in the above figures would be generated only in rare load cases, such as extreme vertical convection of the air around the chimney structure.

Added mass. Elementary hand calculations yield that the effect of these added masses are trivial, and can therefore be ignored.

4.4 Practical implications

Configuration of parameters. Results such as those found in the frequency analyses yield the prospect of scaling down, or configuring some of the dimensions and characteristics of the concrete chimney and the steel stiffeners.

For example, the most vulnerable part of the global structure is the top 500 metres with constant wall thickness of 0.250 metres. Many of the extreme deformations, as well as the deformation because of frequency generation, take place here. Our analyses reveal nothing about real stresses and strength, only that a higher stiffness is required for the structure – consequently adding more reinforcement steel will not necessarily solve this problem.

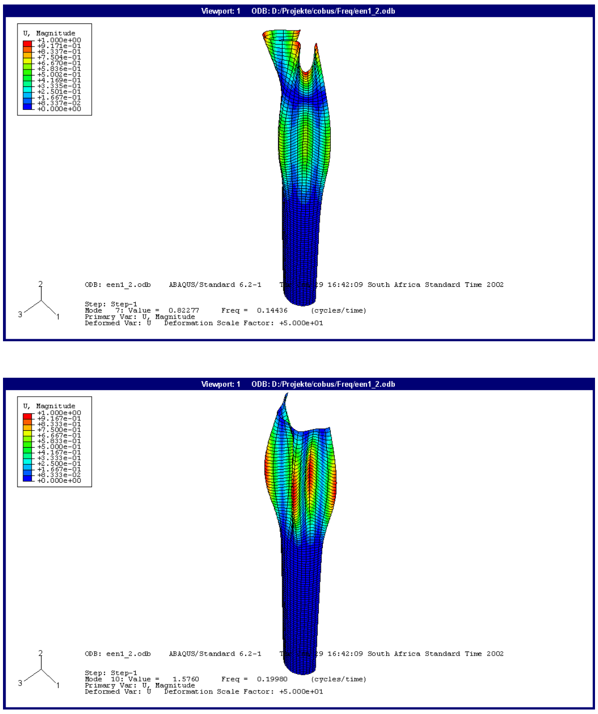

Fig 16

During interpretation of many of the visualizations of the analyses it became apparent that the change from linearly decreasing to constant wall thickness caused sudden behavioural changes or response. A proposal for further study would be this aspect – smoothening the conversion from linear to constant wall thickness.

The only definite is that there is still a lot of research to be done on a solar chimney of such great dimensions.

Solution: two rings. The presence of local modes at very low wind speeds is a great source of concern, especially when viewed in the light of the fact that the stiffeners play a cardinal role in the sustenance, as an effective structure, of the solar chimney.

A proposed solution lies in adding another ring(s) on the structure of the ring stiffener, just as in the case of the static analysis.

Two rings: advantages. There are several advantages to the application of another ring:

- **Shortening effective length.** Adding another ring will stabilize the deformation of the stiffener structure while under loads due to wind pressure on the chimney shell. In Fig 14 the stiffeners undergo excessive deformation. (This figure is taken from the first global bending mode.) By adding the second ring the effective length of the stiffener beams (local deformation) shortens considerably, causing increased resistance against bending, making way for a more stable structure.

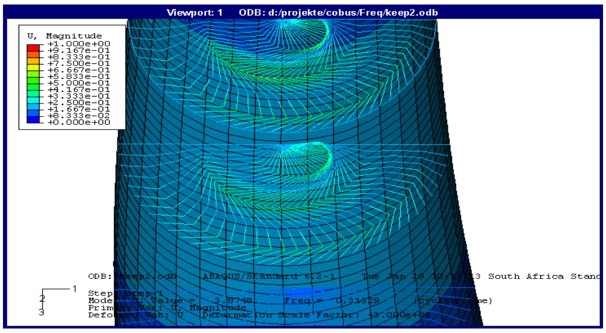

Fig. 14

- **Strengthening global structure by uniting individual beams.** Globally the second ring on the stiffener structure will hold the individual beams in place, making the stiffener sounder as an entity. The local buckling modes of the beams will now occur at higher frequencies, hopefully higher than the global buckling modes.
- **Extreme bending.** Another fear overcome by the improvement is the separation of individual beams from getting in each other's way. Previous analyses have shown that under severe deformation the stiffener beams bend through to such an extent that, eventually, they touch each other. This phenomenon leads to more uncertainty in the design of the chimney, and the second ring improves this problem.
- **Torsional bending.** Torsional bending could very easily take place in the individual beams because of their slenderness and extensive effective length. Again shortening this length will reduce the danger of torsional bending. The physical constraint that the fastening (welding) will exert on the beams will contribute to lessen the effective length.

Two rings: disadvantages. Excessive research had been done on the effects of the single-ring stiffeners. The energy loss, due to air friction and turbulence exerted by air passing the stiffeners, was always a major concern. Adding another ring would add to this loss. The extent to which energy is lost by adding another ring would determine whether it is at all an option. The fact that not only one extra ring might be necessary to shorten the effective length of the beams sufficiently will worsen the prospect.

5. PROPOSALS FOR FURTHER STUDY

Much research is yet to be done on the solar chimney. Everyday there are new ideas for the improvement of the solar chimney.
The following subjects are areas encountered during the work on this paper:

- In depth study into wind speed at great heights.
- A detailed study on the chimney foundation, its interaction with the turbine, inlet guide vanes and other vital parts of the solar chimney. The use of fin stiffeners would be included in such a study.
- A material and innovative study for further ring stiffener optimisation (the relation between inner ring weight and the elasticity modulus).
- Shell thickness optimisation.
- Reinforcement steel quantity survey.

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