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Wind load testing methodology for measuring drag coefficient of aerodynamically efficient base station antenna profiles

Abstract

On a cellular tower, the base station antennas account for a significant portion of the total wind load forces imparted on the tower's structural members. To accurately calculate and account for antenna-based wind loads, tower engineers must have complete and precise data regarding antenna drag coefficients and wind loads. However, the standards-based drag coefficients cannot account for the unique, more aerodynamic antenna profiles such as those developed by CommScope.

To provide tower engineers the wind load data required, CommScope contracted with an independent third party to conduct wind tunnel testing in order to derive accurate and precise drag coefficients. The results characterize wind load performance for a variety of antenna profiles across a wide range of wind directions, from zero to 180 degrees. This paper details the methodology, results and analysis of the testing.

Across the wireless landscape, cell tower space is at a premium. As mobile operators continue building out their networks, tower loads—specifically, wind loads—increase. Base station antennas account for much of the increase. For today's tower engineers, managing antenna wind loads is more difficult and more critical than ever.

To help estimate antenna wind loading, tower engineers use drag coefficients (C_d) published in current standards such as EN-1991-1-4 and TIA-222. These values are based on simple geometric shapes such as rectangles and cylinders. CommScope base station antennas, however, are engineered to be aerodynamically efficient. Many of the aerodynamic benefits are the result of geometries not reflected by the published C_d.

To accurately establish the wind load values of our base station antennas, CommScope contracted with an independent third party to conduct a thorough analysis. This involved wind tunnel testing in order to characterize the real-world behavior of select antenna profiles across a complete range of wind directions.

The results of this testing are significant as they reveal the discrepancies in antenna wind loads that can occur by using the general standards-based C_d. They also illustrate how the wind load forces change as the wind direction shifts from zero to 180 degrees.

This paper details the methodology, analysis, derivation and the results of these efforts. The goal is to provide tower engineers the key information needed in order to optimize tower utilization and reduce the cost and time to deploy antennas.

Basic wind load calculations

For calculating wind load values, the same basic equation is presented in multiple forms across several industry standards. This equation is used to allow a tower designer or structural engineer to determine the wind load values for a variety of wind speeds. The basic form of this equation is:

$$F_w = ½ \cdot \rho \cdot (C_{dp} \cdot \lambda) \cdot V^2 \cdot A$$

Where:

- Fw = wind load force (lbf, N)
- ρ = air density (0.0765 lb/ft^3, 1.226 kg/m^3)
- C_{dp} = profile drag coefficient (antenna dependent, based on testing or standard)
- λ = length/width aspect ratio correction factor
- V = wind velocity (ft/s, m/s)
- A = projected area normal to wind direction

The length/width aspect ratio correction factor (λ factor) is a constant found in published literature. It enables the scaling of the profile drag coefficient (C_{dp}) for different antenna lengths. The λ factor must be taken into account in calculating the drag coefficient (C_d). For an antenna with a given length, C_d is represented by the following equation:

$$C_d = (C_{dp} \cdot \lambda)$$

Figure 1 shows the λ factor versus the length/width aspect ratio. The aspect ratio used to calculate the C_d of the CommScope antennas is consistent with TIA-222.

Once the drag coefficient for a given profile is established, the wind load for any antenna length or wind velocity can be calculated using the formula above. It is important to remember that all variables except C_d are defined by industry standards. Therefore, to improve wind load performance, engineers must optimize C_d during the antenna design phase. Wind tunnel testing is then used to measure and quantify improvements in C_d.

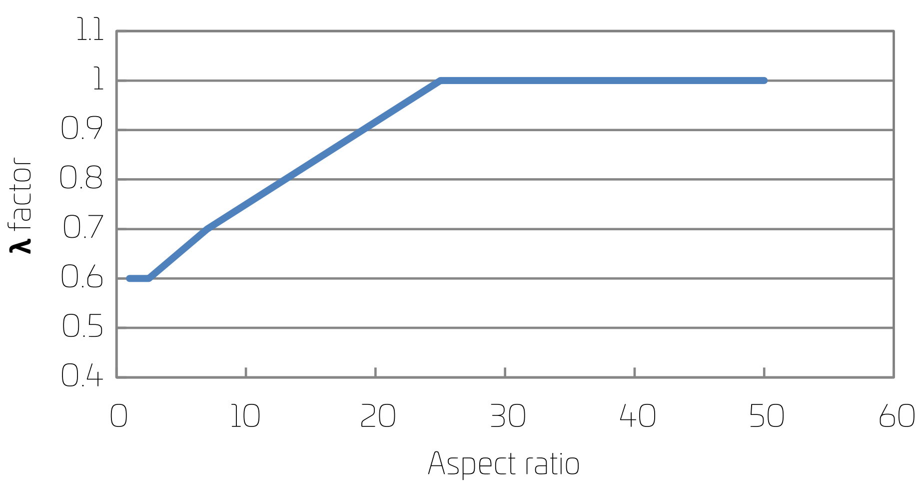

Figure 1. λ factor as a function of the aspect ratio

Aspect ratio (L/W)	2.5	7	25
λ factor	0.6	0.7	1

Based on the data in Figure 1, Table 1 indicates the (λ) for various length/width aspect ratios.

Table 1. λ factor for selected aspect ratios

Applicable standards and wind tunnel testing

Tower operators design to structural codes/standards such as TIA-222 in the U.S. and EN-1991-1-4 for EU countries. These standards are limited to simple shapes that approximate complex geometries. When it comes to antennas, for example, TIA-222 accounts for only rectangles and cylinders. But the difference in wind loads between a basic rectangle and an aerodynamically contoured radome can be significant. Figure 2 is created using computational fluid dynamics (CFD); it indicates the predicted wind load on a basic rectangular radome (left) versus a CommScope optimized radome (right). The larger wake behind the basic rectangle indicates a much higher wind load than the smaller wake behind the tapered radome of the aerodynamically optimized antenna.

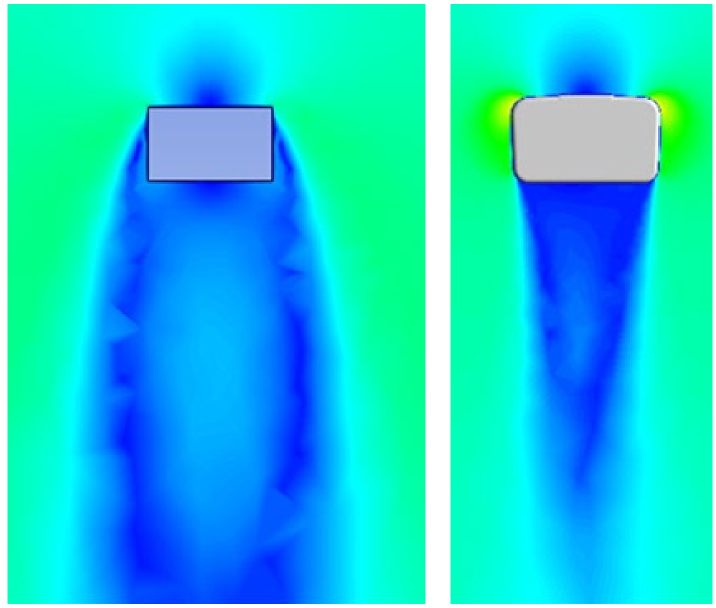

Figure 2. CFD results between basic rectangle and optimized radome

Wind tunnel test method

Wind tunnel tests are necessary to calculate accurate wind loads for shapes not covered by the standards. In 2017, CommScope contracted with JDH Consulting (Mentone, Australia), and the Department of Mechanical and Aerospace Engineering at Monash University (Melbourne, Australia) to conduct third-party wind tunnel testing at the Monash Wind Tunnel Research Platform (see Figure 3). The purpose was to obtain accurate drag coefficients for select CommScope antenna profiles. CommScope collaborated with engineers at Monash University and JDH Consulting to develop the wind tunnel testing methodology and the test setup. All findings relate to aerodynamic measurements performed on an isolated antenna-pole configuration. A ground clearance of 300 millimeters to the bottom of the antenna was maintained to minimize the interaction with the turbulence region from the floor effect. Turbulence intensity was measured to ensure proper test results.

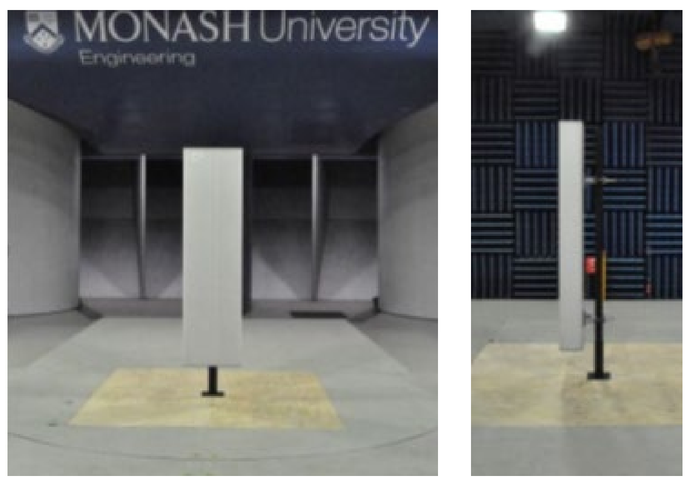

Figure 3. Antenna testing inside Monash Wind Tunnel Research Platform

The test methodology was designed to evaluate the impact of both wind speed and wind direction on antenna wind loading. The following wind tunnel tests were completed on each of the antennas selected for wind tunnel testing:

1. Constant speed yaw sweeps—Wind load was measured for a variety of yaw angles at 10-degree increments, starting with the frontal direction (0 degrees) and ending in the rear direction (180 degrees). The test was conducted at a constant velocity of 150 km/h and steady state measurements, averaged over a period of time to ensure no transient effect on wind load.
2. Velocity sweeps (Reynolds number sweeps)—Wind load was measured while increasing velocity to characterize the impact that speed (and, thus, the Reynolds number) has on the drag coefficient. The velocity sweep began at 40 km/h and ended at 180 km/h. Steady state measurements were taken at various speeds to establish a speed sweep curve. This test was conducted in the frontal and lateral directions for all antenna profiles. (See Figure 5 for the test results.)
3. In select cases, the testing process was repeated to demonstrate the quality and stability of the test setup. Table 2 gives a detailed example of the results seen from repeatability tests in the frontal direction. We can see that the worst-case standard deviation was 1.01 percent of the mean, with the majority of antennas falling well below that value.

Reynolds number: A dimensionless value that measures the ratio of inertial forces to viscous forces and describes the degree of laminar or turbulent flow.

Effective drag area* CD.A (m^2) measurements—frontal

Antenna	A	B	C	D	E
Test 1	0.263	0.282	0.340	0.647	0.718
Test 2	0.264	0.282	0.340	0.645	0.720
Test 3	0.263	0.282	0.341	0.642	0.717
Test 4	0.263	0.283	0.340	0.646	0.717
Test 5	0.264	0.283	0.340	0.631	0.718
Mean	0.263	0.282	0.340	0.642	0.718
Std deviation (% mean)	0.21%	0.19%	0.13%	1.01%	0.19%

Table 2. Repeatability test results at 150 km/h

*Effective drag area (EDA) is defined as: EDA = $C_d \cdot A$
Where C_d = drag coefficient and
A = projected area of the antenna

The setup for all test antennas included the mounting hardware, mounting pole and zero mechanical tilt. The derivation of wind load values and manner of accounting for the projected area of the pole are discussed in the drag coefficient derivation section of this paper.

Figure 4 illustrates the wind load directions from 0 to 180 degrees for the yaw sweeps conducted at 10-degree increments. After the conclusion of testing, the data was analyzed to detail the C_d values as well as wind load values in the frontal, lateral and maximum directions for each tested antenna profile.

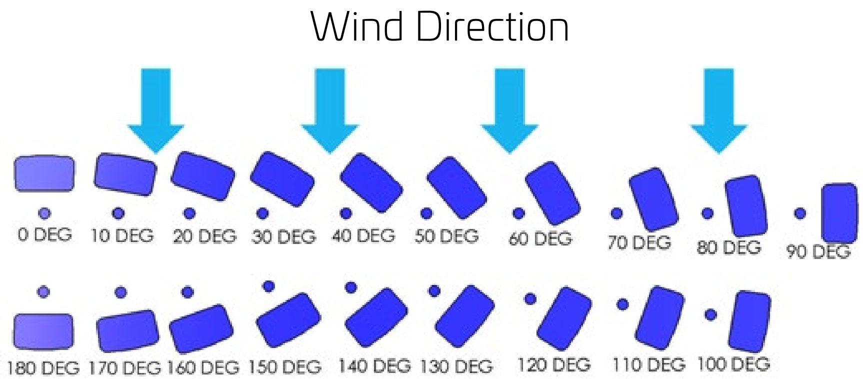

Figure 4. Yaw sweep angles from zero to 180 degrees

Wind tunnel test results

The wind load results from wind tunnel testing confirm that CommScope antennas do benefit from the aerodynamic features designed into the radomes. Figure 5 details the drag coefficient results of a frontal (zero degree) velocity sweep conducted on one of the antennas. The blue line indicates the measured results of the wind tunnel test as wind velocity is increased from 40 km/h to 180 km/h. The green line represents the drag coefficient for the identical radome based on TIA-222.

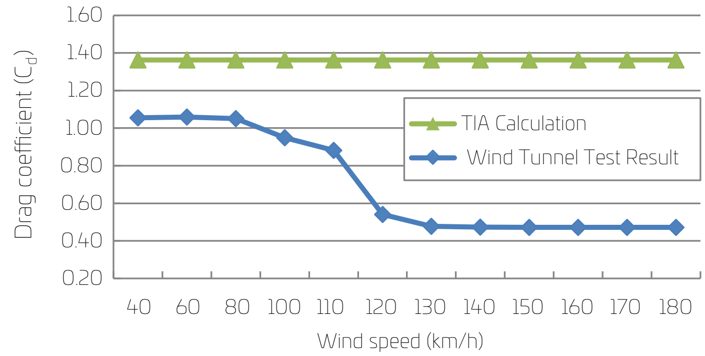

Figure 5. Drag coefficient versus velocity

We can see that the tested drag coefficient is lower than the drag coefficient values from industry standards for all velocities. The difference in values is especially pronounced at wind speeds greater than 100 km/h due to the onset of drag crisis, a phenomenon in which drag coefficient drops off suddenly as the Reynolds number increases.

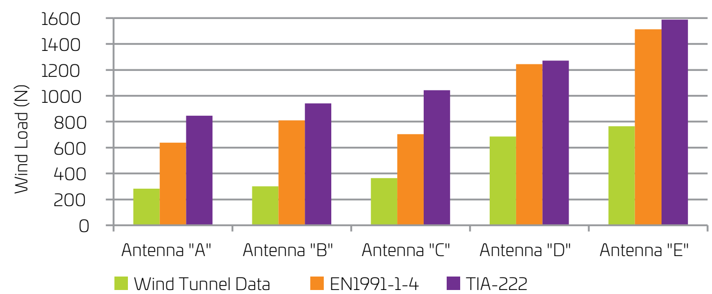

Figure 6. Frontal wind load at 150 km/h

Figures 6, 7 and 8 compare the measured versus published standard wind load for five different antenna profiles. Each profile was tested at 150 km/h in order to obtain frontal, lateral and maximum wind load values. The wind tunnel test results appear in green; wind load values using the EN-1991-1-4 standard are in orange; and those using the TIA-222 calculation are in purple.

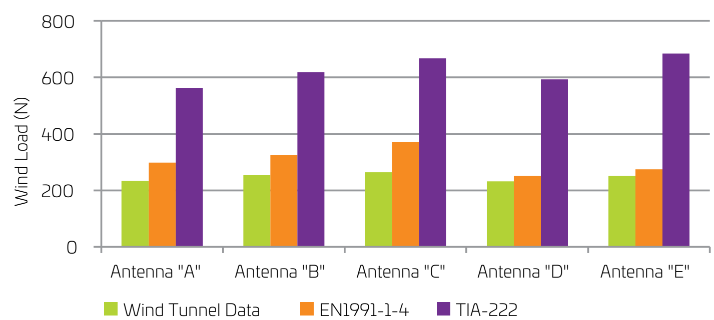

Figure 7. Lateral wind load at 150 km/h

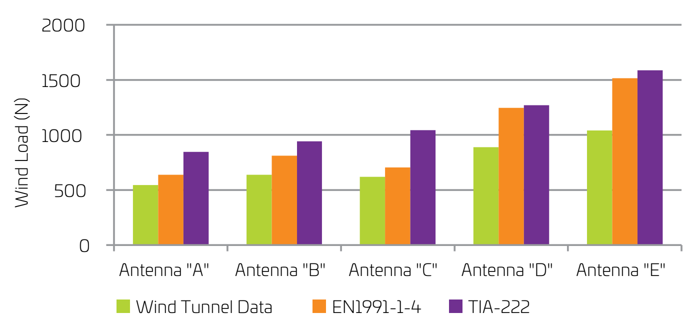

Figure 8. Maximum wind load at 150 km/h

In the frontal direction we see a pronounced reduction in wind load compared to the standards for all cases. The measured lateral wind load is also lower than the wind load calculated per TIA-222 and EN 1991-1-4 standards. When it comes to the maximum wind load, the measured wind load remains lower than values calculated per the standards.

As previously mentioned, yaw sweeps were conducted in 10-degree increments at 150 km/h to calculate the drag coefficient from different wind angles. In Figure 9, the graph on the left details the wind load force for a specific antenna profile. The graph on the right converts the wind load force to the drag coefficient. The difference in shapes is due to the change in projected area based on the wind direction. For more on converting wind load force to C_d, refer to the section on drag coefficient derivation, later in this paper.

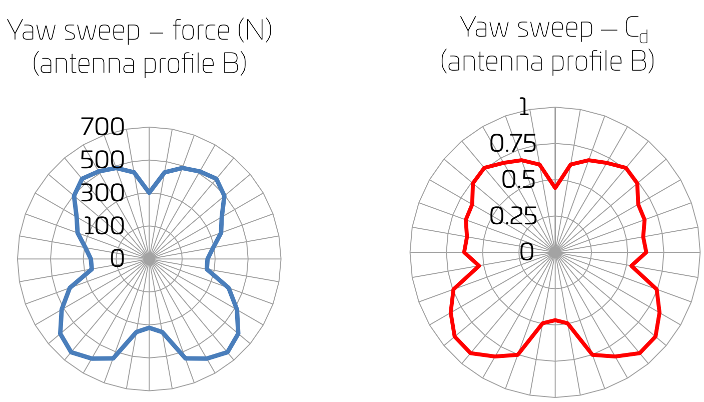

Figure 9. Yaw sweep data

As a frame of reference, the projected area of this profile ranges from 0.452 m^2 in the lateral direction to 0.607 m^2 at 50 and 130 degrees. Notice, in Figure 9, the maximum wind load is just over 600 N at a yaw angle of 140 degrees. At this angle, the projected area is 0.577 m^2 while the frontal projected area is 0.558 m^2. For reference, wind angles of 0 and 140 degrees are shown in Figure 10.

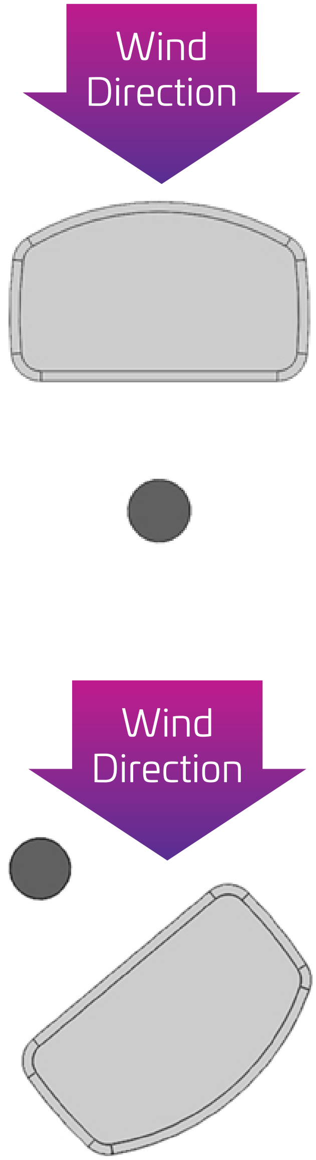

Figure 10. Wind direction at 140 degrees

This data shows the importance of publishing a maximum wind load when wind tunnel test data is used.

Calculating incremental wind loads from 0 to 180 degrees

Variances in wind load can be expected to occur as the wind shifts from a full frontal position (zero degrees) to a fully lateral position (90 degrees). Therefore, standards allow the designer to use the larger of the frontal or lateral as the maximum. Alternatively, TIA-222 allows for a trigonometric approach to calculate the wind load at incremental angles. The formula below is derived from those published in the standard:

$$F_{w,\theta} = F_{w,Frontal} \cdot (Cos^2\ \theta) + F_{w,Lateral} \cdot (Sin^2\ \theta)$$

However, using this formula to determine incremental wind loads between zero and 180 degrees can result in underestimating the true wind loads. Figure 11 illustrates this point.

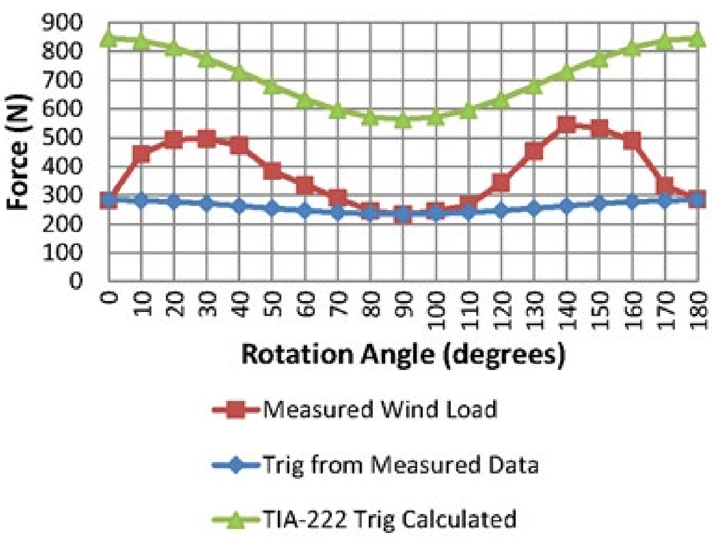

Figure 11. Three methods of calculating wind loads at angles between 0 and 180 degrees

Figure 11 details a 150 km/h wind load at various angles from zero to 180 degrees. The green line represents the trigonometrically estimated wind loads. They are derived using frontal and lateral wind loads calculated from the equation

$$F_w = ½ \cdot \rho \cdot (C_{dp} \cdot \lambda) \cdot V^2 \cdot A$$

discussed at the beginning of this paper, as well as the drag coefficients as derived from the TIA-222 standard. The blue line indicates frontal and lateral values from wind tunnel tests that have been extrapolated using trigonometric functions and applied to angles from zero to 180 degrees. The red line is the actual data from wind tunnel testing taken at 10-degree increments from zero to 180 degrees.

The gap between the red and green lines indicates the standard trigonometrically derived approach overestimates the wind load at every angle. Conversely, comparing the blue and red lines shows that—except for the frontal and lateral positions—the measured and trigonometrically derived data underestimates wind loads at every angle. In either case, engineers are more likely to over- or under-engineer the tower—neither of which is an optimal solution.

To ensure structural calculations are based on the most accurate data, CommScope recommends using the measured maximum wind load values.

Drag coefficient derivation (pole effect)

The method for deriving the antenna's frontal drag coefficient is well defined. As we rotate the antenna, however, the projected area changes. This becomes especially complicated when the pole begins to add to the overall projected area. While the pole may not add to the projected area of the antenna, it does, in certain instances, affect the wind load on the antenna. Figure 12 shows a CFD rendering in which the leading surfaces of the antenna with pole (left) are subject to a much different pressure profile than the free-stream antenna without a pole (right). The difference is due to the disruption in the air stream.

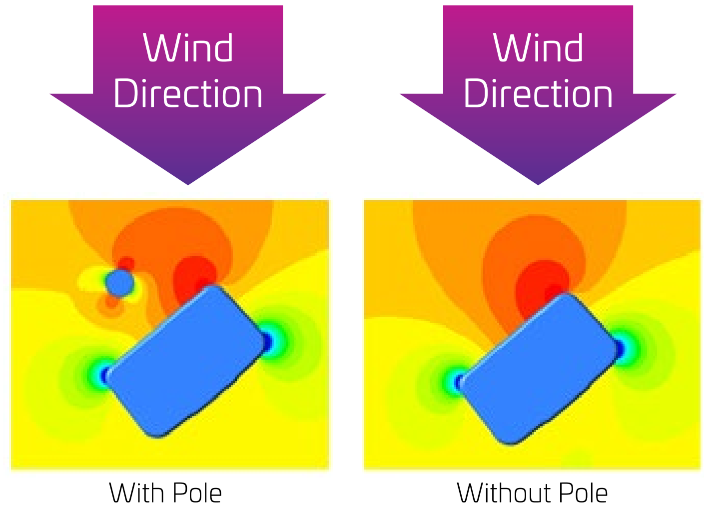

Figure 12. CFD illustrates the pole's effect on antenna wind loading

The published wind load values in CommScope's datasheets apply to the antenna only. The pole's contribution is removed from our published data. The mounting hardware is also excluded as it represents an irregularity of less than 10 percent of the antenna's projected area. This calculative approach is consistent with Table 2-8 of TIA-222.

To account for the pole's contribution during testing, as well as changes in projected area, CommScope used a case-by-case approach.

1. For angles where the mounting pole did not add to the projected area, the calculated projected area was based on the area (width x height) normal to the wind direction. This is shown in Figure 13. The pole mounting clamps have been omitted for clarity.

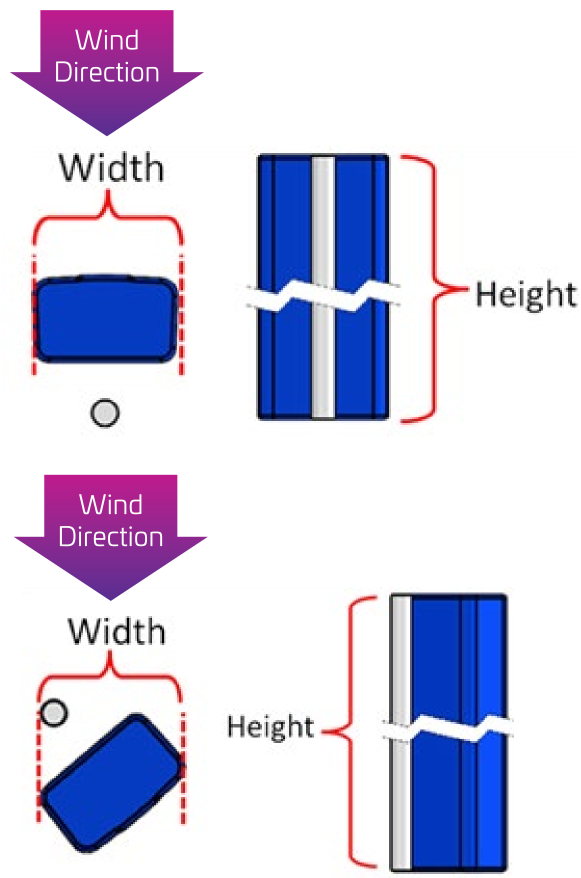

Figure 13. Pole does not affect projected area

2. When the pole was exposed to the flow AND contributed to the total projected area, an average drag coefficient method was used when calculating the wind load. The images in Figure 14 indicate the contributions to the projected area from both the pole and antenna for two different wind angles. The image on the left shows a 50-degree wind angle while the image on the right is of a 90-degree wind angle. The red brackets illustrate the pole's contribution to the total projected area and the green brackets show the antenna's contribution to the projected area.

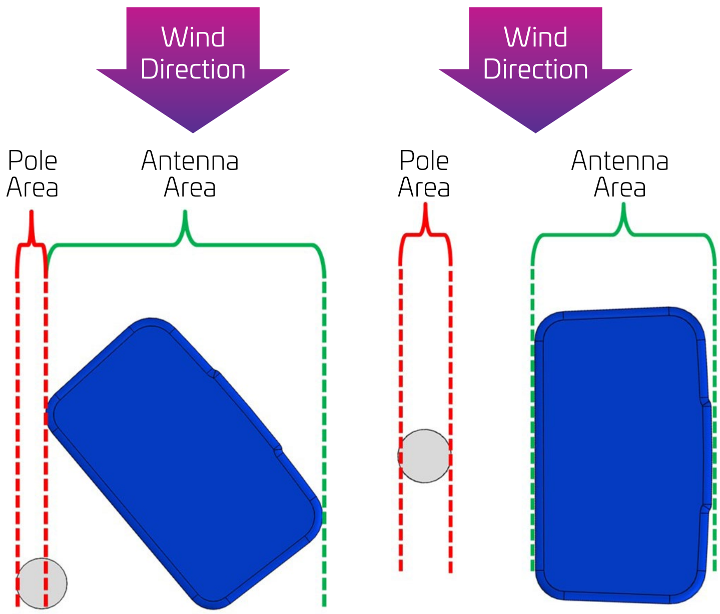

Figure 14. Contribution to projected area

In instances where the antenna and pole both contribute to the projected area the effect of the antenna must first be isolated. The first step in determining the antenna's contribution to the wind load is to calculate the drag coefficient for the combined antenna + pole system. Next, the projected area of the antenna is used to calculate the wind load contribution of the antenna. This is mathematically represented in the formulas below:

$$C_d = C_{d\,(antenna+pole)} = \frac{F_{(antenna+pole)}}{\frac{1}{2} \cdot \rho \cdot V^2 \cdot A_{(antenna+pole)}}$$

For each of the profiles tested in the wind tunnel, a profile drag coefficient is calculated based on the formula below using the average drag coefficient calculated above:

$$C_{dp} = C_d / \lambda$$

After a drag coefficient has been established for a given profile, the wind load for an antenna using that profile can be calculated using the formula below:

$$F_w = \frac{1}{2} \cdot \rho \cdot (C_{dp} \cdot \lambda) \cdot V^2 \cdot A_{antenna}$$

In summary, the drag coefficient is calculated based on the antenna + pole system's inter-related response to a wind event. This drag coefficient is then used to calculate the wind load on the antenna's projected area for a given length and wind speed.

Using CommScope wind load values

The tests described in this paper involved CommScope pole-mounted, stand-alone antennas in a controlled, wind tunnel lab. The wind load values stated in CommScope data sheets are rated for wind speed of 150 kilometers per hour under the testing circumstances described. These values should be used only as a starting point for the tower design and not as absolute values. The test results cited are meant to provide guidance only and are not a guarantee of performance. Engineers should consider all site-specific factors, including but not limited to: geographic location where max wind speed could be lower or higher than 150 km/h, tower height, type of tower or building structure, terrain, and the shielding effect from other structures including other mounted antennas. Additionally, the tower design must consider all safety factors depending on the risk category.

Conclusions

Due to their contoured aerodynamic designs, CommScope antennas cannot be accurately characterized using standards-based drag coefficients. Therefore, CommScope conducted wind tunnel testing in 2017 at Monash University to obtain accurate drag coefficients. Testing was conducted using full-scale antennas and the procedures were developed in collaboration with well-respected third-party firms that specialize in the field of wind loading on civil structures. These tests were conducted in a manner consistent with requirements of TIA-222 and EN-1991-1-4 and were witnessed, reviewed and given Professional Engineering (P.E.) approval by an independent professional engineer.

A careful review and analysis of the test results provides the following takeaways:

- The aerodynamic improvements designed into CommScope radomes have a beneficial impact on overall wind load performance.
- In all cases—and from virtually every wind angle—the tested wind load of the CommScope antennas was lower than that calculated per TIA-222 and EN 1991-1-4.
- Using trigonometrically extrapolated values (whether standard or measured) to estimate wind loading across a range of angles is likely to result in overestimating or underestimating true wind loads. Therefore, it is necessary to publish a maximum wind load value. This especially is true when using data measured in a wind tunnel.
- The antenna and pole behave as a system. To accurately characterize the wind load on the entire system, it is necessary to understand and account for the projected area created by the two.

The ability to minimize and manage wind loading on the tower is a key factor in helping wireless operators and tower owners reduce leasing cost while ensuring quality of service. It is critical that tower engineers have the most accurate and precise wind load specifications for base station antennas. With efforts such the wind tunnel testing documented here, CommScope is committed to helping our customers and partners make more informed decisions and continually improve their network's performance.

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