Aerodynamics of ancient egyptian Obelisks and their structural response to Boundary Layer wind

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Abstract
Ancient Egyptian obelisks have been carved thousands of years ago and survived many earthquakes and wind storms. This study examines the aerodynamic characteristics and the response of two of the tallest and slenderest ancient Egyptian obelisks to boundary layer winds using a two-phase methodology. The firstphase involved preparing computational fluid dynamics (CFD) models for the two obelisks with different angles of projection to wind. The variations in the wind pressure coefficient and the forces on the obelisks have been studied for different projection angles, different reference velocities and along the height of each obelisk. Within the second phase structural analysis was performed subjecting each obelisk to a wind load under different angles of loading. The results show that when subject to boundary layer winds, the pressure coefficient on the surface and the stresses within the obelisks vary significantly with the angle of attack and dimensions of the obelisk.

Highlights:
● This study examines the aerodynamic characteristics and the response of two of the tallest and slenderest ancient Egyptian obelisks to boundary layer winds through CFD modeling followed by structural analysis.
● The variations in the wind pressure coefficient, the forces and stress have been studied for variations in angles of projection, velocities and along the height for each obelisk.
● The pressure coefficient and the stresses within obelisks vary significantly with the angle of attack and dimensions of the obelisk.

Keywords CFD · Wind Engineering · Obelisks · Structural analysis · Pressure coefficient · Ancient egyptian monuments
1 Introduction

Several fascinations of the ancient Egyptian engineering exist today, one of these fascinations are obelisks. A good number of obelisks are currently located in major cities in Europe and North America after being transported from Egypt, in addition to other obelisks still existing in Egypt. The number of obelisks with a height exceeding 10 m could be more than 50 [1]. Natural disasters and soil problems are considered the main reasons for the drop in numbers of obelisks existing today compared to thousands of years ago. One of the most famous obelisks is the one currently located in the Vatican. This obelisk was moved to Italy during the Roman rule of Egypt and then repositioned to the Piazza di San Pietro in the sixteenth century. On the other hand, the tallest of all ancient Egyptian obelisks is the Lateran obelisk. That obelisk was raised in Laterano in Rome in the sixteenth century [1].

Meanwhile, historical and geological evidences confirmed that ancient Egyptian obelisks were carved from the granite formation located in Luxor, Egypt [2]. The granite from which the obelisks are carved is generally called the “Red Aswan Granite” consisting of reddish feldspar crystals together with quartz, plagioclase and biotite [3] [4]. The properties of this granite have been experimented by [5] and it was found that this material had an average compressive strength of 140 MPa which is nearly quadruple that of concrete however it experienced a brittle mode of failure with no plastic deformation experienced by any of the tested samples. Within that same study, it was found that the average modulus of elasticity was 5.4 GPa [6] studied the response of five different obelisks when subject to seismic loading. That was done by performing a free vibration analysis followed by a time-history dynamic analysis. The high modulus of elasticity of this material (when compared to other natural stones) was found to be the main reason for the relatively low lateral deflections and low stresses when subject to earthquakes [6].

Furthermore, one of the main things that makes obelisks unique from a wind engineering perspective is their slenderness. The height to width ratio of such structures could vary from 9 to 12 which makes such structures considered to be significantly slender. This is a point of similarity that these structures share with tall buildings as a sky-scraper could approach that range of slenderness ratio however the difference in scale between skyscrapers and obelisks is expected to cause a different response to wind loads. Extensive research was conducted on the response of tall buildings to wind loads by numerous researchers like [7] [8], [9], [10] and [11] within the past four decades however nobody has studied the behavior of obelisks under wind loading.

Most of the research studying the pressure coefficients of tall buildings was either using field results that are very difficult to acquire or relatively expensive wind tunnel testing or CFD modeling. It has been proven that although field results and experimental results are the most accurate techniques to model tall buildings subject to boundary layer winds, CFD modeling could provide sufficiently accurate results especially with proper meshing and boundary conditions [12] [13] [14]. However, the slenderness of the buildings studied by the vast majority of researchers was less than the slenderness of a typical ancient Egyptian obelisk which could have a height-to-width ratio ranging from 9 to 12. This fact could cause the wind pressure distribution on the surface of an obelisk to be significantly different than that of a tall building in addition to the fact that it will make it less stiff.

Another unique feature of ancient Egyptian obelisks is the taper that they have. The cross section dimension of each obelisk varies with its height with a significant taper that could
have a taper ratio ranging from 26 to 43 [1]. This taper may affect the pressuredistribution on the surface of each obelisk. Some of the research studying the response of tall buildings to

Fig. 1 (a) Lateran obelisk (b) Vatican obelisk
Front and top views of Lateran and Vatican obelisks
boundary layer wind was performed on buildings with a taper however not as that of ancient Egyptian obelisks and not as slender[15]. Additionally, no researchers so far has studied the effect of varying the taper of any structure on the pressure coefficients.

Meanwhile, another interesting feature about obelisks is that although they do have a taper, they always maintain a squared cross-section causing each two successive translational modes of vibration to have identical natural periods due to having the same stiffness and mass distribution within the two perpendicular horizontal axes [6]. This is also the reason why the torsional mode of vibration was a very high mode causing no torsional component of the response when such structures were subject to lateral earthquake loads as the perfect symmetry caused the center of mass and the center of rigidity to coincide negating the presence of any torsional effects [6]. A similar behavior is expected to happen if wind loads are applied on such structures provided that these loads are symmetric on the structure itself; however, no researcher has studied the response of ancient Egyptian obelisks to wind loads till now further than studying the effect of taper and height variation.

Unfortunately, until this research at hand has been initiated, no research was done to study the variation of the wind pressure and the pressure coefficient on the surfaces of slender structures with a taper similar to that of ancient Egyptian obelisks. Furthermore, nobody studied the structural response of these obelisks under any type of wind loading to determine whether such structures will fail due to wind loads or not. This scarcity of information regarding their response of obelisks to wind loading initiated the need for the current presented research.

The objective of this research is to study the pressure variation within obelisks when subject to boundary layer wind with the obelisks’ heights and taper and under different angles of attack (θ). Furthermore, it is necessary to determine the most critical wind load case that will cause the largest stresses within each of these structures. This is necessary to determine whether such structures could fail due to wind loads or not.

Fig. 2 The four different studied loading directions
In order to achieve this goal, CFD models were prepared for two of the longest existing ancient Egyptian obelisks located in Lateran and the Vatican having different heights, cross-sections and tapers as shown in Fig. 1. The CFD modeling was performed for each obelisk under four different angles of projection to the wind load as shown in Fig. 2 and for three different reference velocities hence performing twenty four different CFD models. The output of this process was used to perform structural analysis for each of the studied obelisks under their different load cases representing the different angles of attack. Finally, the most critical load case was determined for each obelisk based on the maximum stresses identified from the structural analysis stage. The endresult is a quantification of the variation in the pressure coefficient on the surfaces of the two ancient Egyptian obelisks under study. Additionally, the stresses within the two obelisks under different angles of projection to boundary layer wind are acquired, providing an assessment of the obelisks’ structural performance that will inform the scientific community whether these obelisks need to be further protected from wind loads or not.

2 Materials and methods

2.1 Mathematical modeling

The present mathematical research was built on solving 3-D principal equations that described airflow around two ancient Egyptian obelisks (one at a time) by the CFD program fluent ver. 19.0 [17]. This mathematical approach solves the partial differential equations (PDEs) governing the transport of mass, three momentum, in a fully turbulent three dimensional domain under steady state and incompressible ideal gas conditions. In addition the standard k-ε model equations for turbulence closure were used. The different governing partial differential equations are usually expressed in a general form as:

\[
\frac{\partial}{\partial x} \rho U \phi + \frac{\partial}{\partial y} \rho V \phi + \frac{\partial}{\partial z} \rho W \phi = \frac{\partial}{\partial x} \left( \Gamma_\phi \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma_\phi \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_\phi \frac{\partial \phi}{\partial z} \right) + S_\phi
\]

Where \( \rho \) represents the air density, \( \phi \) represents the dependent variable, \( S_\phi \) represents the source term of \( \phi \), \( (U, V, W) \) are the velocity vectors, and \( \Gamma_\phi \) represents the effective diffusion coefficient.

The standard k-ε model was chosen based on an earlier comprehensive verification study of the buildings for the aerodynamics of a building, including the standard, Renormalization Group (RNG) k-ε model and realizable, the standard k-ω model, Large Eddy Simulation and the Shear Stress Transport (SST). A study, presented by [16], showed that the k-ε model was capable of more accurately predicting aerodynamic clouds, with a variation that is less than 3% compared to the result of the corresponding wind tunnel.

2.1.1 Mesh generation

Figure 3 represents an ancient Egyptian obelisk, which has main domain dimensions \((12 \ H \times 3 \ H \times 4 \ H)\) (length \times height \times width) where \( H \) is the obelisk height, meshed with more
than $1.936 \times 10^7$ tetrahedral cells. The mesh on the obelisk wall has a size of 0.1 m with an inflation on the obelisk walls. The first layer value is 0.1 m and increases to 1 m with the remaining whole domain, and the rest of the field is 1 m. The domain size has been optimized, to optimize the mesh size and the computing time. This control volume has been previously proven to be sufficient [18]. Fine meshing around obelisk walls is used to precisely capture boundary layer characteristics and hence boost model dependability. A grid independence research was carried out to guarantee the numerical solution’s stability and convergence, as well as its independence from the mesh size chosen. The exterior model of the
configuration is created using well-known solid modeller Pro-Engineer and ANSYS ICEM-CFD. The ICEM-CFD generated surface configuration is used to generate a good mesh in the form of a mesh file. Fluent ver. 19.0 solver is used to solve the generated domain matrix equations while CFD-post is used to imagine the results. Figure 4 demonstrates grid independence check. The mesh dependency was studied by solving the flow field for seven mesh configurations made of (2.35 × 10^7, 1.936 × 10^7, 1.6742 × 10^7, 1.3678 × 10^7, 1.0968 × 10^7, 8.825 × 10^6 and 6.621 × 10^6 cells) respectively, results presented that 8% variance in the pressure-coefficient between the coarser and finer mesh and less than 0.07% variance exists between the two finer meshes.

### 2.1.2 Boundary conditions

At the inlet, uniform velocities of 20, 25 and 30 m/s (with different angles of projection to wind 0°, 15°, 30° and 45°) are applied with a turbulence intensity of 5%, demonstrating air movement due to wind speed. When based on the building heights, the corresponding Reynolds numbers \( \text{Re} = \frac{\rho U H}{\mu} \) for Lateran and Vatican obelisks had values of (40.24 × 10^6 – 47.44 × 10^6) and (31.62 × 10^6 – 40.24 × 10^6), respectively. Based on the building width, the Reynolds numbers are (3.74 × 10^6 – 5.6 × 10^6) for Lateran and (3.35 × 10^6 – 5 × 10^6) for Vatican obelisks [19]. The obelisk body surface was demonstrated as a no-slip boundary wall with zero roughness representing the actual condition of the obelisks due to the nature of the granite surface from which they were made. For the lowest and upper side’s boundaries of the domain, a slip-wall boundary (symmetry) was used. At the exit of the computational domain, atmospheric static pressure was selected.

![Fig. 5 Standard k-ε Simulation Results Compared to Wind Tunnel Measurements [13]](image)
2.1.3 Validation

The CFD model used within the current study was compared to a previously published research paper that provided an experimental and numerical comparison of mean pressure coefficient \( C_p \) within the wind tunnel\[13\]. This comparison was performed to examine the validity and applicability of the current CFD model. The standard k-\( \varepsilon \) turbulence model is employed in the simulation and the results are compared against the experimental results\[13\], as presented in Figure 5. This model was picked from a pool of several different turbulence models because it matches the experimental data well.

2.1.4 Numerical Solutions

Pressure-velocity coupling was selected as the coupled algorithm, pressure interpolation was PRESTO and 2nd-order upwind finite difference schemes were used for both the viscous terms and the convection terms of the governing equations. Gradients are computed with the green-gauss node based method. The simulations were achieved with the commercial CFD code ANSYS Fluent 19.0, which uses the control volume method. Convergence was carefully checked and the iterations were finished when not the entire residue showed any additional decrease with an increase in the number of iterations. Besides, the scaled residuals were about \( 10^{-4} \) for continuity, turbulent kinetic energy, turbulence dissipation rate and \( 10^{-5} \) for momentum. While solving the program, important variables like \( (C_p) \) should be monitored to ensure that the solution is convergent.

The pressure coefficient is defined as:

\[
C_p = \frac{(P - P_{\infty})}{0.5 \rho U_{\infty}^2}
\]  

Where the reference static pressure (atmospheric pressure) \( (P_a) \), \( P \) is the static pressure \( (P_a) \), \( \rho \) is the density of air \( (\text{kg/m}^3) \) and is uniform inlet velocity \( (\text{m/s}) \).

2.2 Structural analysis

The four different angles of attacks studied represent the four different wind load cases studied for each of the two obelisks. The pressure was multiplied by the surface area to give the load perpendicular to the surface. This load was applied within the structural analysis process to acquire the stresses within each obelisk under each of the four studied load cases.

Each of the two obelisks was modeled on SAP2000 \[20\], in which 3-D 8-node solid finite elements were utilized. The choice of such elements was to represent the stiffness along the obelisk height in the most accurate way as the significant taper within each obelisk will cause a variation within its moment of inertia along its height. If 1-D or 2-D elements were used, the analysis would have been significantly inaccurate within at least one dimension; however, using 3-D elements guarantees the highest achievable accuracy in the analysis. Each of the two obelisks was modeled in its original dimensions representing the condition of each during the era in which it was originally carved.

Each of the four load cases representing the different angles of attack has been applied on each of the two modeled obelisks. The forces produced by the CFD were used in the struc-
tural analysis of each of the two obelisks when subject to a 30 m/s wind event at the four different projection angles. The target of this exercise is to determine the most critical wind load case for each of the two obelisks.

In order to determine whether a static analysis is sufficient or a dynamic analysis will be needed, the natural frequencies of the obelisks were compared to the dominant frequencies of winds. The natural frequencies of vibration of the two modeled obelisks are 1.015 Hz for the Lateran Obelisk and 1.308 Hz for the Vatican Obelisks as reported by [6]. These values of natural frequencies are significantly higher than the values of dominant frequencies of winds which can be as low as $10^{-3}$ Hz or even $10^{-4}$ Hz [21] [22] [23]. Hence, the analysis performed was a static analysis as there was no need to analyze these structures dynamically.

3 Results and discussion

The pressure coefficient contours at 60% of the height of the Vatican obelisk are shown in Fig. 6. As expected, a symmetric distribution of pressure is shown in Fig. 6a and d representing the 0° and 45° cases respectively as each of these two cases is a symmetric load case and the distribution of pressure is expected to be symmetric for these cases. Meanwhile, the two asymmetric load cases of the 15° and 30° have caused an expected asymmetric pressure distribution as shown in Fig. 6b and c. A very similar behaviour is seen when examining the pressure coefficient contours at 60% of the height of the Lateran obelisk are shown in Fig. 7 in which a symmetric distribution of pressure for the symmetric load cases is shown in Fig. 7a and d while, the two asymmetric load cases have caused an asymmetric pressure distribution.

![Fig. 6](image)

Fig. 6 The pressure coefficient contours at 60% height of the Vatican Obelisk for 4 different angles of wind projection.
distribution as shown in Fig. 7b and c. However, although the distributions of pressures for the two obelisks look similar, the values of the pressure coefficients for the Vatican obelisk are different from their counterparts in case of the Lateran obelisk. For most of the cases, the values of the pressure coefficients for the Vatican obelisk were higher than their counterparts in the Lateran obelisk. This could be attributed to the differences in taper and slenderness between the two obelisks as the Lateran obelisk is more slender than the Vatican obelisk while the Vatican obelisk has a more significant taper as shown in Fig. 1.

Furthermore, the variation of the maximum positive pressure coefficient ($C_{p_{\text{max}}}$) along the height of the Vatican obelisk and Lateran obelisk is shown in Fig. 8. The maximum positive pressure coefficients for the Vatican obelisk shown in Fig. 8 are slightly larger than the maximum positive pressure coefficients for the Lateran obelisk. However, it could be noticed that for each projection angle the differences in $C_{p_{\text{max}}}$ between the two obelisks are negligible. The general trend of a nonlinear increase of the maximum positive pressure coefficient with the height very similar to the boundary wind velocity profile is common between the two obelisks as shown in Fig. 8.

Meanwhile, the situation seems different for the maximum negative pressure coefficient ($C_{p_{\text{min}}}$) that is shown in Fig. 9 as a unique trend was experienced for each of the four angles of wind projection studied. In general, and for both obelisks, the cases with small angles of 0° and 15° have experienced higher magnitudes of suction than the larger angles of 30° and 45°. However, the trends of the variation of the maximum negative pressure coefficients of the Vatican obelisk shown in Fig. 9 are different from those of the maximum negative pressure coefficients of the Lateran obelisk. These differences are more significant when examining the cases with small angles of 0° and 15°. This significant change could be attributed to the

![Fig. 7 The pressure coefficient contours at 60% height of the Lateran Obelisk for 4 different angles of wind projection](image-url)
fact that the suction for these cases had higher values than the other two cases with larger angles and these high values are more sensitive to the differences in slenderness and taper than the low values experienced by the 30° and 45° angles as the taper and slenderness of these two obelisks are significantly different as shown in Fig. 1.

Figures 10 and 11 show the vertical variation of the pressure coefficient contours at an angle of attack of 0° for the Vatican and Lateran obelisks respectively. The pressure coefficient contours in the vertical plane perpendicular to the wind are shown in Figs. 10a and 11a while those in the vertical plane parallel to the wind are shown in Figs. 10b and 11b. The variation in the pressure coefficients in the vertical plane perpendicular to the wind are very similar for both obelisks showing an increase in the negative pressure with height till reaching the maximum negative pressure at the location of the pyramid on at the top of each obelisk however the difference in taper and difference in slenderness between the two obelisks caused the negative pressure on the Vatican obelisk to be higher than that acting on the Lateran obelisk as the Lateran obelisk has a higher taper and is more slender as shown in Figs. 10a and 11a.

On the other hand, the variation in the pressure coefficients in the vertical plane parallel to the wind are very similar for both obelisks showing an increase in the positive pressure with height in the windward direction. However, the difference in the taper of the pyramid on each obelisk caused the pressure coefficients to significantly differ between the two obelisks at the location of the pyramid as shown in Figs. 10b and 11b.

Figures 12 and 13 show the vertical variation of the pressure coefficient contours at an angle of attack of 45° for the Vatican and Lateran obelisks respectively. The pressure coef-
The variation in the pressure coefficients in the vertical plane perpendicular to the wind are very similar for both obelisks showing an increase in the negative pressure with height till reaching the maximum negative pressure at the location of the pyramid at the top of each obelisk. However, the difference in taper and difference in slenderness between the two obelisks caused the negative pressure on the Vatican obelisk to be higher than that acting on the Lateran obelisk as the Lateran obelisk has a higher taper and is more slender as shown in Figs. 12a and 13a.

**Fig. 9** Variation of the maximum negative pressure coefficient along the height of the two obelisks for 4 different angles of projection

**Fig. 10** Vertical variation of the pressure coefficient of the Vatican Obelisk for a 0° angle of wind projection
On the other hand, the variation in the pressure coefficients in the vertical plane parallel to the wind are very similar for both obelisks showing an increase in the positive pressure with height in the windward direction. However, the difference in the taper of the pyramid on in Fig. 13

Fig. 11 Vertical variation of the pressure coefficient of the Lateran Obelisk for a $0^\circ$ angle of wind projection

Fig. 12 Vertical variation of the pressure coefficient of the Vatican Obelisk for a $45^\circ$ angle of wind projection

Fig. 13 Vertical variation of the pressure coefficient of the Lateran Obelisk for a $45^\circ$ angle of wind projection

On the other hand, the variation in the pressure coefficients in the vertical plane parallel to the wind are very similar for both obelisks showing an increase in the positive pressure with height in the windward direction. However, the difference in the taper of the pyramid on in
each obelisk caused the pressure coefficients to significantly differ between the two obelisks at the location of the pyramid as shown in Figs. 12b and 13b.

**Fig. 14** Variation of the total wind load acting on the Vatican obelisk with the angle of projection for different wind velocities.
Meanwhile, the variations of the total wind forces with the angles of projection for different velocities are plotted for the Vatican obelisk and the Lateran obelisk and shown in Figs. 14 and 15 respectively. As expected for both obelisks, the magnitudes of the forces increase with the increase in wind velocity and the major component of the force for all of the cases is in the x-direction as shown in Figs. 14a and 15a which is the direction parallel to the wind load itself. When examining the total forces in the z-direction (perpendicular to

![Graph showing variation of total wind force with angle of projection.](image)

**Fig. 15** Variation of the total wind load acting on the Lateran obelisk with the angle of projection for different wind velocities.
the wind load) shown in Figs. 14b and 15b, the forces were clearly of lower order than the forces parallel to the wind direction and these transverse forces were 0 for the two symmetric cases of 0° and 45° angles which is expected to happen. Meanwhile, the general trend for the resultant forces shown in Figs. 14c and 15c show a general trend of the forces increasing with the angle of projection angle reaching a maximum value at an angle of 45° causing this angle to be the most critical load case for both obelisks. Also as expected when comparing the resultant forces acting on the Vatican obelisk shown in Fig. 14c to the resultant forces acting on the Lateran obelisk shown in Fig. 15c, the forces acting on the Lateran obelisk were significantly higher than the forces acting on the Vatican obelisk which could be attributed to the fact that the Lateran obelisk was larger in size and hence larger in surface area subject to wind load.

Furthermore, the variation of the total resultant force with the wind velocity was directly proportional to the square of the velocity as shown in Fig. 16. This is considered as proof that the results produced by the CFD are valid and sufficiently accurate in terms of obeying the principal relationships between the wind speed and the wind force.

The forces produced by the CFD were used in the structural analysis of each of the two obelisks when subject to a 30 m/s wind event at the four different projection angles. The maximum force reached at an angle of 45° caused the highest normal stresses within each of the two obelisks as shown in Fig. 17, where the normal stresses increased with the increase in projection angle. Meanwhile, and despite the fact that the Lateran obelisk had a larger cross-section and was expected to have lower stresses, the maximum normal stresses within the Lateran obelisk was higher than the maximum normal stresses in the Vatican obelisk. This is due to the higher wind forces acting on the Lateran obelisk compared to the Vatican obelisk in addition to the fact that the Lateran obelisk was taller hence the bending
moments experienced by this obelisk were larger than its Vatican counterpart. However, all of these maximum stresses were even less than 0.35 MPa which is significantly less than the strengths reported by [6]. That could explain how these structures existed for millennia and survived natural disasters along that long period of time as the material used to carve these structures had a strength that was higher than any stresses these structures could encounter while loaded laterally.

4 Conclusions and recommendations

In lieu of the results found, the following could be concluded:

- The CFD models have proven to be valid in terms of producing symmetric pressure coefficient contours and symmetric resultant forces for the symmetric load cases of angles of attack of 0° and 45°.
- The CFD models have proven to be valid in terms of producing resultant forces that are directly proportional to the square of the reference wind speed.
- The slenderness and the taper are the main factors that govern the variation in pressure coefficient whether along the vertical or horizontal planes.
- The variation of the pressure distribution at the top of the obelisks significantly varied with the dimensions and angles of the pyramid existing at the top of each obelisk.
- The largest resultant forces were achieved at an angle of 45° for both of the studied obelisks.
- The largest normal stresses were achieved at an angle of 45° for both of the studied obelisks.

Fig. 17 The maximum normal stresses within the two studied obelisks due to different wind load projection angles
For all of the four different angles of attack included in the study, the total resultant forces acting on the Lateran obelisk were larger than the total resultant forces acting on the Vatican obelisk mainly due to the larger surface area of the Lateran obelisk.

The structural analysis revealed that for all of the four different angles of attack included in the study, the normal stresses were significantly lower than the strength of the Red Aswan granite from which the obelisks were carved.

For all of the four different angles of attack included in the study, the structural analysis revealed that both obelisks could safely withstand boundary layer winds with reference speeds as high as 30 m/s.

The following recommendations could be drawn from the performed study:

- The responses of the obelisks to wind load need to be experimentally studied in wind tunnel tests in order to study the effects of turbulence, presence of surrounding structures and terrain variations.
- The responses of the obelisks need to be studied under high intensity winds such as downbursts and tornadoes.
- Thorough studies need to be performed by engineers in cooperation with Egyptologists to further understand how the ancient Egyptians designed such obelisks to withstand such winds further than how they designed them.

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