the same dimensions. An approximate natural frequency can be determined from Eq. (10) by using for w_s the weight of the shell plus lining, divided by the thickness of the plate. The weight and thickness should be taken at about one-fourth the height above the base.

Base flexibility may need to be considered in determining frequency. For example, when stacks are supported on a roof structure or a steel frame, the translational and rotational spring constants of the support must be taken into account.

STEEL STACKS

There are many types of steel stacks, including self-supported, guyed, and braced. The choice of a particular type should be based on the evaluation of its comparative costs and the site conditions. The three profile types commonly used are shown in Fig. 5. Short stacks, less than 100 ft high, may be straight cylinders. For taller stacks a bell base may be used to reduce plate thickness and anchor-bolt size. The bell height is usually between one-fourth and one-third of the total stack height. The diameter of the flared base D_b is usually about $1\frac{1}{3}$ to $1\frac{3}{4}$ times the cylinder diameter D_t.

Most steel stacks are built from plate conforming to ASTM A36. In some cases, A242, A588, A131B or CS, A283C, or other grades of steel have been used as dictated by individual experience and specific requirements. Stiffeners are normally A36. Steel for stacks in cold climates should have a low transition temperature (Sec. 4).

The steel stack and its anchorage should be designed for the loads discussed in preceding articles. When subjected to wind and/or earthquake loads, the stack may be treated as a beam column and analyzed by the conventional beam theory. Except in guyed and braced stacks, nonuniform temperature differentials will not induce bending moments. Particular attention is required in the design of reinforcing at the cone-to-cylinder junction and at the breeching opening.

To reduce heat loss, insulation of the exterior surface of unlined steel stacks, including the projecting flanges of all attachments, is recommended. This is common practice in England to reduce soot fallout. Proper lining should be applied to the interior surface of the shell to protect the bare steel from high temperature, abrasion, and corrosion from the flue gases. The weight of insulation and lining should be taken into account in the frequency calculation for resonance under the lined condition. Unless an integral shotcrete or brick lining is used, no credit should be given to the lining in calculating stack stiffness.

ASTM STS-1[2] provides the requirements and guidelines for design, fabrication, erection, and maintenance of steel stacks and their appurtenances.

9. Allowable Stresses The allowable longitudinal compressive stresses due to vertical load and bending moment can be determined by[7]

$$F = XY \tag{14}$$

where

$$X = \begin{cases} 0.0625Et/R & \text{for } 0 \leq \dfrac{t}{R} \leq \dfrac{8F_p}{E} \\ 0.5[F_y - k_s(F_y - F_p)] & \text{for } \dfrac{8F_p}{E} \leq \dfrac{t}{R} \leq \dfrac{20F_y}{E} \\ 0.5F_y & \text{for } \dfrac{t}{R} > \dfrac{20F_y}{E} \end{cases}$$

$$k_s = \left(\frac{F_y - 0.05Et/R}{F_y - 0.4F_p}\right)^2$$

$$Y = \begin{cases} 1 & \text{for } \dfrac{L}{r} \leq 60 \text{ and } F_y \leq 50 \text{ ksi} \\ \dfrac{21{,}600}{18{,}000 + (L/r)^2} & \text{for } \dfrac{L}{r} > 60 \text{ and } F_y \leq 50 \text{ ksi} \end{cases}$$

F_y = yield strength at mean shell temperature, ksi
F_p = proportional limit at mean shell temperature, ksi; may be taken as $0.7F_y$
E = modulus of elasticity at mean shell temperature, ksi

t = shell-plate thickness, in, at the section under consideration
R = radius of shell, in
L = length of stack between points of lateral support. For a self-supporting stack, L should be taken as the effective length, i.e., $L = 2 \times$ stack height, in
r = radius of gyration $= 0.707R$, in

The factor Y in Eq. (14) is intended to account for a possible interaction of cylindrical shell buckling, which depends on t/R, and column buckling, which depends on L/r.

The allowable stress given by Eq. (14) is based on a factor of safety of 2 and is suggested for load combinations which include either wind or earthquake forces.

Because of possible corrosion the computed required thickness should be increased. The allowance may vary from $\frac{1}{16}$ to $\frac{1}{8}$ in, depending on the properties of flue gases, the types of insulation and lining provided, and the operating gas temperature. Including the corrosion allowance, it is recommended that the shell thickness be not less than $\frac{5}{16}$ in for unlined stacks and $\frac{1}{4}$ in for lined stacks. Outstanding elements of rolled shapes and built-up members should have a minimum thickness of $\frac{1}{4}$ in

10. Cone-to-Cylinder Junction A stiffening ring is required at the junction of the cone and the straight cylinder sections of stacks. It is normally designed to resist the circumferential compression that results from the vertical loads and bending moments at the junction. Where external pressure due to stack draft is significant, the resulting additional circumferential forces should also be considered.

The maximum vertical force N_x per unit length of circumference in the cylinder at the junction is

$$N_x = \frac{W}{2\pi R} + \frac{M}{\pi R^2} \tag{15}$$

where W = axial load at junction
M = wind or other moment at junction

The total circumferential compression Q in the ring is

$$Q = R[N_x \tan\theta + 0.78P_d(\sqrt{Rt_1} + \sec\theta\ \sqrt{Rt_2 \sec\theta})] \tag{16}$$

where θ = acute angle between cone wall and cylinder
P_d = external pressure per unit area, psi
t_1 = thickness of cylinder wall, in
t_2 = thickness of cone wall, in

The required area A_s and moment of inertia I_s of the ring are

$$A_s = \frac{Q}{F_a} \tag{17}$$

$$I_s = \frac{QR^2}{E} \tag{18}$$

The allowable ring compression F_a in Eq. (17) is usually limited to 8000 psi to minimize the secondary vertical bending stresses. For stacks of diameters greater than 15 ft, or where higher values of F_a are used, it would be advisable to evaluate the secondary stresses. In addition, bending stresses due to the circumferential variation in wind pressure should be checked by Eqs. (7).

In determining the section properties of the stiffening ring the area of a portion of the shell (Fig. 6) can be included, but the area so included should not exceed the area of the ring itself to ensure a nominal-size stiffener. The maximum permissible longitudinal compressive stresses in the cone may be determined by Eq. (14) with the horizontal radius R replaced by the cone radius $R \sec\theta$.

11. Circumferential Stiffeners In addition to the stiffener at the cone-cylinder junction a stiffener is required at the top of the stack. Intermediate ring stiffeners may also be required. The purpose of such stiffening is to prevent excessive deformations of the stack shell under wind pressure and to provide adequate structural resistance to negative draft.

Intermediate stiffener spacing L_s can be determined by

$$L_s = 720 \sqrt{\frac{Dt}{12P_w}} \tag{19}$$