be reasonably estimated by considering a small number of key variables related to the overall geometry of the open-frame structure. This approach does not require the designer to consider the combination of effects from framing, equipment, and other elements. This method is presented in Appendix 5B.

Wind forces on equipment, piping and cable trays located on or attached to the structure should be calculated according to the applicable provisions of Chapter 5 and added to the wind forces acting on the frame in accordance with 5.3.6.

Scarce experimental work to date (Qiang 1998, Levitan et al. 2004, Amoroso and Levitan 2009) has considered the inclusion of three-dimensional solidity (e.g., vessels, heat exchangers) placed in the framework. In general, it is expected that the total wind load on equipment will be less than the sum of the loads on the individual items owing to shielding by the frame and other neighboring equipment.

Thus, the approach taken in 5.3.6 is the reduction of the total wind load on equipment by a multiplication factor η_{equip} to account for this shielding.

5.3.1.2 Force Coefficients for Components

Wind loads for the design of individual components, cladding, and appurtenances (excluding equipment, piping, and cable trays) should be calculated according to the provisions of ASCE 7-16. Based on common practice, force coefficients and areas for several items are given in Table 5-1. Force coefficients for open-frame structures with partial cladding are given in 5.4.

5.3.2 Frame Load

For open-frame structures, design wind forces for the main wind-force-resisting system should be determined by the equation

$$F_S = q_z\ G\ C_f\ A_e \qquad (5\text{-}1b)$$

C5.3.2 Frame Load

The structure is idealized as two sets of orthogonal frames. The maximum wind force on each set of frames is calculated independently.

Note: In this equation, C_f accounts for the entire structure in the direction of the wind.

Table 5-1. Force Coefficients for Wind Loads on Components.

Item	C_f	*Projected area*
Handrail including toe board	2.0	0.80 ft^2/ft
Ladder without cage	2.0	0.50 ft^2/ft
Ladder with cage	2.0	0.75 ft^2/ft
Solid rectangle and flat plate	2.0	____
Round or square shape	See ASCE 7-16, Figure 29.4-1	___
Stair with handrail		
Side elevation	2.0	Handrail area plus channel depth
End elevation	2.0	50% of gross area

In Equation (5-1b), F_S is the wind force on the structural frame and appurtenances, q_z and G are as defined in Section 5.1, and

- The force coefficient C_f is determined from the provisions of 5.3.3.
- The area of application of force A_e is determined per 5.3.5.
- The design load cases are computed per 5.3.6.

5.3.2.1 Limitations of Analytical Procedure

Design wind forces are calculated for the structure as a whole.

The method is described for structures that are rectangular in plan and elevation.

C5.3.2.1 Limitations of Analytical Procedure

No information is provided about distribution of loads to individual frames. However, the windward frame will experience a larger percentage of the total wind force than any other frames, except possibly for the case where the solidity ratio of the windward frame is much less than that of other frames.

5.3.3 Force Coefficients

The force coefficient for a set of frames shall be calculated by

$$C_f = C_{Dg}/\varepsilon \qquad (5\text{-}2)$$

where C_{Dg} is the force coefficient for the set of frames given in Figure 5-1, and ε is the solidity ratio calculated in accordance with 5.3.4.

Extrapolation of the charts is required for frame solidity ratios greater than 0.35.

Alternately, C_f may be determined using Appendix 5A.

C5.3.3 Force Coefficients

Force coefficients C_{Dg} are obtained from Figure 5-1 (see C5.3.1.1 for research references) or Appendix 5A. A single value is obtained for each axis of the structure. This value is the maximum force coefficient for the component of force acting normal to the frames for all horizontal wind angles. Although the wind direction is nominally considered as being normal to the set of frames under consideration, the maximum force coefficient occurs when the wind is not normal to the frames (see C5.3.6.1 and 5A.1). The angle at which the maximum force coefficient occurs varies with the dimensions of the structure, solidity, number of frames, and frame spacing.

Force coefficients are defined for wind forces acting normal to the frames irrespective of the actual wind direction.

A method to estimate this angle is given in Appendix 5A, which also provides C_f values for a larger range of S_F/B and ε values than Figure 5-1.

The frame spacing ratio is equal to S_F/B, where S_f is the frame spacing in the direction parallel to the wind and B is the frame width as shown in Figure 5-1.

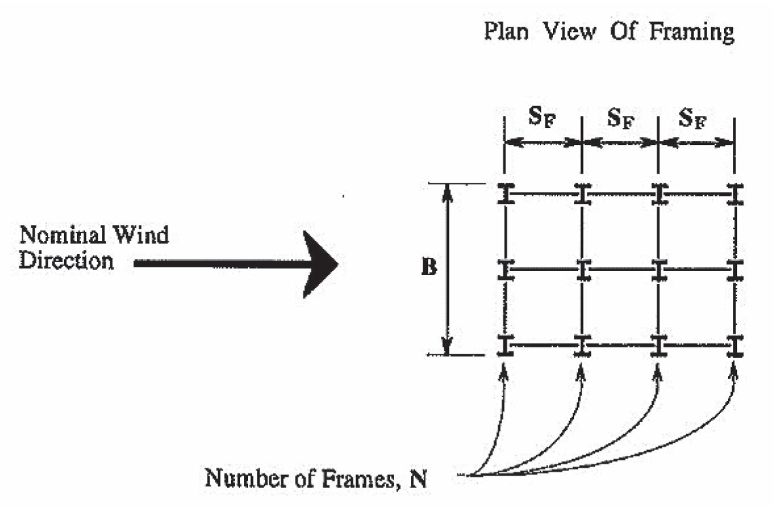
Extrapolation of the charts is required for frame spacing ratios greater than 0.5.

The force coefficients C_{Dg} were developed for use on the gross area (i.e., envelope area) of the structure as used by the British wind loading standard (Willford and Allsop 1990). These are converted to force coefficients that are applied to solid areas as used in ASCE 7-16 by Equation (5-2).

The force coefficients C_{Dg} were developed from wind tunnel tests for structures with a vertical aspect ratio (ratio of height to width perpendicular to the flow direction) of 4.

Although vertical aspect ratio does not play a large role in determining overall loads, the coefficients given in Figure 5-1 may be slightly conservative for relatively shorter structures and slightly unconservative for relatively taller structures.

Force coefficients C_{Dg} are applicable for frames consisting of typical sharp-edged steel shapes such as wide flange shapes, channels, and angles. Georgiou et al. (1981)



Notes:

1. Frame spacing ratio is defined as S_F/B.
2. Frame spacing, S_F, is measured from centerline to centerline.
3. Frame width, B, is measured from outside edge to outside edge.
4. Number of frames, N, is the number of framing lines normal to the nominal wind direction (N=4 as shown).
5. Linear interpolation may be used for values of S_F/B not given on the following pages.

Figure 5-1. Force coefficients, C_{Dg}, for open-frame structures.

suggest a method to account for structures containing some members of circular or other cross-sectional shape.

5.3.4 Solidity Ratio

The solidity ratio ε is given by

$$\varepsilon = A_S/A_g \qquad (5\text{-}3)$$

where A_g is the gross area (envelope area) of the windward frame, and A_S is the effective solid area of the windward frame

C5.3.4 Solidity Ratio

Willford and Allsop (1990) present a method to account for the effects of secondary floor beams (beams not in the plane of a frame). Use of the Willford and Allsop method may result in a small increase in

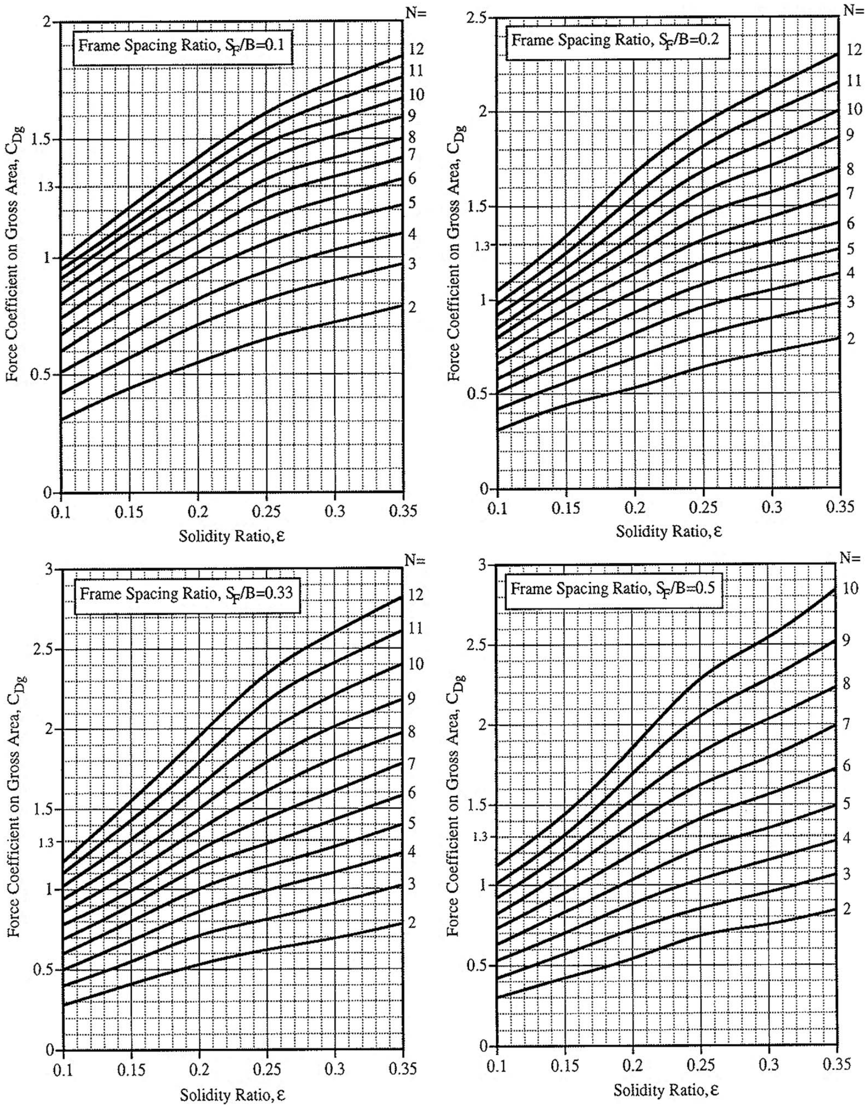


Figure 5-1. (Continued). Force coefficients, C_{Dg}, for open-frame structures.

defined by the following subsections:

the total wind force on the structure. With the associated uncertainties with the determination of the wind forces, this minor addition may be ignored.

5.3.4.1 Solid Area of a Frame

The solid area of a frame is defined as the solid area of each element in the plane of the frame projected normal to the nominal wind direction. Elements considered as part of the solid area of a frame include beams, columns, bracing, cladding, stairs, ladders, and handrails. Items such as equipment, piping, and cable trays are not included in calculation of the solid area of a frame; wind loads on these items are calculated separately.

5.3.4.2 Load-reducing Effects of Solid Flooring

The presence of flooring or decking does not cause an increase of the solid area of 5.3.4.1 beyond the inclusion of the thickness of the deck. Load-reducing effects of solid flooring (not grating) may be considered by adjusting the wind load by up to the shielding factor η_{floor}

$$\eta_{floor} = 1 - 0.2(A_{fb}/A_S) \quad (5\text{-}4)$$

where A_{fb}/A_S is the ratio of the projected area contributed by horizontal beams (in the vertical windward plane) supporting solid floors to the total projected solid area. This factor should be applied to the frame force coefficient.

C5.3.4.2 Load-reducing Effects of Solid Flooring

Experimental work (Qiang 1998, Levitan et al. 2004, Amoroso and Levitan 2009) indicates that the presence of solid decking decreases the wind forces compared to those of a bare frame. A history of research on bluff bodies with wake splitter plates reveals a reduction in drag owing to a disruption of the vortex shedding pattern. This mechanism may explain the reductions in drag observed for open frames with solid floors. The relationship for the reduction factor given here is an empirical representation of the reduction of the wind load as a function of the solid area provided by floor beams (Amoroso and Levitan 2009).

No research related to open-grating floors has been published. There is no evidence that open-grating floors will significantly affect the wind forces on the structure.

5.3.4.3 A_S for Structures with Frames of Equal Solidity

For structures with frames of equal solidity, the effective solid area A_S should be taken as the solid area of the windward frame.

5.3.4.4 A_S for Structures with Frames of Unequal Solidity – Case 1

For structures where the solid area of the windward frame exceeds the solid area of the other frames, the effective solid area A_S should be taken as the solid area of the windward frame.

C5.3.4.4 A_S for Structures with Frames of Unequal Solidity – Case 1

The force coefficients of Figure 5-1 were developed for sets of identical frames. Research shows that the solidity of the windward frame is the most critical (Cook 1990, Whitbread 1980), leading to the recommendation. This provision is likely to yield slightly conservative loads because the greater the solidity of the windward frame with respect to the other frames, the greater the shielding of the other frames.

5.3.4.5 A_S for Structures with Frames of Unequal Solidity – Case 2

For structures where the solid area of the windward frame is less than the solid area of the other frames, the effective solid area A_S should be taken as the average of all the frames.

5.3.4.6 A_S for Structures with Vertical Bracing Members

When vertical bracing members in frames parallel to the nominal wind direction are present, the vertical projected area normal to the nominal wind direction for the vertical bracing members shall be added to A_S. Regardless of the configuration of the vertical bracing (e.g., diagonal bracing, chevron bracing, K-bracing, X-bracing) or arrangement (bracing located totally in one bay or distributed among several bays of a bent), the vertical projected area of only one brace member per story per braced bent parallel to the wind direction shall be considered.

C5.3.4.6 A_S for Structures with Vertical Bracing Members

Experimental work (Amoroso and Levitan 2009) indicates that neglecting the contributions of vertical bracing to the solid area for wind directions nominally parallel to the plane of the bracing can lead to unconservative estimates of the wind load on an open-frame structure.

5.3.5 Area of Application of Force

The value of A_e shall be calculated in the same manner as the effective solid area in 5.3.4, except that it is for the portion of the structure height consistent with the velocity pressure q_z.

5.3.6 Design Load Cases

The total wind force acting on the structure in a given direction, F_T, is equal to the sum of the wind loads acting on the structure and appurtenances (F_S) plus the wind load on the equipment and vessels (per Section 5.5) plus the wind load on piping. See Figure 5-2 for complete definitions of F_T and F_S.

C5.3.6 Design Load Cases

In some cases, this design load will exceed the load that would occur if the structure were fully clad. It is also possible that the wind load on just the frame itself (before equipment loads are added) will exceed the load on the fully clad structure. This happens most often for structures with at least four or five frames and relatively

If piping arrangements are not known, the engineer may assume the piping area to be 10% of the gross area of the face of the structure for each principal axis. A force coefficient of 0.7 should be used for this piping area.

The two load cases shown in Figure 5-2 should be considered.

higher solidities. This phenomenon is very clearly demonstrated in Walshe (1965), which presents force coefficients on a building for 10 different stages of erection, from open frames to partially clad to the then fully clad building. The wind load on the model when fully clad is less than that during several stages of erection.

5.3.6.1 F_T and F_S

F_T **and** F_S are applied to each of the two design load cases as follows: Frame load + equipment load + piping load (F_T) for one axis, acting simultaneously with 50% of the frame load (F_S) along the other axis, for each direction.

The combination of wind with other loads shall be computed in accordance with ASCE 7-16 Section 2.0.

C5.3.6.1 F_T and F_S

While the maximum wind load normal to the frame for a structure consisting of a single frame occurs when the wind direction is normal to the plane of the frame, this is not the case for a structure with multiple planes of frames. The maximum load normal to the plane of the frames occurs when the wind direction is typically 10° to 45° from the normal (Willford and Allsop 1990). This is because for oblique winds there is no direct shielding of successive columns and a larger area of frame is therefore exposed to the wind directly (without shielding) as the wind angle increases. Thus, the maximum wind load on one set of frames occurs at an angle that will also induce significant loads on the other set of frames (Willford and Allsop 1990, Georgiou et al. 1981).