

Wind Load Effects on Manufactured Home Foundations

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Abstract: Problem statement: Manufactured homes are susceptible to hurricane damage. Each year, significant losses, in terms of fatalities and property damage, are reported. There is always a prevalent concern about lateral load resistance capacity of tie-down system of manufactured homes when subjected to windstorms. This study is performed to determine the effects of hurricane wind on manufactured homes' foundations. **Approach:** A 1:120th scale model of single wide manufactured home of size 14 ft by 80 ft was designed for the wind tunnel test. Proper instrumentations and simulations were considered to measure wind forces applied on the model. Sting balance and Pitot static tube were used to measure forces and air velocity during the wind tunnel test. Displacements of anchors were observed during the test. **Results:** The ultimate forces as well as the displacements of the anchors were determined at different angles of wind direction ranging from 30-180°. Wind speed inside the tunnel was increased at the rate of 5 miles h⁻¹. **Conclusion/Recommendations:** Test result showed that auger anchors used to support lateral load are incapable to resist hurricane wind loads. It was found that anchors displaced 2 in. vertically and 4 in. horizontally at loads less than 4725lb. Tested manufactured homes anchors experienced maximum force of 4087 lb when 45 miles h⁻¹ wind acted in transverse direction to the wall. The manufactured home anchors displaced more than 2 inches in vertical direction and 4 inches in horizontal direction due to this wind load. This research indicated that manufactured homes ground anchors can sustain wind velocity of 95 miles h⁻¹ when the wind is acting at longitudinal direction.

Key words: Wind tunnel, manufactured home, ground anchors, wind load, hurricane, simulation

INTRODUCTION

Mobile homes have been recently renamed as "manufactured homes" because 95% are never moved from initial site. However, wheels and axles of manufactured homes have been used as means of transporting to the home-site. Each year, millions of dollars of property damage is reported due to hurricanes (Islam *et al.*, 2011; Beven and Cobb, 2004). For instance, hurricane Isabel who occurred in September, 2003 in North Carolina, USA produced a property damage of 450 million dollars. Damages that occur every year due to high wind storms have adversely affected the sale of manufactured homes in areas susceptible to frequent hurricanes. It is an imperative to find an effective way to protect manufactured homes and understand the aerodynamic aspect of high wind speed on these structures.

A typical manufactured home consists of prefabricated walls, floor and roof. Standard manufactured home Widths (W) are 12, 14 and 16 ft. Lengths (L) vary from 40-80 ft in 10 ft increments. Corresponding basic frame beam Spacing's (S) are 6 ft for 12 ft and 14 ft wide homes and 8 ft for 16 ft wide homes. The height of the unit (H₁) is approximately 8 ft. The height off the ground (H₂) varies depending on the local terrain. A typical height is approximately 3 ft. The normal roof slope is between 2:12 and 4:12. Manufactured homes are, normally, supported on piers made of concrete blocks. The components are held in place by metal frame ties or combination of frame ties and over-the-top-ties. The ties are galvanized metal straps 0.035 in. thick by 1.25 in. wide with specified minimum strength. Ground anchors are widely used in manufactured home installations. They consist of an explicit anchoring assembly designed to transfer lateral

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loads to the ground. The most common types of anchors available are ground anchors, cast-in-place concrete footings, drilled concrete anchors and cross drive anchors. Auger anchors are manufactured in several sizes and with one or two auger disks per anchor. The most frequently used anchor is the 4 ft long anchor with single 6 in auger disk. The diameters of the available shaft are 5/8 in., 11/16 in. and 3/4 in. Manufactured homes designed after July 1994 are based on "Federal Manufactured Home Construction and Safety Standards" (FMHCSS). The Manufactured Home Construction and Safety Standards has establish three wind speed zones I ,II and III with wind speeds of 90, 100 and 110 mph, respectively (Marshall and Yokel, 1995). Manufactured homes in wind zones I are not required to have diagonal ties, while for wind zone II and III it should have diagonal and vertical ties. Although the number of ties and tie spacing are not specified, it is required that ties should not be closer than 2 ft to either end of the home. It implies that anchor and tie spacing will be based on anchor capacity. It is required that all anchors must be capable of resisting an allowable working load equal to or exceeding 3,150 lb and be capable of withstanding a 50% overload, i.e., 4,725lb without failure of either the anchoring system or the attachment point on the manufactured home. Further, aerodynamic wind pressure is developed when air flows over and around the unit which causes damage to manufactured homes. External pressures drag walls, roof and floor apart. This drag forces can overturns the unit if it is not adequately anchored (McDonald and Mehnert, 1989).

Numerous studies have been conducted on wind load effects on bridges (Saeed *et al.*, 2010) and on low rise buildings such as manufactured homes and modular homes. McDonald and Mehnert (1989) reviewed the standard practice for wind resistant manufactured housing. They concluded that the enforced wind loads design criteria need to be reevaluated. Pearson *et al.* (1996) investigated the lateral load resistance as well as the behavior of manufactured homes soil anchors subjected to axial and shear loads. They conducted comprehensive tests on the pullout capacity of ground anchors installed in silt, sand and clay soils. The test performed showed that anchors typically used to tie down manufactured homes do not achieve the desired resistance. Harris (1980) conducted an experimental testing for wind forces on mobile homes on four basic models of 25 ft, 40 ft, 50 ft and 60 ft, made to a scale of 1/16. The four basic models were tested at wind directions ranging from 0-180° measured with respect to the longitudinal direction of the model. The study investigated the relationship between maximum wind velocity and anchorage requirements for the mobile

homes. Full-scale test results of Yokel *et al.* (1981) clearly showed that, in most cases, the load-resisting capacity of ground anchors were significantly below that required in the installation standards. Manufactured Housing Institute (MHI) performed a series of structural test on typical single wide (14 by 62 ft) manufactured home, primarily, to address the need to improve the ability of manufactured housing to withstand high wind loads. They concluded that most of the permanent horizontal deformation is due to slippage in the tie-down straps and horizontal displacement of the foundation. Surry *et al.* (2005) discussed simple models that have reproduced certain forms of failure under realistic wind loads simulated in a wind tunnel. Fritz *et al.* (2008) attempted to quantify the variability of wind effects estimated based on tests conducted at six wind tunnel laboratories. The researcher made a prediction that modeling of suburban terrain contributes significantly to the variability. Macha *et al.* (1983) performed research to compare wind pressures on a manufactured home in model and full scale structure. A model of 1:25 was used to measure the wind pressures in the model and was compared with the full scale structure pressures. Vermeulen and Visser (1980) conducted research on the determination of similarity criteria for wind tunnel model testing of wind flow pattern close to building facades. Tieleman (1992) discussed a criterion for the simulation of atmospheric boundary layer in wind tunnels for the purpose of predicting wind load on low rise buildings. A model of 1:100 was tested to prove that small scale turbulence parameter is more important than the simulation of the velocity profile or integral length scale.

The objective of this experimental study is to investigate the wind loads effects on the manufactured homes anchors and to determine the ultimate forces as well as the displacements of the anchors at different angles of wind direction varying from 30-180°. The dimensions of the model were determined based on Buckingham Pi Theorem. The basic parameters considered were velocity of wind, displacement of anchors and wind force on the manufactured home.

MATERIALS AND METHODS

Materials: The experimental processes involve the design of a model for the wind tunnel test. The model was prepared based on the size of the wind tunnel. The dimension of the model was 8 in. by 1.4 in. by 0.8 inch. The frame structure of the scaled manufactured home was prepared from balsa wood and plywood for roof, floor and walls. Nails and steel wires were used to represent anchor and strap of the prototype.



Fig. 1: Image of the utilized wind tunnel

Wind tunnel: The wind tunnel test was performed at the aerospace laboratory of North Carolina A and T State University. The utilized wind tunnel (Fig. 1) is closed circuit, simple and easy to use. The wind inside the tunnel is generated by a fan positioned on the downstream side of the wind tunnel. The “on and off” button of the wind tunnel fan is on the upstream side. Wind speed can be controlled using a Velocity Frequency Drive (VFD) in lab view software. Specifications of the utilized wind tunnel are listed as follows: (a) Test section dimensions: 16 in. Long by 12 in. wide by 12 in. high (b) Closed circuit, closed test section (c) Maximum velocity: 100 mph (d) Instruments connected to the tunnel: Data Acquisition system and desktop (e) Test section static pressure: atmospheric or slightly below (f) Force measuring instrument: Sting balance (g) Velocity measuring instrument: Pitot static tube

A 12 inch long and 1/4 inch thick Pitot static tube is used to measure the dynamic pressure observed during the wind flow. It consists of several holes drilled from outside and central hole down the axis of the tube. The center hole pointed towards the flow direction observes the total pressure and outside hole observes the static pressure. Pitot static tube is allied to the pressure transducer box by two silicon pipes. The dynamic pressure is taken as the difference between total pressure (P_t) and static pressure (P_s). Theoretically, after obtaining dynamic pressure, Bernoulli's equation may be used to calculate the air velocity inside the wind tunnel by using the equation:

$$V = \sqrt{2 * (P_t - P_s) / \rho}$$

The laboratory Pitot static tube provides the pressure reading in inches of water column and wind velocity in terms of miles per hour. The velocity pressure ranges from 0.01-10 in. of water. The air velocity inside the wind tunnel is calculated by Eq. 1 and 2 as follows:

$$V_{th} = 1096.2 \sqrt{(P_v / \rho)} \quad (1)$$

$$\rho = 1.325 \times P_B / T \quad (2)$$

Where:

V_{th} = The Air velocity

P_v = Velocity pressure in inch of water

ρ = Air density in lb/ft³

P_B = The barometric pressure in inch of mercury

T = The absolute temperature

The above air velocity equation was used to determine the accuracy of readings observed by the Pitot static tube. Accuracy of readings for wind velocity observed should be within 2 percentage points of the calculated value.

Similarly, the sting balance is an instrument used to measure forces and moments. It is connected to desktop computer, pressure transducer box and Data Acquisition instrument SCC68 interconnect. The sting balance responds to the change in forces and moments on the model mounted on it, then transmit this response to signal conditioning and display unit. A three component internal sting balance is used in this research. The normal force is used to calculate lift force and axial force to calculate the drag force; thus providing relevant forces acting on the model attached to the sting.

Data acquisition system: Sting balance mounted on the model and Pitot static tube within the wind tunnel are connected to computer that has labview software installed in it. The forces, moment, wind velocity and velocity pressure exerted on the sting balance and Pitot static tube are recorded in the lab view software.

Modeling and simulation: For the purpose of this study, the widely used model of the manufactured homes was chosen for modeling. The design details of the prototype (Fig. 2) are: Length (L) = 80 ft; Width (B) = 14 ft; Height (H) = 8 ft; Depth of I beam (d) = 10 in as per HUD code 24 CFR for 14 ft width home; Height of pier (h) = 3 ft; Height of anchor (h_1) = 4 ft; Total Height (H_1) = 15.83 ft; Roof slope (θ) = 14°; Size of roof = 7.21 ft; Weight of manufactured home (W) = 15000 lbs or 13.39 lbs/ft²; Diameter of anchor = 0.63 in; footings used are single stacked.

Selection of a suitable wind tunnel model scale is a significant step in the design of the experiment. The selection usually depends on the area of the test section to avoid blockage of the wind tunnel. In this experiment, the size of test area inside the wind tunnel is 16 in. × 12 in × 12 in. which gradually reduced to 16

in. ×8 in ×8 in. Upon consideration of the above factors, a scale of 1:120 was selected. The model size details are: Length (L) = 8 in; Width (B) = 1.4 in; Height (H) = 0.8 in; Depth of I beam (d) = 0.08 in; Height of pier (h) = 0.3 in; Height of anchor (h₁) = 0.4 in; Total Height (H₁) = 1.58 in; Roof slope (θ) 14°; Size of roof = 0.72 in; Weight (W) = 1.04 lbs; Spacing of beam = 0.60 in; Diameter of anchor (d) = 0.0052 in. After determining the size of the model, quarter inch thick plywood was cut into desired sizes to prepare frame structure of the model. The wooden pieces were glued together and once the frame is built, the plywood of wall, roof and floor size were made and glued to the frame. As this research is focused on determining the displacement of anchors due to wind loads so piers were also made of plywood. A thin steel wire of ¼ in. diameter was used as the straps connecting the anchors. Nails of 18×5/8 in. were used to represent the anchors of the model. Soil was sieved through number 100 sieve using mechanical vibrator. The soil obtained represents silt soil foundation in prototype.

After attaining geometric similarity, the next step is to determine kinematic and dynamic similarity of the model to represent the actual manufactured home in the field. This can be achieved by dimensional analysis (Chongcharoen, 2011; Zaidi *et al.*, 2010). Buckingham pi theorem is used herein to perform dimensional analysis, from which six variables (F, V, H, L, v, ρ) and three fundamental dimensions ([M], [L], [T]) exist. Further, three pi terms were analyzed to obtain dimensionless numbers. From these parameters; wind speed, forces and weight of model inside the wind tunnel are determined. Pi terms are determined as follows Eq. 3 and 4:

$$F = f(V, H, L, v, \rho) \quad (3)$$

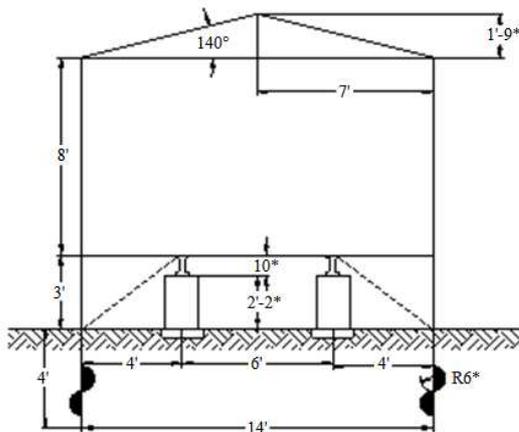


Fig. 2: Schematic diagram of prototype

$$F_{D,L} / H^2 V^2 \rho = \phi [(L/H), (v / (H V \rho))] \quad (4)$$

Where:

v and ρ = Viscosity and density of air

M and L = Mass and length

V = The wind velocity

Now, from the above pi terms, Reynolds number for the model and prototype should match [(Re)_m = (Re)_p]. Thus:

$$(\rho V L / v)_m = (\rho V L / v)_p \quad (5)$$

From Eq. 5, one can determine wind velocity of the wind tunnel as Eq. 6:

$$\begin{aligned} \left(\frac{\rho V L}{v} \right)_m &= \left(\frac{\rho V L}{v} \right)_p \\ (m V L)_m &= (m V L)_p \\ \left(\frac{1.04 * 8}{8 * 1.4 * 0.8} \right) V_m &= \left(\frac{15000 * 80 * 12}{80 * 14 * 8 * 12^3} \right) V_p \\ 0.9317 V_m &= 0.9300 V_p \\ \text{Therefore, } V_m &= V_p \end{aligned} \quad (6)$$

Reynolds number modeling is confirmed and thus velocity inside the wind tunnel is taken as the actual wind velocity of the prototype. The final step is to determine the forces acting on the prototype due to wind load. The force in the model was determined from the sting balance used in wind tunnel testing. After obtaining the forces from wind tunnel test, the actual force in the prototype is calculated by equating the coefficient of force for model and prototype:

$$\begin{aligned} C_{F(\text{model})} &= C_{F(\text{prototype})} \\ \frac{F_m}{\left(\frac{1}{2} \rho_m V_m^2 A_m \right)} &= \frac{F_p}{\left(\frac{1}{2} \rho_p V_p^2 A_p \right)} \\ F_p &= \left(\frac{\rho_p}{\rho_m} \right) \left(\frac{V_p^2}{V_m^2} \right) \left(\frac{A_p}{A_m} \right) (F_m) \end{aligned} \quad (7)$$

It should be noted that the coefficient of force (C_F) becomes coefficient of drag (C_D) when drag force is used and coefficient of lift (C_L) when lift force is used in the analysis.

Test setup and testing procedures: The wind tunnel test can be briefly described as follows: (1) The model was placed inside the wind tunnel as required for the test; (2) All computers were connected and Lab VIEW VI software is opened; (3) Wind speed button is used

Table 1: Maximum force exerted in manufactured home at different velocity and wind angle

Angle of attack (θ)	Wind velocity (V) mph	Ultimate force on anchor (F_a) lb
30°	61	2901
45°	51	2498
60°	65	2959
90°	45	4087
120°	60	2592
135°	50	1900
150°	50	2364
180°	107	985

Table 2: Wind load acting in manufactured homes at angle of 90, 120 and 135°

Force in anchor (F_a) (lb)	$D_{vertical}$ (D_v) (inch)	$D_{horizontal}$ (D_h) (inch)
At 90°		
0000.000	0.00	0.00
0759.523	0.25	0.13
0872.318	0.86	0.51
0985.113	1.13	0.63
1323.500	1.59	0.74
1605.488	1.76	0.89
2000.272	1.94	1.12
2677.044	3.92	1.60
3184.623	4.13	1.84
4086.986	7.93	2.24
At 120°		
0000.000	0.00	0.00
0731.324	0.19	0.12
0815.920	0.32	0.23
0872.318	0.43	0.31
0956.915	0.87	0.67
1097.909	1.23	0.92
1182.505	1.54	1.13
1379.897	1.76	1.54
1633.687	1.94	1.79
1831.079	4.17	3.00
2028.471	5.04	4.62
2592.448	5.27	6.26
At 135°		
0000.000	0.00	0.00
0743.004	0.18	0.12
0782.883	0.33	0.21
0862.642	0.56	0.35
0942.400	0.89	0.66
1062.038	1.06	0.86
1181.675	1.24	1.11
1341.192	1.54	1.46
1580.467	1.66	1.72
1899.501	2.14	2.33
1899.501	2.45	2.71

Table 1 and Fig. 5 show that none of the anchors were capable to sustain the load of 4725lb before failure. Further, anchors experienced higher force when the wind flow is in a transverse direction to the manufactured home. In this direction, the home could only resist wind speed of 45 MPH. At 180° (wind flow is along the longitudinal direction), the maximum velocity resisted was 95 MPH before overturning. It is worth to mention that when the model is tested without anchors, it overturned at much lower wind velocity.

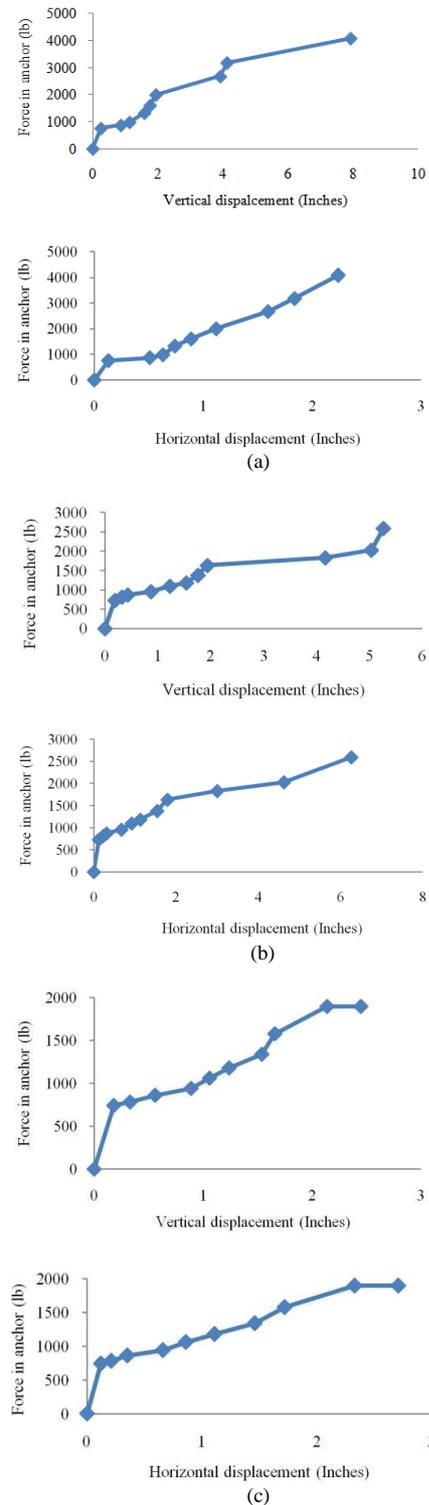


Fig. 6: Force-displacement curves of anchors at wind angles of 90, 120 and 135°

Displacement of anchors: In order to measure the displacement of the anchors at each respective applied force, numbers of anchor's pictures were taken during the test. These pictures were analyzed, using adobe photoshop CS5, software to measure the horizontal and vertical displacements of the anchor. The measured displacements were first converted to the model scale with respect to the scale of photograph and then converted to prototype scale and recorded as shown in Table 2 and Fig. 6. Although tests were conducted at different wind angles ranging from 0-180°, but due to space limitations, only three wind angles (90, 120 and 135°) will be presented herein.

DISCUSSION

Test data such as time, velocity of wind (V_{measured}), Pitot static tube readings and axial forces were obtained from wind tunnel test. The other values such as force in anchor, horizontal and vertical displacement were determined analytically as described earlier. Displacements of anchors at respective forces were calculated for 30, 45, 60, 90, 120, 150 and 180°. It was observed that at wind angle of 30°, the manufactured home could resist wind speed of 60 miles per h before 2 inch displacement of anchors. The ultimate force in anchor before failure was 2900 lb with a vertical displacement of 2.91 inches and horizontal displacement of 3.52 inches. Failure was due to vertical displacement of anchors. Further, it was observed that the drag is less when wind is acting at 30° compared to other orientation except 180°. Both the force and its corresponding displacement increased with wind speed. When the wind is directed at 45°, the manufactured home anchors fail at wind speed of 50 miles per h where the ultimate load resisted by the anchor was 2498 lb. The vertical and horizontal displacement at 2498 lb load were 7.82 and 10.80 inches respectively. The coefficient of drag was 0.358 as determined from the slope of the curve between axial force and Pitot static tube reading. The data observed during the wind tunnel test was close to the slope line, which verifies the accuracy of the observed data. Also, the force versus vertical and horizontal displacement at 45° shows that initially the anchor displaced more in vertical direction at lower wind velocity and with the increase in speed the displacement was higher in horizontal direction. Similar nature of results was obtained at other orientations. Similarly at 60° orientation, the failure of manufactured home anchors occurs when the wind speed was at 65 miles per h. The coefficient of drag was more than that of wind load acting on manufactured homes at an angle of 30 and 45°. Coefficient of drag

was 0.410. At the transverse direction (90°), it is observed that the failure of anchors occurs at a speed of 45 miles per h due to vertical displacement. The ground anchors experienced an ultimate force of 4087 lb at 45 miles per h wind speed. The displacement in the anchor at this speed was 7.93 inches vertical and 2.24 inches horizontal. In case of transverse loading, anchor displaced more in vertical direction than in horizontal direction. The coefficient of drag was maximum when the wind was acting in transverse direction. At 120° orientation, the failure of manufactured home anchors occurred at wind speed of 60 miles per h. The value of coefficient of drag was close to the coefficient of drag obtained when wind load was at 60°. Similarly, when wind load is applied at 135°, the failure velocity of anchor displacement was 50 miles per h. The coefficient of drag was 0.267 which is close to that at 45°. The maximum vertical and horizontal displacements at the ultimate load of 1900 were 2.45 and 2.71 inches, respectively. The failure velocity of manufactured home anchors at 150° was 50 miles per h. The coefficient of drag obtained is almost close to that obtained at 30°. A wind speed of 95 miles per h was resisted by the anchors before failure when the wind was in longitudinal direction (180°). The coefficient of drag was very low at this orientation. In summary, test results show that the drag coefficient increased as wind direction increased from 30-90°. It was highest at 90° and again lower from 120-80°. The coefficient of drag was least when the wind was acting at 180°. A maximum wind speed of 95 miles per h was resisted by manufactured home anchors when wind load was applied along longitudinal direction. The manufactured home anchors experienced highest forces at velocity of 45 miles per h when wind load was acting along transverse direction.

CONCLUSION

The main purpose of this investigation was to determine the capacity of the manufactured homes' ground anchors at hurricane wind speed. The experimental results obtained from wind tunnel test showed that none of the auger anchors used in manufactured homes was able to withstand hurricane wind. Thus, it is needed to develop an effective tie-down system to resist wind load and minimize damages and casualties. The current 4.0 ft anchors inserted in wet silt soil are not capable of withstanding hurricane wind loads. However, the manufactured home was capable of resisting maximum wind velocity of 95 miles per h when wind was in longitudinal direction of the manufactured home. On the other hand, in

transverse direction, the maximum wind speed sustained by the manufactured home was 45 miles per h, the anchors experienced higher forces and the failure occurred before reaching the wind speed of a hurricane. It was seen that anchors were capable to provide ultimate resistance of 4087 lbs before failure when the wind was acting at transverse direction. The coefficient of drag increases with wind directions from 30-90° and reaches the maximum at 90°. After 90° the coefficient of drag decreases and reaches the minimum at 180°.

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