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WIND STRESSES IN STEEL BUILDING FRAMES

(New Fritz Engineering Laboratory)

by

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Submitted to

Professor Lynn S. Beedle

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I. Abstract.

The purpose of this report is to accumulate and present under one cover several factors which affect the wind load stresses in a steel building frame. The factors considered are: a derivation of the relationship between wind velocity and pressure resulting therefrom; the variation of the velocity with height; and, the effect of neighboring structures. A brief discussion of wind bracing in the new Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania, is presented. No experimental work on the subject has been done by the writer.

II. Introduction.

During the destructive hurricane that hit Miami, Florida, in 1926 a rather classic failure occurred. A 17-story steel frame building was twisted about a vertical axis and bent so that portions of it moved 24 inches west and other portions 8 inches east. The wind pressures required to do this were estimated at about 60 pounds per square foot. Many
other buildings came through the hurricane unscathed. One of these was of quite similar dimensions, designed to resist 20 pounds per square foot, and had its wind bracing stored carefully in the basement.

Apparently not everything is known about forces resulting from the wind. But why worry about it? Thousands of buildings resist hurricanes successfully with hardly a thought past a provision for a 20 of 30 psf lateral load. In bygone days, who would be expected to compute wind stresses in a 40-story building? It was an almost insurmountable task. The bracing would simply be made four or five times as strong (and heavy) as could possibly be necessary. The answers lie in the following: today the construction field is more competitive, materials are scarcer, and the Morris Method makes wind stresses something a secretary and an adding machine can handle. Also, traditional methods of design are based on the yield strength of steel beyond which there is a large amount of straining before fracture occurs. More advanced methods (e.g., plastic design) are based on the ultimate strength with a correspondingly lower margin of safety against fracture.

III. Derivation of expression for wind pressure.

The proposition that the external pressure exerted by a fluid is constant is quite a familiar one. This proposition, known as the Bernoulli Theorem, when presented in symbols and referring to a liquid such as water, takes the form:
\[ \frac{v_1^2}{2g} + \frac{p_1}{\rho} + z_1 = \frac{v_2^2}{2g} + \frac{p_2}{\rho} + z_2 = k \]

This particular pressure is expressed in "head" or feet of the liquid.

One of the basic assumptions in the Bernoulli Theorem is that the fluid is an "ideal fluid," that is, it is incompressible, frictionless, and free from rotation. The fact that air is known to be compressible might suggest that it is unreasonable to apply Bernoulli's theorem to air. However, according to Pagon(16)*, while the error involved in assuming air to be incompressible is large in the trans-sonic velocities, it is only about two and one-half per cent at 175 miles per hour and even more negligible at normal velocities.

Adopting this Theorem to the aerodynamic engineer, the following is obtained:

\[ \frac{1}{2} \rho v_o^2 + p_o = \frac{1}{2} \rho v^2 + p = c \]

in which \( \rho \) is the density, or pounds per cubic foot divided by the acceleration due to gravity, \( v_o \) and \( p_o \) the velocity and pressure of the approaching stream, \( v \) and \( p \) those at any point, and \( c \) the total pressure at a great distance from the body against which the fluid is flowing. If pounds, feet, and seconds are the units of measure, each term carries the units of pounds per square foot. The expression states that

* Superscripts in parenthesis refer to references on page 14.
the velocity pressure, \( \frac{1}{2} \rho v^2 \), plus the static pressure, \( p \), is constant at all points along the stream line and equal to that of the free stream at infinity.

Now, when the wind blows perpendicularly against the body, there is a point on the body at which the stream line must come to rest and turn 90 degrees. (See Fig. 1) That is, the velocity is at right angles to that of the stream line. This point is known as the "stagnation point" or, in three dimensions, as the "stagnation meridian." Writing Bernoulli's Theorem between the stagnation point and a distant point,

\[
\frac{1}{2} \rho v_0^2 + p_0 = \frac{1}{2} \rho v_s^2 + p_s
\]

Since we are interested only in the difference in external pressure, we may say the velocity at the stagnation point is zero, and

\[
p_s - p_0 = \frac{1}{2} \rho v_0^2
\]

or, the difference in pressure between the two points is equal to the velocity pressure of the free stream, which is usually denoted by \( q \) and called the stagnation pressure.

Considering an infinitely long cylinder and calling the stagnation meridian zero degrees, it has been found that the velocity at 90 degrees is twice that of the free stream, and,

\[
\frac{1}{2} \rho v_{90}^2 + p_{90} = \frac{1}{2} \rho v_0^2 + p_0
\]

\[
p_{90} - p_0 = \frac{1}{2} \rho v_0^2 - \frac{1}{2} \rho (2v_0)^2
\]

\[
= -3(\frac{1}{2} \rho v_0^2)
\]
finally, \[ P_{90} - P_0 = -3q \]

The minus sign indicates the pressure at 90 degrees is acting in the opposite direction with reference to the center of the cylinder than it is at zero degrees, or, in other words, it is a suction, pulling on the top of the cylinder. Reflect for a moment on the way specifications consider a wind load to be acting. The "three" might also be a little startling. It indicates that the force on the surface of a structure past which the wind is blowing approaches three times that on the surface perpendicular to the wind. On a flat plate perpendicular to the wind the suction at the top is theoretically infinite. While a structure consisting of a flat plate is not usual, billboards and drive-in theater screens approach them.

The distribution of pressure on a body resulting from the action of an ideal fluid is such that the total resultant force on the body is zero. This is demonstrated by Figure 2. The resultants of the two suction forces are equal and opposite as are the pressure resultants. The actual flow follows the dotted line and, since it is not symmetrical, explains why structures may move in space due to wind.

Another interesting fact brought out by ideal flow pertains to a flat plate at an angle other than 90 degrees to the wind. More than half of the wind passes over the trailing edge which tends to move the stagnation point toward the leading edge. (See Fig. 3) This forms a couple which tends to twist the structure so that it is perpendicular to the
wind. While an actual building differs materially from an infinitesimally thin plate it is subject to a turning moment and on a tall, narrow building such as the Meyer-Kiser Building in Miami, which was mentioned before, such a moment would cause a material increase in the shear in the columns at one end and a decrease at the other. The Meyer-Kiser Building failed in just this manner, with parts of the building moving west and parts east.

It would be well to evaluate as nearly as possible the value of \( q \), the stagnation pressure.

\[
q = \frac{1}{2}\rho v_o^2
\]

Air at 59°F weighs 0.002378 slugs per cubic foot, so

\[
\rho = \frac{(0.002378)(32.2)}{32.2} \text{ lb-sec}^2/\text{ft}^4
\]

and,

\[
q = \frac{1}{2}(0.002378)v_o^2
\]

\[
= 0.001189v_o^2 \quad (v_o \text{ in fps})
\]

\[
= 0.002558v_o^2 \quad (v_o \text{ in MPH})
\]

The last expression is the most commonly used.

It now remains to determine a coefficient to account for the fact that air is not an ideal fluid. A study by Sub-Committee Number 31 of the Committee on Steel of the Structural Division[22] involving studies of the forces on the windward and leeward sides of a large number of models indicated that when \( q \) was the velocity pressure of the wind, an external pressure of 0.8q may be expected on the windward face and an external suction of 0.5q on the leeward face.
These were average figures obtained for buildings of average height to width ratios. From this it may be seen that the total unit force that may be expected on a building is \(1.3q\) or about \(0.0033v^2\). If the wind velocity were 70 MPH, the unit force on the building would be \((0.0033)(70)^2\), or about 16 pounds per square foot.

IV. Variation of velocity with height.

Again returning to basic fluid mechanics, it will be remembered that when a fluid moves past a body, the velocity of the fluid at the surface of the body is zero. Close to the body the velocity is diminished, as compared to the free stream velocity, by the friction resulting from the fluid's viscosity. Finally, at some distance from the body the effect of the body is negligible and the velocity beyond this distance is the velocity of the free stream. The layer of fluid between the body and the distance at which the velocity is constant is known as the "boundary layer." In the present case the fluid is the wind and the body is the earth. When the free stream velocity is reached outside the boundary layer it is known as the gradient velocity, \(G\).

In the 1880's, expressions were derived for the variation of velocity with height such as \(\frac{v_1}{v_2} = \left(\frac{H_1}{H_2}\right)^{1/n}\). It remains only to settle upon a reasonable value for \(n\). Early experimenters, using kites, found it to vary between 2.75 and 5.2. Later, using scale models of airships, values of 7 and 8 were found to be correct, and Prandtl and Tollmien,
comparing wind to flow in pipes, considered 6.38 to be the proper value.\(^{(18)}\)

It is of particular interest in the present case to find the average velocity on a structure in order that the average unit force and therefore, total force, may be computed. Letting \(v_2\) be the gradient velocity, \(G\), and \(H_2\), the upper limit of the boundary layer, \(Z\), the expression becomes

\[
\frac{v_1}{G} = \left(\frac{H_1}{Z}\right)^{\frac{1}{n}}
\]

where \(H_1\) is the height of the structure and \(v_1\) the velocity at that height. Keeping in mind that pressure varies as the square of velocity and integrating the previous expression, Pagon found\(^{(18)}\)

\[
\frac{v_{avg}}{G} = \left(\frac{H_1}{1.145Z}\right)^{0.157}
\]

using \(n = 6.38\). For typical values of the several variables, this becomes

\[
v_{avg} \propto 0.3G_{H_1}^{0.157}
\]

A comparison of values of \(\frac{v_1}{G}\) and \(\frac{v_{avg}}{G}\) shows that there is a ratio between \(v_{avg}\) and \(v_1\) of 7/8. This means that the average weighted velocity on a structure is 7/8 of the velocity at the top of the structure. The velocity at the top is

\[
v_1 = G\left(\frac{H_1}{Z}\right)^{\frac{1}{n}}
\]

If overturning moments are of interest, if the entire structure lies in the boundary layer, the center of pressure is at 57 per cent of the height.
Some of the variables upon which the depth of the boundary layer and the gradient velocity depend are the barometric pressure, the air density, the angular rotation of the earth, the latitude, the angle between the gradient and surface wind, the season of the year, and the nature of the surface over which the wind is blowing. If studied of these elements will be carried on in a scientific manner in the various localities, a reasonable basis for establishment of local building codes will result.

This brief discussion has not mentioned the effect of gusts of wind. Concisely, Sherlock (21) has found gust factors up to about 1.5 which means the gust velocity is 1.5 times the five minute average velocity. This factor varies inversely with the gust duration and was found to vary inversely as the 1/16th power of the height.

V. Effect of neighboring structures.

As may be expected from the increased velocities resulting from wind passing obstructions, there is an influence on the wind pressure on buildings resulting from neighboring structures. Professor Harris (11) of Pennsylvania State College made a study of the effect on the wind pressure on the Empire State Building of hypothetical neighboring buildings. While the Fritz Laboratory is a long way from the Empire State Building, it will be of interest to examine the results.

It was found that above the height of the shielding structures, their effect was to increase the suction on the leeward
face and decrease the pressure on the windward so that the total force on the building remained about the same as it would be without shielding. At about half-height of the shielding buildings, however, it was quite another story. The pressure on the windward face shielded by the nearest building decreased to the point of becoming a considerable suction so that the total force on that particular level became about 16 per cent of its normal value. With the shielding building about twice as far away, the pressure on the windward face decreased enough to make the total force on the building at that level about 60 per cent of its normal value.

Placing the neighboring structures on the leeward side of the model had little effect on the total force.

Professor Harris dealt at some length on the torsional effect resulting from the wind blowing non-perpendicularly against the building. By plotting the pressure measured by each of 34 gages at a certain height he was able to find the moment per foot of height at that level. With a wind velocity of 90 MPH blowing approximately diagonally across the building, this moment was found to be about 25,000 ft-lb per foot of height above the shielding structures. The remarkable fact is that well within the supposedly shielded height the moment was 45,000 ft-lb per foot of height, almost twice that above the shielding. This points out clearly that during a windstorm a building's columns are subject not only to bending, shear, and direct stresses, but to torsional stresses as well.
VI. The Fritz Engineering Laboratory.

The new Fritz Laboratory is a building about 130 feet long, 95 feet wide, and 80 feet high, not counting the elevator penthouse. Although rather tall, it would come under the heading of a mill building. It has wind bracing in the roof, on both sides of the west end of the main bay, and in both ends. While a completely theoretical design would investigate the depth of the boundary layer at the various seasons in the locale, a height of 80 feet would hardly warrant it. It is also true that due to its low height to width ratio the torsional effect can probably be ignored. The building is in the wind shadow of two buildings of comparable size so that the evils of "shielding" would certainly be present. There is also room for future building to the north and a tall building there would cause unnatural pressures on the laboratory. The greatest deviation from assumed pressures would occur on the north side, however, and would be dissipated over two distinct structures. Probably not considered as wind bracing but certainly effective as such are the rigidity of supposedly pinned connections and the stiffening effect of concrete floors lain on steel beams encased in concrete. In short, considering the absence of frills on the outside of the new laboratory, it would not appear susceptible to damage due to lateral loads.

As far as determining numerical values of stress is concerned, once the unit force on the building is determined, the problem is one of determining stresses in a truss.
Figure 4 contains the location of the trusses. The joints of the trusses are assumed to be pinned and the diagonal web members act in tension only. The trusses either lie in a horizontal plane (as in the roof) or lie in a vertical plane with their lengths running vertically. References 9 and 10 contain methods of analyzing wind bracing.

As far as conservative design goes, the Fritz Laboratory is a rather special case. Since the main floor is to be used for testing purposes, the columns there will often be used for fixed support for lateral bracing for tests requiring such bracing. Therefore, the columns were designed not only to resist lateral crane loads but loads from the testing machines, too. The columns will be quite effective in resisting lateral loads from external sources as well as internal.

VII. Conclusion.

It has been shown why a greater knowledge of forces resulting from air movements is desirable. While demonstrating that the effects of some of the factors involved in these forces are far from obvious, it is desired that the factors have not been made to appear nebulous, but rather that a rational approach to them can result in a reasonable basis for specifications.
VIII. ACKNOWLEDGEMENTS

The unhesitating aid, both technical and clerical, rendered to the writer by his colleagues at the Fritz Engineering Laboratory is deeply appreciated.
IX. References


3. Chien, Ming, et al., "Wind Tunnel Studies of Pressure Distribution on Elementary Building Forms", Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa, 1951, 1149.


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IX. References (cont.)


18. --- "Wind Velocity in Relation to Height Above Ground", Ibid., p. 742, Vol. 114, 1935


* Fritz Eng'r'g. Lab. Library, Lehigh U., Bethlehem, Penna.
X. NOMENCLATURE

c  sum of the velocity and static pressures in the Bernoulli Equation when applied to air

g  acceleration due to gravity, 32.2 ft/sec/sec

G  gradient velocity

H₁, H₂  heights above body in air stream

k  sum of the velocity, static, and elevation pressures in the Bernoulli Equation when applied to a liquid

n  constant in the expression for variation of velocity with height

P, P₁, P₂  static pressure at any particular point

P₉₀  static pressure 90° from stagnation point

Pₛ  static pressure at stagnation point

q  stagnation pressure \( = \frac{1}{2} \rho v_₀^² \)

v, v₁, v₂  velocity at any particular point

v₀  velocity in free stream of air

v₉₀  velocity 90° from stagnation point

vavg  average weighted velocity over a structure

vₛ  velocity at stagnation point

Z  depth of boundary layer

z₁, z₂  elevation at any particular point

ρ  density, pounds per cubic foot divided by acceleration due to gravity
XI. FIGURES

Fig. 1. Location of Stagnation Point.

Fig. 2. Pressure Distribution on Infinitely Long Cylinder.

(From Reference 16)
XI. FIGURES (Cont.)

Wind

Center of pressure shifted toward leading edge.

Flat plate

Majority of wind passing trailing edge.

\[ \theta \neq 90^\circ \]

Fig. 3. Flat Plate Non-perpendicular to Wind.

Fig. 4 (a). Schematic Plan View of Wind Bracing in Fritz Laboratory.
Fig. 4 (b). Schematic of Section A-A.

Fig. 4 (c). Schematic West Elevation of Wind Bracing in Fritz Laboratory.

(East Elevation opposite hand.)