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Forensic Analysis of Wind Power Generator Tower Cracking

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Abstract

Generators that produce electricity for modern wind farms are mounted atop large steel towers. The hollow cylindrical towers, which are typically more than 250 feet in height, are fabricated from mild steel plates (approximately 1-inch-thick and 10 to 12 feet in diameter). Cracks in the steel plates measuring more than 4 feet long were observed in such a tower. The author was retained to determine the cause of the cracking and if that cause was a result of incorrect design (owner) or poor fabrication quality (contractor). Laboratory examination of the crack morphology and finite element analyses techniques were used to characterize the root cause of the failure. Cyclic loading on the tower was developed from wind rose data for the site. It was ultimately shown that the cause of the steel plate cracking was flow-induced vibrations resulting from von Karman street vortex shedding — not the fore-aft loads of the direct wind forces on the blades.

Keywords

Forensic, wind tower, flow-induced vibration, vortex shedding, crack initiation due to vibration

Background

A forensic analysis was performed to determine the cause of failure of a wind turbine tower at a wind farm in New Mexico in the spring of 2011. A review of documents revealed the following facts: During a routine inspection of the tower, a technician noticed a crack in the middle splice of the steel tower structure. At that location, a forged flange is welded to the rolled tower shell section. According to a report issued by a large, nationally recognized metallurgical laboratory, a crack initiated at the toe of the full penetration weld that joins the flange to the rolled shell section. The laboratory report provided a detailed description of the failed section and how the origin of the crack was determined.

The flange of the tower section is fabricated from ASTM A694 Grade F42 material. The tower shell is fabricated from ASTM A572 Grade 50 or ASTM A709 Grade 50F. The flange is welded to the shell at the neck by means of submerged arc welding using a complete joint penetration (CJP) weld preparation (groove). The welding was performed in accordance with American Welding Society (AWS) specifications. The welded materials are compatible, including the welding rod, and have been used for this application for many years. The welding was performed in accordance with shop weld procedures prepared by the fabricator and approved by the owner, using certified welders that were qualified in the process used. All welding was inspected before the towers were shipped. **Figure 1** shows a schematic drawing of the wind tower. The failure was observed between Section 2 and Section 3. No other weld failures were found in the tower.

Wind turbines are almost always located at sites that experience prevailing winds from one dominant direction. Locations for wind farms are selected very carefully. Typically, a wind and enviromental measuring station is placed at a candidate site and monitored for at least one year. The wind velocity and direction are measured and recorded. In order to be economically viable, the average wind velocity at the site must be more than approximately 18 to 20 mph for a large percentage of the time. Some basic definitions for wind speed (relative to turbines) include:

- *Start-up speed* — This is the speed at which the rotor and blade assembly begins to rotate.
- *Cut-in speed* — The minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7 and 10 mph for most turbines.
- *Rated speed* — The minimum wind speed at which the wind turbine will generate its

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designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 25 mph. Rated speed for most machines is in the range of 25 to 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs called "power curves" that show how their wind turbine output varies with the wind speed.

- *Cut-out speed* — At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shutdown occurs is called the cut-out speed or sometimes the furling speed. Having a cut-out speed is a safety feature that protects the wind turbine from damage.

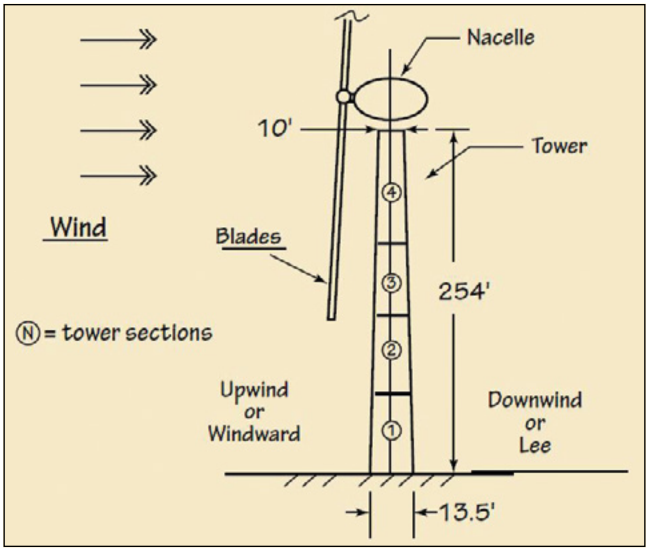

Figure 1
Wind tower schematic drawing.

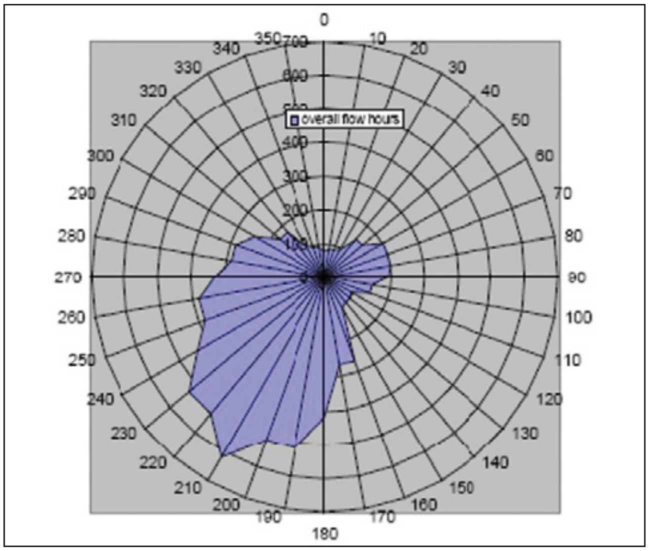

Figure 2
Wind rose for site of tower.

The data obtained from the site measuring station is used to develop a "wind rose," which is shown in **Figure 2**. The wind rose graphically displays the overall wind flow hours and the direction of the wind. The prevailing wind direction can be clearly seen from **Figure 2** to be from the southwest. Since only the nacelle (on which the blades are mounted) is rotated such that the blades face the wind, the upwind/downwind directions for the tower change (depending upon wind direction). However, when the prevailing wind is predominately from the southwest (as in this case), the loading on the tower is dominated by a primary load path shown in **Figure 3**. The location of the crack in the tower is also shown in **Figure 3**. **Figure 4** shows the crack in the tower before the section was removed and taken to the laboratory. The presence of iron oxide stains indicates that the crack existed in the steel for a considerable length of time before it was discovered, which could suggest that maintenance at the site was inadequate. The crack extended a total of 2,110 mm (83 inches) around the circumference.

As can be seen in **Figure 2** and **Figure 3**, the primary loading on the tower is from the southwest toward

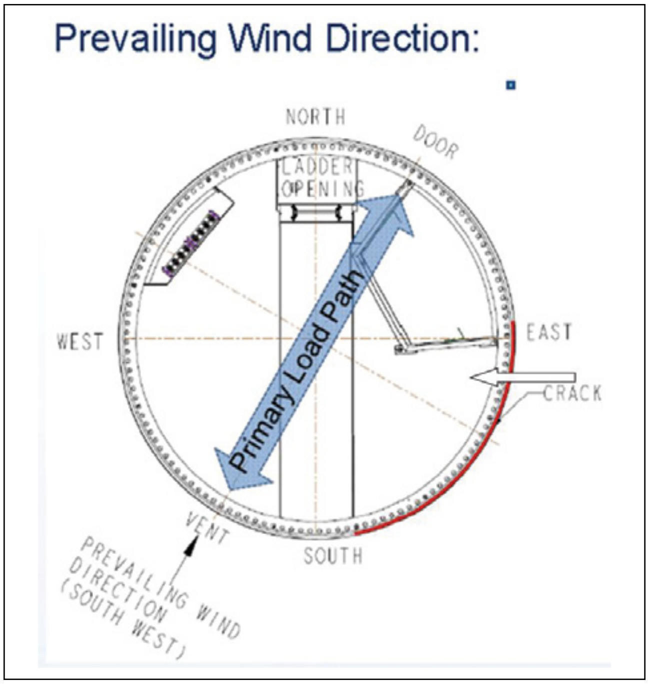

Figure 3
Location of crack with respect to wind direction.

the northeast. Further, the primary direction wind load will result in a tensile load on the southwest side of the tower and compression on the northeast side. The bending stress distribution is shown in **Figure 5**. The crack is located almost exactly at the neutral axis of bending, where the bending stresses are very low. Further, the wind history indicated that site was almost never becalmed. A more or less constant wind would not produce reversed cyclic loading because the upwind side will always be in tension, and the downwind side would almost always remain in compression. Even more confounding, the weight of the tower shell above the crack plus the weight of the nacelle and blades provide a downward force at the crack location. This loading results in compressive stresses on the tower shell at the location of the crack. Virtually all cracks that result from cyclic loading involve a stress cycle in which there is a tensile stress component. In other words, some part of the loading cycle must result in a net tensile stress at the origin of the crack face. Cracks in steel plates rarely, if ever, initiate in a location that is subjected only to cyclic compressive stresses.

Figure 4
Crack in tower.

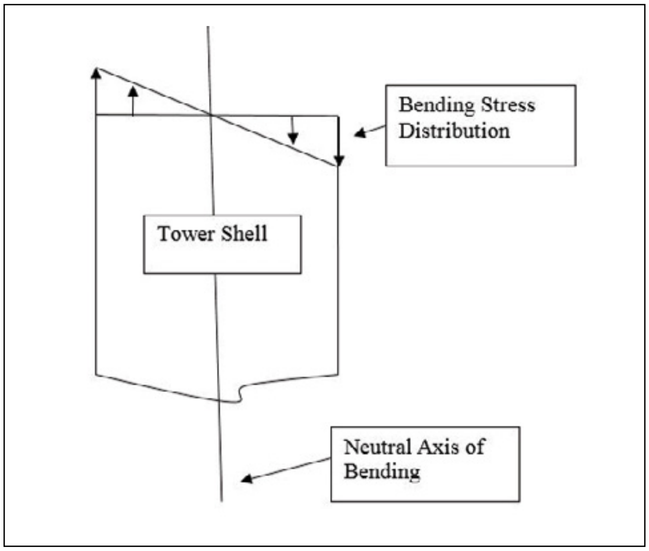

Figure 5
Bending stress distribution.

It would seem that the most logical point to initiate a crack would be the upwind side of the tower, which is subjected to the highest tensile stress. It would also seem logical to assume that the cyclic loading that initiated the crack was caused by the cyclic nature of wind velocity changes, including gusting. This type of loading would result in tensile stresses on the southwest side of the tower and almost no stresses at the actual crack initiation point (90 degrees away). Further, an examination of the tower indicated that there was no significant difference in the geometry at the crack initiation point than at any other point around the tower. The tower was axisymmetric, and no flaws were found at the crack initiation point. Thus, the question arose: Why did the tower crack at the lowest stressed area, and what was the mechanism that caused cyclic stresses of a magnitude to lead to cracking?

The most likely candidate for loading that could cause a crack to form at the observed location is vortex-induced vibration. In Chapter 2 of his seminal book on the subject, Blevins[1] provides an excellent discussion of the mechanism that causes vibration in cylindrical towers and stacks. For smooth cylinders, such as the wind generator tower, lift forces will be developed due to Bernoulli's principle* at the sides of the tower that result in lateral forces (forces perpendicular to the flow direction). The formation and subsequent shedding of vortices that disturb the flow around the cylinder (**Figure 6**) and alternate from side to side provide a harmonically varying (sine or cosine) load on the tower.

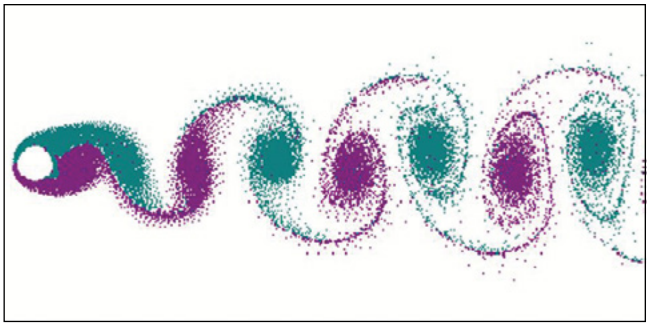

Figure 6
Von Karman street vortex shedding pattern.

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* Bernoulli's principle, i.e., the Bernoulli equation that relates the effects of fluid velocity and pressure effects can be found in almost all books on fluid mechanics. A good introduction to the physics of Bernoulli's principle can be found on the NASA web site at https://www.grc.nasa.gov/www/k-12/airplane/bern.html.

The pattern formed by the vortices is known as a von Karman vortex street. When the frequency of vortex shedding frequency coincides with the first natural frequency of a long cantilevered cylinder, such as the wind tower, then the tower will begin to vibrate in a direction perpendicular to the oncoming wind direction. This is illustrated in **Figure 7**.

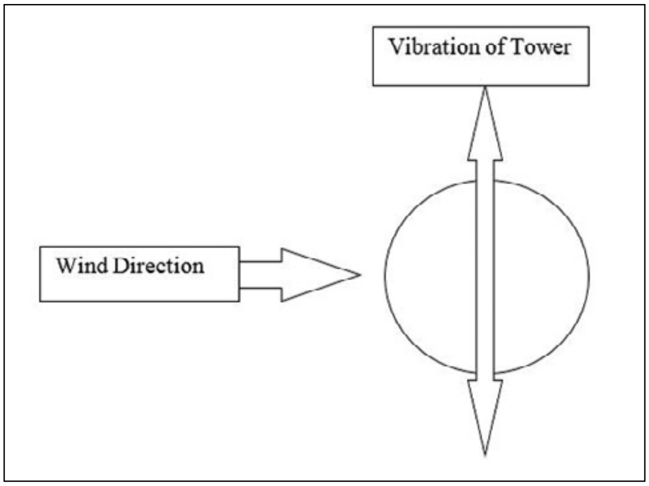

Figure 7
Schematic of wind and vibration directions for cylinder.

This phenomenon can be explained in greater detail as follows. The colors in **Figure 6** (dark and light areas) represent airflow around the cylinder. Vortex shedding is caused by a buildup of the boundary layer on each side of the cylinder, which as it happens, is always out of phase with the opposite side. As a boundary layer builds on the left side, for example, the velocity of the passing air is increased due to the Bernoulli effect — similar to the lift on an airplane wing. This produces a low-pressure zone on the left side of the tower, pulling the tower in that direction. However, the resulting boundary layer is unstable, and collapses into turbulent flow. This will greatly reduce the "lift" on the left side, since turbulent flow is not conducive to producing a net lift effect. This releases the "vortex" that is characteristic of the flow pattern shown in **Figure 6**. However, now the right-hand side of the tower begins to build up a boundary layer in a similar way to the left-hand side. The tower is now pulled to the right by the lower pressure acting on that side. This continues until the right side boundary layer collapses, and the left side begins to build up again. This alternating sequence of pressure patterns, which pulls the cylinder to one side and then the other, provides the sinusoidal driving force that, when occurring at the natural frequency of vibration of the cylinder, can result in large deflections of the tower. This harmonic driving force, while quite small compared to the force of the wind on the blades, causes lateral motion and therefore bending (like a fishing rod) from side to side. The motion is perpendicular to the direction of the wind.

Because the tower is being driven by harmonically varying loading at its natural frequency, the amplitude of the vibration will continue to increase until it is limited by inherent damping in the structure. The tower design is such that hysteresis damping (caused by flexing the steel cylinder and producing heat in the steel) is very low. It was determined that this damping was approximately one to two percent of critical damping. Thus, it is possible for the tower to experience deflection amplitudes of up to one diameter at the point of failure. The effect of the blades moving in air will also provide a form of Coulomb damping (damping that is the result of friction; in this case, motion of the tower and blades resisted by air). Thus, the calculation for maximum amplitude is not straightforward and was not attempted.

Calculation of Vortex Shedding Frequency

Having postulated an alternative loading mechanism for the subject tower failure, it is necessary to show that the tower natural frequency coincided with expectable vortex shedding frequencies. A detailed structural analysis had been performed for the tower by the design engineers and submitted to the local authorities as part of the permitting requirements. A detailed finite element dynamic analysis of the tower, including the nacelle and the blades, was performed. The author used these existing calculations, which showed that the first natural frequency of the tower was 0.341 Hz. The effect of gravity was not included in the design calculations for natural frequency; rather, the author derived an improved formula[2] for calculating the natural frequency of an inverted pendulum. This calculation was made as part of the structural design calculations and used to determine seismic loading on the tower. The mode shape is essentially a cantilever bending mode with the base of the tower fixed against rotation, and the top of the tower experiences the highest deflection.

The vortex shedding frequency can be calculated using the Strouhal number. The equation developed by Strouhal[3] for a smooth cylinder is:

$$f_S = (S)(U)/D \quad (1)$$

Where:

f_S = Vortex shedding frequency (Hz)

U = Free stream velocity approaching the cylinder (feet per second)

D = Cylinder diameter (feet)

Blevins (p 48) shows that for a wide range of Reynolds Numbers (encompassing this case), the value of the Strouhal number is approximately 0.2. Thus, from equation 1 above, the wind speed that will cause vortex shedding at the same frequency as the natural frequency of the tower (f_T) can be determined as follows.

$$f_S = (S)(U)/D = (.2)\ U/D = f_T = 0.341\ \text{Hz} \qquad (2)$$

Rearranging equation 2, find:

$$U = (.341)(D)/.2 = 1.705\ D \qquad (3)$$

The tower diameter varies from 4,120 mm (13.5 feet) at the bottom to 3,620 mm (11.87 feet) in the middle sections and tapers to 3,017 mm (9.89 feet) at the top. At each of these diameters, the free stream velocity (U) to cause vortex shedding (which has the same frequency as the tower natural frequency) can be calculated as follows:

Diameter (feet)	**Free Stream Velocity (ft/sec)**	**MPH**
13.5	23.00	16
11.87	20.23	14
9.89	16.86	12

Figure 8
Free stream velocity necessary to cause vortex shedding at the natural frequency of the tower.

Thus, (for example) if the free stream velocity (wind speed) is exactly 16 mph (**Figure 8**, for a diameter of 13.5 feet), the vortex shedding frequency will be exactly the same as the natural frequency of tower vibration, and the tower will resonate. Once the tower starts to vibrate back and forth (perpendicular to the wind direction), the amplitude of the motion will increase with each cycle until it reaches an equilibrium point where the energy dissipated by the tower motion equals the input energy from the vortex shedding. Of course, the theoretical calculations are never exact, and the wind doesn't blow at a constant speed. Thus, it is useful to investigate the effects of wind speed variation and how this affects the vortex shedding frequency predicted by the Strouhal number.

The available wind data from the site provided only average wind speed over rather long periods of time (reported as quarterly or monthly averages). In order to estimate the wind speeds and how they vary, a normal distribution or Gaussian curve was assumed. This assumption is justified by the fact that most naturally occurring phenomena exhibit a statistical distribution that can be reasonably represented by a Gaussian distribution. Based on this, it can be shown that the wind velocity will be within one sigma (standard deviation) from the mean (average in this case) value approximately 68% of the time. Thus, the wind velocity will tend to vary between plus or minus approximately 35% of the mean value about 68% of the time. Take, for example, a mean velocity of 20 feet per second. The actual wind velocity can be expected to be between a low of 13 feet per second and a high of 27 feet per second 68% of the time. Further, the wind velocity will be closer to the mean velocity more of the time than at the extremes of 13 and 27 feet per second.

As can be seen from **Figure 9**, the vortex shedding velocities for the various tower diameters fall within the measured wind velocities. Taking into account the Gaussian distribution (**Figure 10**), which shows that the one-sigma variation of the wind speeds can vary significantly from the average, every diameter of the entire tower will have vortex shedding frequencies in the range of measured wind speeds. This velocity distribution, combined with measured wind velocities at the site, ensures that the tower could experience some flow-induced vibration over a significant portion of time during the course of every year.

However, there is yet another mechanism that will further increase the already high probability that the tower will resonate with the prevailing winds at the wind farm site. This is the effect of the cylinder *motion* on the frequency of vortex shedding. Blevins[1] states that:

"Transverse cylinder vibration (i.e., vibration perpendicular to the free stream), with frequency at or near the vortex shedding frequency, has a large effect on vortex shedding. The cylinder vibration can:

1. Increase the strength of the vortices.
2. Increase the spanwise correlation of the wake.
3. Cause the vortex shedding frequency of cylinder vibration. This effect is called lock-in or synchronization…"

Date	Wind Speed Average M/sec	Wind Speed Average Ft/sec.(MPH)
2009	7.38	24.0 (16.4)
Q2-2009	5.79	18.8 (12.8)
June 2009	5.79	18.8 (12.8)
Q3 2009	6.73	21.9 (14.9)
July 2009	6.43	20.9 (14.25)
August 2009	7.39	24.0 (16.4)
September 2990	6.36	20.7 (14.1)
October 2009	8.65	28.1 (19.2)
November 2009	7.28	23.7 (16.2)
Q4 2009	8.11	26.4 (18)
December 2009	8.38	27.2 (18.5)
Q1 2010	7.6	24.7 (16.8)
January 2010	6.92	22.5 (15.3)
February	6.91	22.5 (15.3)
March	8.92	29.0 (19.8)
April	10.39	33.8 (23)
Q2 2010	9.14	29.7 (20.3)
May 2010	9.59	31.2 (21.3)
June 2010	7.42	24.1 (16.4)
Data continues through 2011		
Grand Total (Undefined)	8.06	26.2 (17.9)

Figure 9
Measured average wind velocities at tower site.

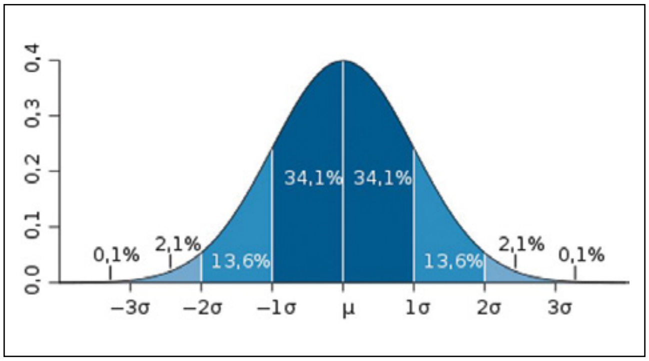

Figure 10
Gaussian distribution.

This so-called "lock-in" effect is explained by Blevins as the condition when the transverse vibration of the cylinder is at or near the shedding frequency; this organizes the wake. Thus, the vibration of the cylinder (tower), which will occur at its natural frequency, will cause a *shift* in the *stationary* vortex shedding frequency such that the frequencies are correlated. In other words, once the tower begins to vibrate at its natural frequency, the effect of the tower motion will cause the vortex shedding frequency to occur at that frequency. Thus, the two frequencies become correlated. Once the tower starts to vibrate at any particular wind velocity, the vibration will continue even if the free stream velocity changes over a wide range of velocities. Blevins' book provides experimental verification of this lock-in phenomenon on page 55. It can be seen from the Blevins reference that lock-in can occur for ratios of vibration frequency to stationary shedding frequency that range from 0.5 to 1.5. Considering that the assumed Gaussian distribution of recorded free-stream velocities extend over and have mean values near the confluence of the vortex shedding/natural frequency of the tower, this lock-in effect virtually guarantees that flow-induced vibration will occur for the towers at this site.

Discussion of Results

The assumption that the tower bends as a cantilever beam is admittedly an assumption, but the author has used this analogy successfully to accurately estimate the natural frequency of a tower of varying cross section. When the results are compared to a computer calculated natural frequency — taking into account the actual cross sections — the simplified analysis is quite accurate. This is probably due to the fact that the natural frequency is a function of the square root of the stiffness, which reduces the error appreciably even if the stiffness is inexact.

The effect of torsional loading was considered as a possible source of stress that could result in a crack. Torsional loading due to the asymmetric geometry of the blades was evaluated and found to be very small compared to the high torsional resistance of a cylinder approximately 12 feet in diameter and an inch thick. Further, the point of crack initiation is on the neutral axis of bending with respect to the wind direction. Since torsional stresses are evenly distributed completely around the circumference, there is absolutely no reason to suspect that the torsional stress contributed to the failure. If torsion was a factor, failure would have occurred near the top of the tower where the diameter is much smaller and the thickness is less, resulting in a smaller torsional moment of inertia.

It is noted that the magnitude of stresses that can be developed by vortex shedding is quite large, which may not be obvious initially. When the vortex shedding frequency is at or near the natural frequency of the tower, the tower will go into resonance. This is a similar phenomenon to the failure that occurred during the 1940 collapse of the Tacoma Narrows Bridge in Washington. However, it was experiencing a similar phenomenon called aerodynamic flutter rather than vortex shedding. Flutter is typically associated with aircraft wing stability and is caused by having a torsional wing stiffness that results in vibrations that interact with lift on the wing surface. As the wing (or bridge surface) rotates about a torsional axis, the lift varies from positive to negative. This provides the driving energy for the oscillation and the fact that the torsional frequency/wind velocity can become synchronized such that the fluid-structural interaction is at a natural frequency of the structure. The motion can become extreme — as was the case at Tacoma Narrows.

In the case of vortex shedding, it is not uncommon to get dynamic motions, side to side, equal to one or more diameters of the cylinder. While the aerodynamic forces on the tower are relatively small compared to the frontal wind forces acting on the blades, the fact that the shedding frequency is at or near the cantilever beam frequency of the tower can magnify the deflection, a result well-known in introductory vibration courses. The tower is, in effect, a single degree of freedom spring-mass oscillator driven by a sinusoidal driving force that has the same frequency as the spring-mass system. Thus, the peak excursions of the tower can be very large when excited at the natural frequency. Theoretically, the displacements can be "unbounded" for a simple spring-mass system driven at its natural frequency. However, there is always some damping in the system in real-world systems that limits the displacements. In welded towers such as this, damping is minimal, usually on the order of 2% of critical. Thus, it is possible to get large motion. In fact, the peak displacement can be approximated from the equation, $M = 1/(2\xi) = 1/(2x0.02) = 25$. ($M$ = magnification factor, a multiple of the static deflection and ξ is the percentage of critical damping expressed as a fraction). Strain in the tower is related to deflection; therefore, bending stresses are developed when the tower sways from side-to-side. The author has personally witnessed this kind of vibration in several instances.

Conclusions

Based on the foregoing analysis, it was shown that the most likely cause of cracking of the steel plate shell comprising the wind generator support tower was flow-induced vibration due to vortex shedding at or near the natural frequency of the tower structure. The location of the crack, at an angle approximately 90 degrees away from the predominant wind direction, is explained by the direction of vibration due to the vortex shedding phenomena. Further, the side-to-side vibration of the tower can easily result in cyclic tensile/compressive stress cycles at the location of the crack. Cylindrical towers such as this are known to be susceptible to flow-induced vibration. Tall cracking towers at refineries and smokestacks are often fitted with "strakes" near the top of the cylindrical structures to prevent vortex shedding and side-to-side vibrations. Underwater cables and pipelines that are located in areas that have significant ocean currents also use this type of design to prevent unwanted vibration. Strakes are typically configured in the form of helical plates that wrap around the tower or stack (see **Figure 11**). A sub-sea riser fitted with strakes is shown in **Figure 12**, as well as smokestacks at an Alaska installation (**Figure 13**).

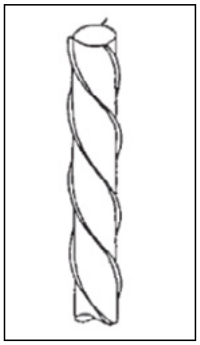

Figure 11
Helical strakes.

Figure 12
Strakes on subsea riser.

Figure 13
Strakes on stacks to prevent vibration.

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