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Lattice structures Part 2: mean fluid forces on tower-like space frames

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LATTICE STRUCTURES: PART 2: MEAN FLUID FORCES ON TOWER-LIKE SPACE FRAMES

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LATTICE STRUCTURES: Part 2: Mean Fluid forces on Tower-like Space Frames

1. NOTATION

		<i>SI Unit</i>
A_e	total area enclosed by front frame or panel including chord members (see Sketch 1.1)	m^2
A_s	shadow area of front frame or panel of basic tower (without ancillaries) projected onto a plane parallel to that through the chord members (see Sketch 1.1)	m^2
A_{sa}	reference shadow area of ancillary	m^2
b	cross-sectional width of flat-faced member	m
C_D	along-flow force (drag) coefficient of basic tower (without ancillaries) acting along flow direction $0u$; (drag force)/($\frac{1}{2}\rho V^2 A_s$), see Section 1.1	
C_{Da}	drag coefficient of ancillary (based on A_{sa}) in isolation from tower	
C_{D0}	value of C_D at $\alpha = 0^\circ$	
C_{D1}	value of C_D for front panel of tower section at $\alpha = 0^\circ$ considered in isolation from remaining sides of tower	
C_L	across-flow (lateral) force coefficient of basic tower (without ancillaries) acting normal to the flow direction; (across-flow force)/($\frac{1}{2}\rho V^2 A_s$), see Section 1.1	
$\Delta C_D, \Delta C_L$	increment in C_D and C_L respectively when ancillary is added to tower; based on A_s	
C_M	torsional-moment coefficient; (maximum torsional moment)/($\frac{1}{2}\rho V^2 A_s B$)	
C_X, C_Y, C_Z	X, Y and Z force coefficients, components acting along body axes $0x, 0y$ and $0z$ respectively; (force)/($\frac{1}{2}\rho V^2 A_s$); see Sketch 1.1	
$\Delta C_X, \Delta C_Y$	increments in C_X and C_Y respectively when ancillary is added to tower	
D	diameter of circular-sectioned member	m
e	offset of ancillary from $0x$ axis of tower; see Figures 8d, 8e	
f_D, f_ϕ	correction factors for effects of D_b/D_c and frame solidity ratio for single frame of circular-section member	
f_s	correction factor for effect on rest of structure of shielding by front frame	

f_{sa}	interference factor on drag coefficient of ancillary when added to tower	
f_{α}	correction factor for effect of incidence on basic tower C_D ; C_D/C_{D0}	
$f_{\alpha,a}$	correction factor for effect of incidence on ΔC_D due to ancillary; $\Delta C_D/\Delta C_{D0}$	
I_u	intensity of u -component of turbulence, σ_u/V , see Table 9.3	
i	bay or panel number	
L	length of frame along Oz direction	m
l	length of individual member	m
r_{L_u}	lateral integral length scale of u -component of turbulence, see Table 9.3	m
M_x, M_y	mean moments for basic tower (without ancillaries) about Oy and Ox axes respectively	N m
$\Delta M_x, \Delta M_y$	increment in M_x and M_y when ancillary is added to tower	N m
M_z	maximum torsional moment (see Section 2.4.2)	N m
R_{CD}	ratio of minimum to maximum drag coefficients for ancillary	
Re_c	Reynolds number based on chord member diameter, VD_c/ν	
Re_{ec}	effective Reynolds number, $\lambda_R \lambda_T Re_c$	
V	time-averaged* free-stream velocity, see Table 2.4	m/s
$0u, 0v, 0w$	flow axes, set of right-handed coordinate axes fixed with reference to mean flow direction, see Section 1.1	
$0x, 0y, 0z$	body axes, set of right-handed coordinate axes fixed with reference to longitudinal axis of tower (Oz)	
α	incidence angle, angle between the $0xz$ plane and a plane containing the Oz axis and the flow velocity vector, see Sketch 1.1	degree
$\alpha_a, \alpha_e, \alpha_f$	effective incidences (see Figures 8d, 8e)	degree
ε	effective roughness height of member surface, see Table 9.2	m
$\lambda_R, \lambda_T, \lambda_{Tcrit}$	factors accounting for effects of member surface roughness and flow turbulence in determining effective Reynolds number for round members, see Section 4.2 and Figure 4	
ν	kinematic viscosity of fluid	m ² /s
ρ	density of fluid	kg/m ³

ϕ solidity ratio of frame or bay of frame, A_s/A_e

Suffixes

a denotes value for ancillary

b denotes value for bracing member

c denotes value for chord member

circ denotes value for circular section members

flat denotes value for flat-faced members

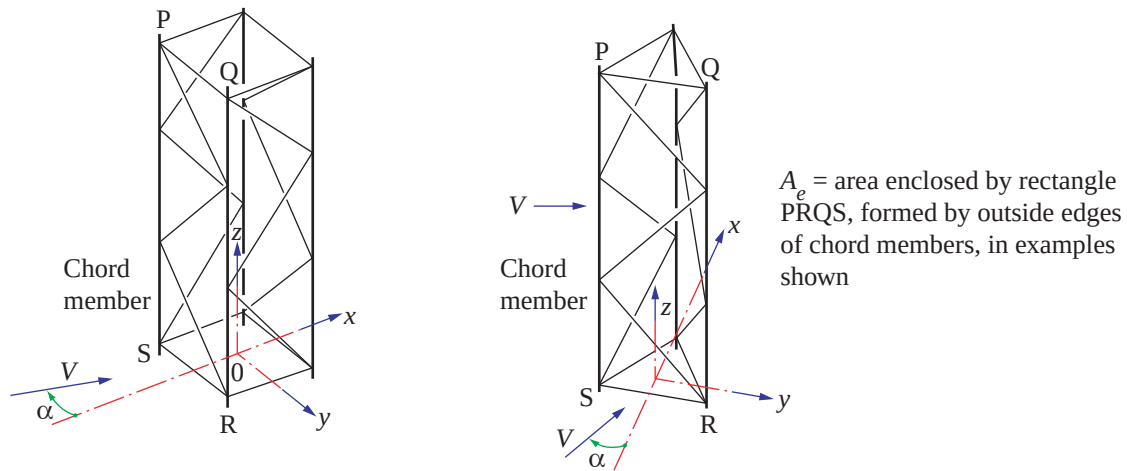
i denotes value for *i*th panel of tower

mix denotes value for tower with both flat-faced and circular-section members

P, Q relates to values for faces of tower section designated *P* and *Q* respectively

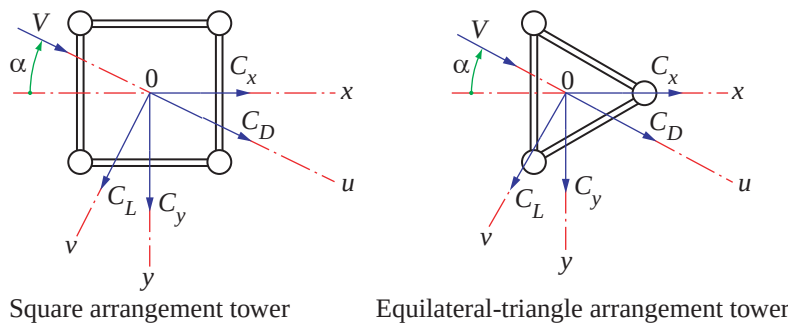
α denotes value appropriate to incidence angle α

* The appropriate averaging time depends on the structure and the design method adopted (see Section 2.2).



Square arrangement tower

Equilateral-triangle arrangement tower



Square arrangement tower

Equilateral-triangle arrangement tower

Sketch 1.1 Definition of axis system

1.1 Axis Systems and Force Coefficients

There are two systems of axes widely used in fluid-loading studies; (i) a flow-axis system $0u, 0v, 0w$, fixed in relation to the mean flow and with $0u$ aligned along the mean flow direction and (ii) a body-axis system, fixed in relation to the structure and with $0x$ commonly aligned normal to a principal face of the structure.

In this Item the mean force coefficient data are presented in terms of the drag coefficient, C_D , acting along the $0u$ axis and the lateral force coefficient, C_L acting along the $0v$ axis. In practice the force coefficients, C_X and C_Y acting along body axes $0x$ and $0y$ are usually required; using the axis system as defined these are given by

$$C_X = C_D \cos \alpha - C_L \sin \alpha, \quad (1.1)$$

$$C_Y = C_D \sin \alpha + C_L \cos \alpha. \quad (1.2)$$

Additionally, the force coefficient C_Z acts along the $0z$ axis which coincides with the $0w$ axis for the cases considered in this Data Item.

2. PURPOSE, SCOPE AND USE OF THIS DATA ITEM

2.1 Purpose and Scope

This Data Item provides data for estimating the mean fluid forces and moments on spatial lattice structures such as towers. It is the second of a series* that supersedes and extends the information on lattice structures in ESDU 82007. The first Data Item⁴ in the series covers single and multiple plane lattice frames.

The present Data Item can be used in the design of tower-like lattice structures such as communications towers, pylons and masts. The data are also applicable to other types of spatial frames such as crane jibs, gantries and lattice booms but only when normal to the flow.

The scope of the data presented is indicated in Table 2.1. A worked example is provided in Section 7 and Calculation Sheets on Tables 9.4, 9.5, 9.6 and 9.7.

2.2 Applicability, Limitations and Uncertainty

The Item may be used to estimate the mean loading induced by gas or liquid flows. For gas flows the Mach number should be less than about 0.4. For liquid flows, the possibility of significant forces arising from free-surface effects or from cavitation should be considered separately.

A particular application is to structures in the natural wind. The data may be used to derive the mean component of wind loading (using the mean-hourly wind speed) as part of a statistical approach to the total wind loading. In this approach, for design purposes, it is necessary to superimpose on the mean component the fluctuating components such as those caused by buffeting due to turbulence. The calculation procedure of ESDU 87035, using force coefficients from this Data Item, will provide values for the fluctuating components caused by buffeting due to turbulence.

The data in this Item may also be used in a quasi-static discrete-gust loading approach in which the total wind loading is assumed to be produced by a discrete gust. In this case the variation of mean wind speed with height is broadly equivalent to that exhibited by a discrete gust sufficiently large to envelop the structure. The time over which the gust velocity is averaged will depend on the structure size; the smaller the structure, the shorter the averaging time and the higher is the gust velocity. Further implications in the discrete-gust loading approach which make it less reliable than the statistical approach are discussed in Section 3.1 of ESDU 81017³.

* A Data Item covering 'structural sections' such as angle- and I-section beams will be issued to supersede the remainder of ESDU 82007.

TABLE 2.1 Scope of Data Item

	<i>Chord Member Arrangement</i>		
	<i>Equilateral Triangular</i>	<i>Square</i>	<i>Rectangular</i>
How to deal with non-uniform structures in shear flow	2.4	2.4	2.4
Data for basic tower or boom at zero and non-zero incidence:			
– flat-faced members	3.1	3.2	3.3
– circular-section (round) members	4.3	4.4	4.5
– mixed members	5	5	5
Effect of added solidity:			
– to all faces	6.1		
– to one face	6.2		
– between front and rear faces	6.1		
Effect of specific ancillaries:			
– gusset plates	6.1		
– ladders	6.2		
– feeder tubes or cable banks, waveguides	6.2		
– flue or stack or access tower inside tower section	6.2		
– dish aerials or large plate-like additions	6.2		
Worked example	7		
Calculation Sheets	Tables 9.4, 9.5, 9.6 and 9.7		

Specific limitations on the application of the data are included as comments in the text or on the Figures. Where possible an estimate of the uncertainty of the data is given on the Figures, based on the spread of experimental data. These uncertainties apply only to variations in the parameter directly being considered and the combined application of two or more corrections may increase the uncertainty. The ranges of experimental data on which the correlations are based are given in Table 9.1.

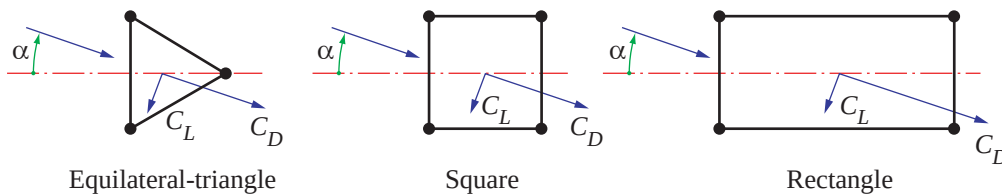
2.3 Use of the Data Item

- Note the general scope and applicability of the Data Item, as set out in Section 2.1 and 2.2, in relation to the problem under consideration.
- Select the appropriate Calculation Sheet or Sheets from Tables 9.4 – 9.7. The Calculation Sheets can be used as a convenient, self-contained guide to the calculation procedure and they refer to the appropriate Figures for data. The Figures include estimates of uncertainty and important limitations are noted. For repeated calculations the data in this Item can be programmed using the equations in the Appendix. A worked example is given in Section 7 and advice on the input data required for the calculations is given in Section 2.5.

- (iii) To make best use of the Data Item, read also the appropriate background notes, selected by reference to Table 2.1. This is particularly important where data are tentative or extrapolated. Reference to Table 9.1, giving ranges of the parameters covered by experimental data, may also assist in establishing applicability in such cases.

2.4 Summary of Calculation Procedure

The calculation procedures, summarised in the sheets in Tables 9.4–9.7, are for tower-like structures where the main chord members are in an equilateral-triangular arrangement or a square or rectangular arrangement (see Sketch 2.1).

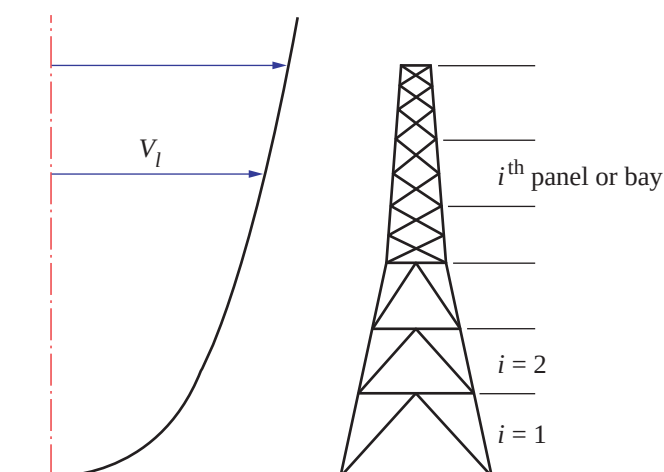


Sketch 2.1 Various arrangements of the main chord members located at each corner

For a square-arrangement tower it is often assumed that the maximum leg load occurs at $\alpha = 45^\circ$ and the maximum bracing load at $\alpha = 0^\circ$. This is not necessarily so. Data are therefore presented for the whole range of incidence so that all situations can be properly studied.

2.4.1 Forces and bending moments

Methods are provided for estimating C_D and C_L for the basic tower, with or without ancillaries, and Equations (1.1) and (1.2) then give the force coefficients C_X and C_Y acting along the principal body axes. (The force coefficient C_Z is usually approximately zero but in some situations, principally with angle-section members, it can be significant – see Section 3.)



Sketch 2.2

Except for uniform structures in uniform (constant velocity) flow (such as a horizontal crane jib or boom) it will be necessary to calculate the forces acting on individual bays or panels using force coefficients appropriate to the local panel geometry and a mean flow velocity, V_i , appropriate to that panel (as illustrated

in Sketch 2.2). Thus the local forces acting on panel i are

$$X_i = \frac{1}{2} \rho V_i^2 A_{si} C_{Xi} \quad (2.1)$$

and
$$Y_i = \frac{1}{2} \rho V_i^2 A_{si} C_{Yi}. \quad (2.2)$$

Overall forces and moments are then calculated by summing the contributions from individual panels assuming that the local forces act at the centre of each local panel and ancillary.

Sections 3, 4 and 5 explain how the mean force coefficients for a basic tower-like structure (without ancillaries) are estimated. Section 6 provides data giving the incremental force coefficients when ancillaries such as ladders, feeder pipes, screens, aerials and flues are added.

2.4.2 Torsional moments

Torsional moments about the Oz axis (or an axis parallel to Oz through the centre of stiffness) may also be important particularly when ancillaries are placed asymmetrically on the tower, or even if the loading is symmetrical but the centre of stiffness of the tower is not centrally located.

As a general guide, Table 2.2 provides data¹⁶ giving the maximum torsional moment that can be expected for basic towers with or without ancillaries. They are given in the form of a torsional moment coefficient, C_M , defined as

$$C_M = \frac{\text{maximum torsional moment}}{\frac{1}{2} \rho V_i^2 (A_s + A_{sa}) B}$$

where, in this particular case only, the coefficient is based on the shadow area A_s of the basic tower plus the shadow area A_{sa} of the ancillary in isolation from the tower. For a basic tower, made of flat-faced or mixed members, ϕC_M is approximately constant.

For concentrated ancillaries, it is recommended that the increment in the maximum torsional moment due to the addition of the ancillary is calculated as the moment, about the centre of stiffness, of the forces acting on the ancillary as if it were in isolation from the tower. Where, for example, several such ancillaries are symmetrically placed about the vertical (Oz) axis of the tower, it is recommended that the maximum torsional moment is estimated as the contribution from one of the ancillaries acting in isolation.

TABLE 2.2 Approximate Values of C_M

<i>Tower chord-member arrangements</i>	<i>Basic-tower member shape</i>	<i>Ancillary</i>	<i>Location</i>	C_M
Equilateral-triangular	flat-faced	—	—	0.015/ ϕ
	round-section	—	—	0.06
	mixed flat and round	—	—	0.015/ ϕ
	flat or round*	flat or round members frame parallel to front face (flat or round members)	front face	0.11
	flat or round*		inside tower	0.05
	flat or round*	internal cylinder	central	0.04
Square	flat-faced	—	—	0.022/ ϕ
	round-section	—	—	0.08
	mixed flat and round	—	—	0.022/ ϕ
	flat or round*	flat or round members frame parallel to front face (flat or round members)	front face	0.17
	flat or round*		$x = \pm 0.25B$	0.11
	flat or round*		$x = 0$ (central)	0.07
	flat or round*	internal cylinder	central	0.06

* extrapolated information.

2.4.3 Shear flow and taper effects

The effect of a shear flow, that is a flow with velocity varying along the Oz axis, is allowed for in the calculation method by use of the mean velocity over a bay or panel of the tower.

For towers with panels that are inclined to the Oz axis, the effect of the inclination will be to reduce the forces but this effect is unlikely to be significant for angles up to about 20° . However, the accompanying effects of taper may significantly affect the exposed area of the structure for some member shapes, *e.g.*, unequal-angle or double-angle members.

2.4.4 Effects of icing

Ice accretion on lattice structures exposed to the Earth's atmosphere may have two effects on wind loading. Firstly, it may increase the shadow area and solidity of the structure, which will generally increase the wind loading. Secondly, it may deform the shape of the members, especially of circular-section members, as a result of non-uniformity of ice accretion. This will particularly affect across-wind forces (lateral and vertical) on a tower structure and may also lead to aerodynamic instability of slender members.

It is difficult to predict accurately the amount and form of ice accretion due to large variations in weather conditions between different locations. Reference 5 considers the data currently available and gives recommended values of uniform ice thicknesses to be assumed for designs in the UK. For other countries the appropriate Standards (or Codes of Practice) or Meteorological Office should be consulted.

2.5 Input Data Required

The input data required for the evaluation of the overall forces and moments fall into three categories. These are (i) tower geometry, (ii) flow properties and (iii) force coefficients.

2.5.1 Tower geometry

Unless the tower considered is completely uniform along its length and is immersed in a uniform flow it will be necessary to divide the tower into convenient sections and consider the loading on each separately.

The required geometrical parameters for the tower or for each panel of the tower are set out in Table 2.3.

2.5.2 Flow properties

The required flow properties are set out in Table 2.4.

2.5.3 Force coefficients

The force coefficients are presented in terms of C_D and C_L . The drag coefficient is expressed as a basic coefficient, C_{D0} , corresponding to $\alpha = 0$, to which a correction factor, f_α , is applied to account for incidence effects. Sections 3 to 5 deal with basic tower-like structures (with equilateral-triangular, square and rectangular arrangements of the chord members) made from flat-faced members, round members and composite (flat and round) members respectively. Section 6 provides methods for estimating, separately, the incremental drag coefficient when ancillaries are added to the basic tower structure. The coefficients C_X and C_Y are calculated using Equations (1.1) and (1.2).

The force coefficient, C_Z , is significant only for towers constructed with angle-section members as discussed in Section 3.

TABLE 2.3 Tower Geometry

<i>Parameter</i>	<i>Comment</i>
Tower arrangement of chord members Shadow area, A_s , of front frame Solidity ratio, $A_s/A_e = \phi$	Equilateral-triangular, square or rectangular Evaluated preferably from detailed dimensions or from scaled drawings but Appendix A1 of ESDU 81027 ⁴ gives equations which assist estimation of A_s to within about ± 10 per cent provided that the bracing connections are close to the bay limits.
Chord member diameter, D_c Surface roughness parameter, ε/D_c Diameter ratio, D_b/D_c	For circular-section members only. An assessment of ε may be made from Table 9.2.
Shadow area of flat-faced members, $A_{s(flat)}$ Shadow area of circular-section members, $A_{s(circ)}$	For frames with a mixture of member types.
Shadow area of gusset plates and ancillaries	See Section 6 for treatment of ancillaries.
Centre of stiffness	If this is not symmetrically placed then significant torsional moments can occur even when the loading is symmetrical.

TABLE 2.4 Flow Properties

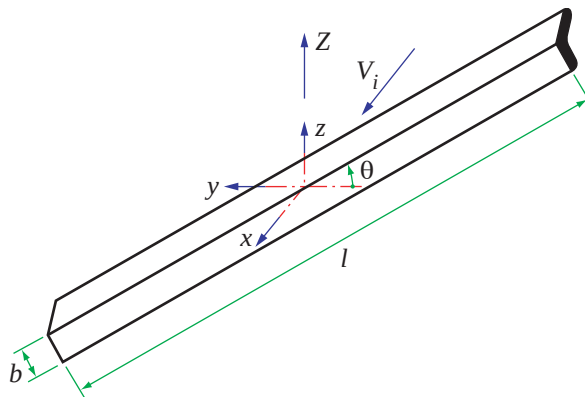
Parameter	Comment	
	Uniform flow	Shear flow
Velocity, V_i (see Section 2.2)	Single value required for each panel (i) location.	Use mean value over each panel. Table 9.3 summarises velocity profile data for the mean-hourly wind; more detail is given in ESDU 82026.
Turbulence – intensity, I_u – lateral scale, rL_u	Required for frames of circular-section members only. Table 9.3 summarises values for the natural wind and gives approximate values for some internal flow environments. ESDU 85020 and 86010 provide more detailed information for the wind. Single value required for panel location	Use value at centre of each panel.
Fluid density, ρ	Standard reference value for air = 1.23 kg/m^3 . Nominal value for fresh water $\approx 1000 \text{ kg/m}^3$ and for sea water $\approx 1025 \text{ kg/m}^3$. Note however that these values vary appreciably with temperature, and with pressure for air and salinity for sea water, even over the typical ranges experienced under natural atmospheric conditions.	
Fluid kinematic viscosity, ν	Standard reference value for air = $1.45 \times 10^{-5} \text{ m}^2/\text{s}$. Nominal value for fresh water $\approx 1 \times 10^{-6} \text{ m}^2/\text{s}$ and for sea water $\approx 1.08 \times 10^{-6} \text{ m}^2/\text{s}$. Note that, as for density, appreciable variations from these values do occur.	

3. BASIC TOWERS: FLAT-FACED MEMBERS (Calculation Sheets 1, 3)

The drag coefficient C_D for a basic tower-like structure constructed from flat-faced members (*e.g.*, angle or square sections) is considered in Sections 3.1 to 3.3 depending on the chord member configuration. The addition of ancillaries to each panel are dealt with separately and data on this aspect are provided in Section 6. In each case the variation of C_{D0} with solidity has been extrapolated to cover the complete range from $\phi = 0$ to 1 using the limiting values for each chord member configuration as a guide. The derivation of these limiting values is discussed separately in each Section.

When the longitudinal axis of the tower or space frame is normal to the flow direction the lateral-force coefficient, C_L , is usually small but not necessarily negligible. Figure 9 gives values of C_L for the basic tower. When ancillaries are added, the net change in C_L can be comparatively large (see Section 6).

The force coefficient, C_Z , acting on the 0z direction, can be significant for towers made of angle-section members. In order to provide weather protection the preferred mode of construction for the bracing members is with a flange uppermost. This configuration can induce significant forces in the 0z direction for those bracing members on the front face where flanges are pointing into the oncoming flow as illustrated in Sketch 3.1.



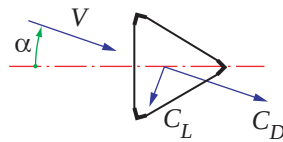
Sketch 3.1

This is an important consideration in the design of tower foundations. In this case the maximum vertical lifting force (Z) can be as much as 25% of the drag force²¹. An approximate method of estimating it is to sum the individual Z -component forces on each member on the front face as if they were isolated from the tower. The maximum Z -force on an individual member will be given approximately by

$$Z \text{ (single angle member)} = \frac{1}{2} \rho V_i^2 \times C_{Zb} b l \cos \theta \quad (3.1)$$

where C_{Zb} is either approximately 2 or 0.5 depending on whether the upper flange is pointing into the flow (Sketch 3.1) or away from the flow respectively.

3.1 Equilateral-triangular Arrangement of Chord Members



$$C_D = C_{D0} \times f_\alpha$$

(Fig. 1a)(Fig. 1b)

$$C_L : \text{(Fig. 9a)}$$

Sketch 3.2 Equilateral-triangular arrangement of flat-faced chord members

The drag coefficient at incidence α is given by

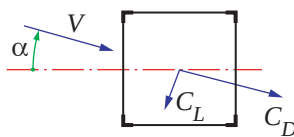
$$C_D = C_{D0} f_\alpha \quad (3.2)$$

where C_{D0} is the drag coefficient for flow normal to a face ($\alpha = 0$) and f_α is a correction factor for the effect of flow incidence. For an equilateral-triangular arrangement of the main chord members the maximum drag coefficient occurs when one face is normal to the flow ($\alpha = 0$). Values of C_{D0} for this condition are given in Figure 1a as a function of solidity. Typical variations of $f_\alpha = C_D/C_{D0}$ with α are shown in Figure 1b which demonstrates that the effect of flow incidence is relatively small.

The limiting value of C_{D0} at $\phi = 1$ in Figure 1a will correspond to a solid equilateral triangular section prism for which $C_{D0} = 1.85$ (ESDU 79026)¹. As $\phi \rightarrow 0$ the frame will comprise essentially three nearly independent chord members for which C_{D0} (based on A_s) will be approximately 3 depending on the cross-sectional shape the chord members and their orientation to the flow.

The lateral force coefficient, C_L , is given directly by Figure 9a.

3.2 Square Arrangement of Chord Members



$$C_D = C_{D0} \times f_\alpha$$

(Fig. 2a)(Fig. 2b)

$$C_L : \text{(Fig. 9b)}$$

Sketch 3.3 Square arrangement of flat-faced chord members

The drag coefficient at incidence α is given by

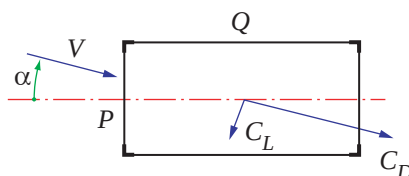
$$C_D = C_{D0} f_\alpha \quad (3.3)$$

where C_{D0} , given by Figure 2a, is the drag coefficient for flow normal to the front face ($\alpha = 0$) and f_α , given by Figure 2b, is a correction factor for the effect of flow incidence. In practice both C_{D0} and f_α are dependent on ϕ and Figure 2b shows that the maximum value of C_D for a basic tower occurs at a value of α between about 20° and 45° depending on ϕ .

The limiting value of C_{D0} at $\phi = 1$ in Figure 2a will correspond to that for a square prism with nominally sharp edges so that $C_{D0} \approx 2.05$. The limiting value of C_{D0} at $\phi = 0$ has been obtained by considering the frame as comprising only four independent chord members; the actual value of C_{D0} (based on A_s) will then depend on the member cross-sectional shape but for most purposes a value of $C_{D0} \approx 4$ will apply.

The lateral force coefficient, C_L , is given directly by Figure 9b.

3.3 Rectangular Arrangement of Chord Members



Sketch 3.4 Rectangular arrangement of flat-faced chord members

There are few data relating to rectangular towers. Although the data with one face normal to the flow ($\alpha = 0$) are similar to the data for the equivalent square section arrangement of the same solidity, the lack of symmetry causes differences in C_D for other than zero incidence cases. A recommended procedure¹⁶, confirmed by tests on a rectangular tower of side ratio 2:1, is to treat each pair of parallel faces separately as if they were part of a square-section arrangement and to combine the resulting drag coefficients taken from Figure 2. Thus, for a rectangular section at incidence α ,

$$C_D = C_{D0P} f_{\alpha P} \cos^2 \alpha + C_{D0Q} f_{\alpha Q} \frac{A_{sQ}}{A_{sP}} \sin^2 \alpha \quad (3.4)$$

where C_D is based on A_{sP} , the shadow area of face P (which is normal to the flow at $\alpha = 0$) and where C_{D0P} , $f_{\alpha P}$ and C_{D0Q} and $f_{\alpha Q}$ relate to values for two separate square-section arrangements of sides P and Q (see Sketch 3.4) respectively.

A similar procedure is recommended for estimating the lateral force coefficient, C_L , i.e.,

$$C_L = C_{LP} \cos^2 \alpha + C_{LQ} \frac{A_{sQ}}{A_{sP}} \sin^2 \alpha \quad (3.5)$$

where C_{LP} and C_{LQ} are the values of C_L taken from Figure 9b corresponding to square-arrangement towers, based on sides P and Q respectively, both at incidence α .

4. BASIC TOWERS: CIRCULAR-SECTION MEMBERS (Calculation Sheets 2, 3)

4.1 Summary of Data

The drag coefficient for frames constructed of circular-section (round) members is dependent not only on the geometrical arrangement and solidity but also on Reynolds number. In addition, at high Reynolds number (Re_c greater than about 10^5) the surface roughness of the members can have a strong influence on C_D .

For these reasons the data for tower-like structures of round members are presented in the form

$$C_D = C_{D1} \times f_s \times f_\alpha \quad (4.1)$$