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George Abdel-Sayed

Ching Fung

Frank Monasa

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STATE OF THE ART -
CYLINDRICAL COLD-FORMED STEEL FARM STRUCTURES

by

George Abdel-Sayed[1], Ching Fung[2], and Frank Monasa[3]

INTRODUCTION

Cylindrical cold-formed steel structures are widely used in farm structures for grain storage, as well as for stock facilities, storage buildings and utility structures. A task committee has been established under the "ASCE Committee on Cold-Formed Steel Members" with the objective of defining the problems encountered in the design and construction of these structures, as well as for gathering and developing reliable information which could lead to rational methods of design.

The present paper examines the state of the art with regard to the loading and analysis of cylindrical farm structures and outlines a few related research projects which are in progress. It deals with upright cylindrical grain bins (grain tanks) and with barrel shells (quonset buildings).

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[1] Professor of Civil Engineering, University of Windsor, Windsor, Ontario.

[2] Senior Engineer, Westeel-Rosco Ltd., Toronto, Ontario.

[3] Associate Professor, Department of Civil Engineering, Michigan Technological University, Houghton, Michigan.

I. GRAIN BINS

The on-farm grain storages are usually built of cold-formed steel sheets in the form of upright cylindrical shells (Fig. 1). Their diameters range from 10 ft. (3.05 m) to 60 ft. (18.29 m) and their height to diameter ratio is usually less than 1.5. These storages can be classified as shallow flexible bins.

The analysis and design of these bins are governed primarily by the characteristics and magnitude of the horizontal and vertical pressures induced by the grains. Snow and wind loading may also govern the design, especially for bins with diameters larger than 30 ft. (9. 14 m). The different cases of loading can be outlined as follows:

a) Static Pressure

Many theories have been developed to determine the static internal pressure. Frankhauser (11) presented a summary and comparisons between some of the theories and code requirements used for the design of grain bins. These are Janssen's Theory, the modified Janssen Theory, as well as the German and Russian standards, in which the grain pressure is attributed to the arching effect of the grain. However, this arching normally develops in deep silos and is not likely to take place in shallow flexible bins.

The grain pressure in shallow bins can be more realistically attributed to a sliding wedge mode of action, and thus Coulomb's Theory is considered by many designers to be adequate for application in shallow bins. Coulomb's theory could also be modified to consider the sliding of the grain mass over a central cone and thus takes into account the circular shape of the bin walls (1). Herein, as in Coulomb's Theory, the lateral displacement of the wall is assumed to be large enough to mobilize the sliding wedge. However, the wall displacement is restrained by the hoop tension developed in the cylindrical walls of the bin, causing the pressure to be increased with the increase in the hoop membrane rigidity (20). Therefore, the pressures obtained, based on Coulomb's theory, represents a lower boundary for the grain pressure. Also, for relatively flexible walls the lateral deformation of the bin walls exceeds the deformation required to mobilize the wedge movement at some points along the height. This causes nonuniformity for both the lateral and vertical pressures which violate the hydrostatic pressure distribution assumed by Coulomb (20).

The Canadian Farm Building Code (6) calculates the horizontal pressure on the basis of Rankin's formula by applying an "equivalent fluid density" for the stored material. Although Rankin's Theory does not account for friction between the wall and stored material the Canadian Code considers the vertical load to be equal to the horizontal pressure multiplied by the coefficient of friction between the wall and stored material.

Recently, the finite element method has been applied considering a composite slice of the grain and the surrounding walls (20). It accounts for the flexibility of the bin walls and the interaction between the grain pressure and the wall displacements.

A comparison between grain pressures measured on the walls of a model bin and those obtained from the above mentioned theories is shown in Fig. 2 (20). Similar results were observed by Hamilton and Nelson (16) who found the hoop tension in the bin walls to be 75% greater than predicted by Rankin's Equation, 41% greater than predicted by Janssen's Theory and 110% greater than predicted by Airy's Equation (3).

b) Dynamic Effects

Test results (19) show that the dynamic effect due to loading is negligible in shallow bins. It was also observed that funnel flow is dominant when discharging the grain and therefore only a slight increase in the grain pressure was recorded as a result of central discharge (about 20%) (19, 21). This increase in pressure is very small when compared with that applied for deep silos in which mass flow is dominant (9).

c) Eccentric Discharge

Shallow grain bins are often subjected to eccentric discharge conditions. An experimental program is in progress at the University of Windsor to study the effect of eccentric discharge in shallow bins. Early results indicate that the pressure remains almost unchanged on the far side while it is considerably reduced on the discharge side. The resulting non-symmetric loading leads to the development of bending moments in the circumferential direction and could develop denting in the bin walls (17).

d) Grain Consolidation

It has been observed that grain bins located near railway tracks are more susceptible to failure. This could be attributed to the effect of consolidation of the grain due to the vibrators caused by nearby traffic. Also, grain consolidation is expected to increase with time. For this reason the Canadian Farm Building Code requires an increase of 25% in the calculated static pressures for storage longer than one year (6).

e) Passive Pressure

Passive pressures can be developed in grain bins due to relative lateral movement of the side wall and the grain tending to compress the grain mass. This relative movement can be the result of an increase in the moisture content of the grain; or, a temperature change in grain and the bin walls. Under these conditions the hoop tension is found to be a function of the depth below grain surface and the amount of lateral displacement of the bin wall. Hamilton and Nelson found the strains due to passive pressure at the bottom of a model bin to be as much as 2.7 times the strains due to active (static) pressures (16).

f) Wind Loading

It is unlikely that wind loading has any significant effect on fully loaded bins; however, some failures were reported for empty bins subjected to severe wind conditions.

At the present time, only limited information is available concerning the magnitude and distribution of wind loading (7, 12, 30). The magnitude of the maximum pressure is found to be governed by the roughness of the bin walls (type and direction of cold-forming of the panels) as well as by the ratio of the height to diameter of the bin (30). The distribution of the wind pressure around the bin was found experimentally by Cowdrey and O'Neil (7), Fig. 3. However, it should be noticed that these model tests were mainly for isotropic oil tanks with no or very shallow covers. For cylindrical structures covered by hemispherical dome, the pressure coefficients are set by the French Code, Regeles NV65 (12). Additional research is needed in order to develop information directly related to grain bins made of cold-formed steel and having conical roofs.

g) Snow Loading on Conical Roof

Hitherto, little information is available on the snow accumulation on conical roofs. The nearest shape contained in the National Building Code of Canada is the simple gable roof. However, the magnitude of the snow load given is considerably higher than that observed in the field. This is due to the effect of wind on the concial roof, which is substantially different from that on the two-dimensional gable roofs. In addition, the galvanized steel, the most common material used in construction of grain bin roofs, absorbs more solar heat, hence, most snow accumulation slides off the relatively steep sloped roof. Recent small scale model test in a water flume to simulate the snow drift supports the observation that lesser snow load can be used in the design of conical grain bin roof.

ANALYSIS AND DESIGN

A. Axi-Symmetric Loading

Under axi-symmetric loading (static Loading) the bin is subjected mainly to hoop tension and axial vertical compression in the walls. A membrane solution is usually considered adequate for this case of loading.

B. Non-Symmetric Loading

While membrane solution is suitable for the symmetric cases of loading it becomes inadequate for non-symmetric loadings as in the cases of wind loading or eccentric discharge. Herein, bending moment M_ϕ is developed along the meridian of the bin.

Grain bins made of cold-formed steel can be treated as orthotropic cylindrical cantilever shells. A set of governing differential equations found to adequately describe the prebuckling elastic behaviour of such shells is given as follows (13, 22).

$$D_x u_{xx} + D_{x\phi}(u_{\phi\phi} + v_{x\phi}) = -R P_x \tag{1a}$$

$$D_\phi(v_{\phi\phi} - w_\phi) + D_{x\phi}(u_{\phi x} + v_{xx}) = -R P_\phi \tag{1b}$$

$$B_\phi(w_{\phi\phi\phi\phi} + 2w_{\phi\phi} + w) + B_x w_{xxxx} + 2B_{x\phi} w_{xx\phi\phi} - R^2 D_\phi(v_\phi - w) = R^3 P_z \tag{1c}$$

in which x is nondimensional longitudinal cylindrical coordinate shown in Fig. 1; R is the radius of the bin; u, v, w are nondimensional displacement components in x, ϕ and z directions, respectively; D_x, D_ϕ = axial rigidity in the x- and ϕ directions, respectively; $D_{x\phi}$ is the shear rigidity in x-ϕ

plane; B_x and B_ϕ are bending rigidities in x-z and ϕ-z planes, respectively; $B_{x\phi}$ is the torsional rigidity; P_x, P_ϕ and P_z are the load components acting in x, ϕ and z directions. For a general or non-symmetric case of horizontal pressure, P_z can be presented in the form

$$P_z = P_o \sum_{n=0,1}^{\infty} \sum_{m=1,2}^{\infty} a_n b_m \cos n \phi \sin \bar{m} x \tag{2}$$

in which P_o is the maximum intensity of load; a_n and b_m are constants governing the distribution of loading in the ϕ and x directions, respectively; $\bar{m} = m\pi R/h$ and h is the total height of shell. By representing the displacement components in a trigonometrical series form, a homogeneous, as well as particular solutions for the governing equations are introduced (13). Satisfying the eight boundary conditions at $x = 0$ and $x = h$ leads to a group of closed form expressions for the displacement and the internal force components (13).

The stability of the grain bins is examined using Trefftz's variational theory (14). The buckling load is calculated for any case of loading by introducing an expression of the second variation of the total potential energy of the shell.

Computer programmes are written for the analysis and for the stability study of grain bins subjected to any case of loading. The analytical results showed good agreement with experimentally obtained ones (13).

The above mentioned solutions (13, 14) did not consider the actual conditions at the upper edges of the bin as connected to the conical roof. They considered the two extreme cases of that edge as being free or fully restrained to remain in its original circular condition. Jerath and Boresi (18) presented a solution based on Donnel's formulation and took into consideration the actual shape and interaction between the conical roof and the bin walls.

II. BARREL SHELLS

The barrel shells which are often referred to as quonset buildings (Fig. 4), are constructed using doubly corrugated or crimped cylindrical panels as shown in Fig. 5. The building is made of a series of arches bolted together. End plane walls are usually built to complete the system in the form of shell supported along its four edges.

Apart from dead weight, these cylindrical structures are subjected to the following loadings:

a) Snow Loading

Snow loading constitutes the major loading system to be considered for the design of barrel shells in Canada and the Northern states of the U.S.A. Adequate statistical data on snow load on ground is generally available (24). The relationship between the ground and roof snow load is mainly a function of the geometric and thermal properties of the roof and also the wind environment in the proximity of the roof in question. In general, two cases have to be considered for snow loading, namely balanced snow loading over the entire building and non-balanced loading accounting for the snow drift from one side of the building on to the other.

The published information on the ground to roof snow load conversion factors are limited and lack comprehensive consideration of the parameters involved. This can be noticed from the fact that the non-mandatory information contained in the commentary on Part 4 of the National Building Code of Canada (24) has been showing considerable changes in the consecutive editions including the forthcoming proposed changes for the 1980 edition. Taylor (29, 28) examined in detail the design snow loads and the emperical formulas which are intended to give design snow load distribution and loads as realistic as possible without undue complication. He also presented data and historical background, as well as a discussion on the recommendations of the Canadian National Building Code.

b) Wind Loading

Experience shows that quonset cylindrical buildings possess very good characteristics against wind loading. However, published information on the magnitude and distribution of wind load is very scanty for this type of building. At present, the only recommendation known to the authors is that of the ASCE Task Committee on Wind Forces (30). The pressure coefficients are given for four segments of circular arches: The center half and the leeward and windward quarters. These coefficients are given as a function of the rise-to-span ratio r. Fig. 6 shows wind pressure distribution on rounded roofs springing from the ground level. These data are for a transverse wind. If the wind is parallel to the barrel axis, the wind pressures are similar to those on a flat-roofed structure.

At present, a research project is in progress conducted by Dr. Davenport of the University of Western Ontario in cooperation with Fairford Industries of Saskatchewan. The findings of this project will be of special value for quonset shell builders, especially in the warm zones where snow loading is not governing.

c) Grain Pressures

In the last few years many farmers used the quonset building for grain storage. The grain pressure can be calculated using Coulomb's Theory considering the sliding of a wedge. Herein, consideration should be given to the nature of the curved wall supporting the grain.

Because of the considerable flexibility of the wall, Coulomb's Theory is expected to lead to realistic values for the grain pressures. Also, further studies are being conducted at the University of Windsor to examine the grain pressure taking into consideration the interaction effect between the wall displacement and the induced pressures.

It should be noted here that the grain pressure develops moments of similar distributions as those induced by snow loading. Therefore, special attention should be paid for quonset buildings used for grain storage and located in heavy snow areas.

ANALYSIS AND DESIGN

The analysis and stability problems in cylindrical quonset can be examined by using the method of finite element (5) or finite strip or by applying the theory of orthotropic shells (10, 23). Additional details on the application of orthotropic cylindrical shell theory are outlined in reference (2) and full scale tests are reported in reference (27).

It is also noted that, in case of long cylindrical buildings (length to span ratio of more than 1.5), the load is carried mainly in the arch direction. The middle part of the shell becomes not affected by the end walls and behaves as arches. These arches are flexible and can be analyzed using matrix method taking into consideration the geometric matrix accounting for their nonlinear behaviour (2).

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APPENDIX II - NOTATION

The following symbols are used in this paper:

a_n = constant governing distribution of loading in x-direction

b_m = constant governing distribution of loading in ϕ-direction

B_x, B_ϕ = bending rigidity in x-z and ϕ-z planes, respectively

$B_{x\phi}$ = torsional rigidity

D_x, D_ϕ = axial rigidity in x- and ϕ-directions, respectively

$D_{x\phi}$ = shear rigidity in the x-ϕ plane

h = height of grain bin

L = total length of shell

$\bar{m}$ = $m\pi R/L$

M_ϕ = bending moment in the meridian direction

P_x, P_ϕ, P_z = external loads per unti are of middle surface in x-, ϕ- and z-directions, respectively

P_o = maximum intensity of applied wind load in z-direction

R = radius of shell

r = rise to span ratio of quonset buildings

u, v, w = nondimensional displacement components in x-, ϕ- and z-directions, respectively

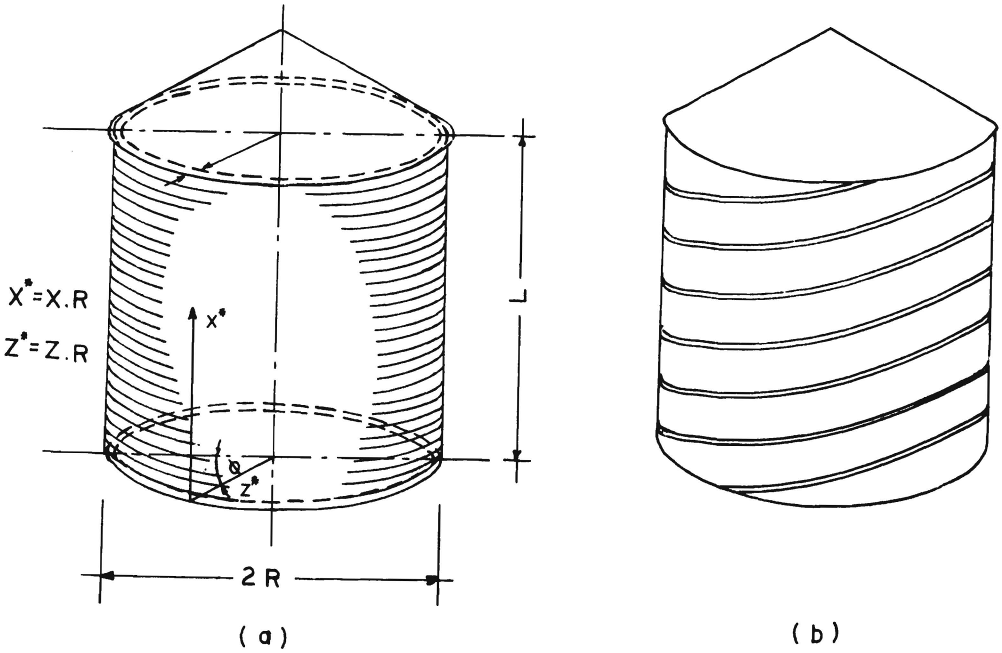

Figure (1) GRAIN BINS MADE OF COLD-FORMED STEEL SHEET
(a) CORRUGATED WALLS AND (b) SILO LIPP SYSTEM

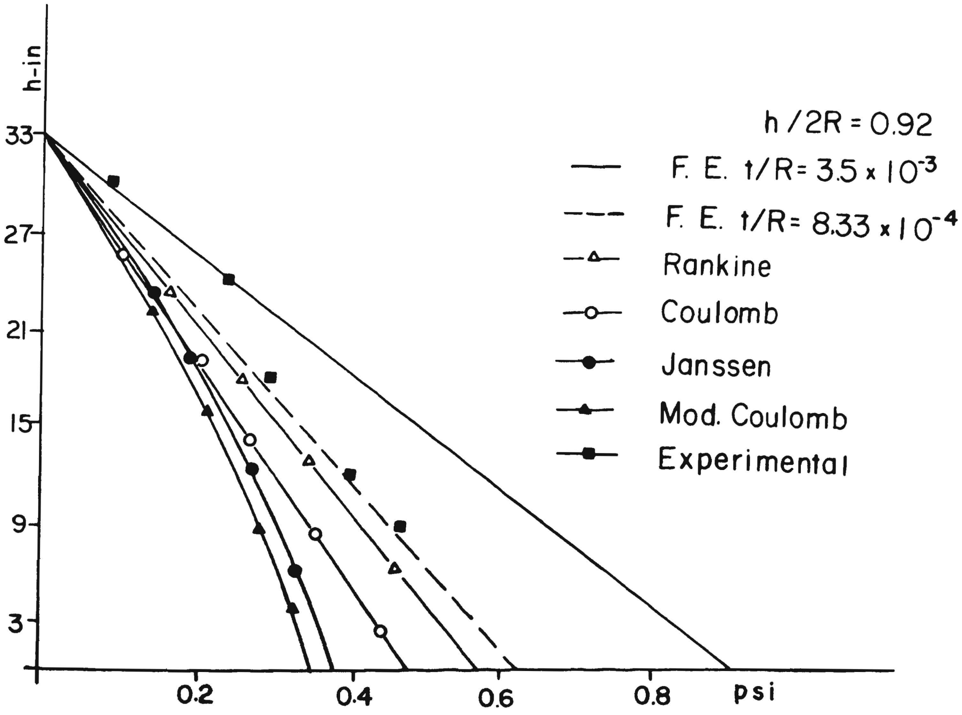

Figure (2) GRAIN PRESSURE ON THE WALLS OF A MODEL BIN WITH DIAMETER D = 36 in. (914.4 mm) FILLED WITH SAND (20)

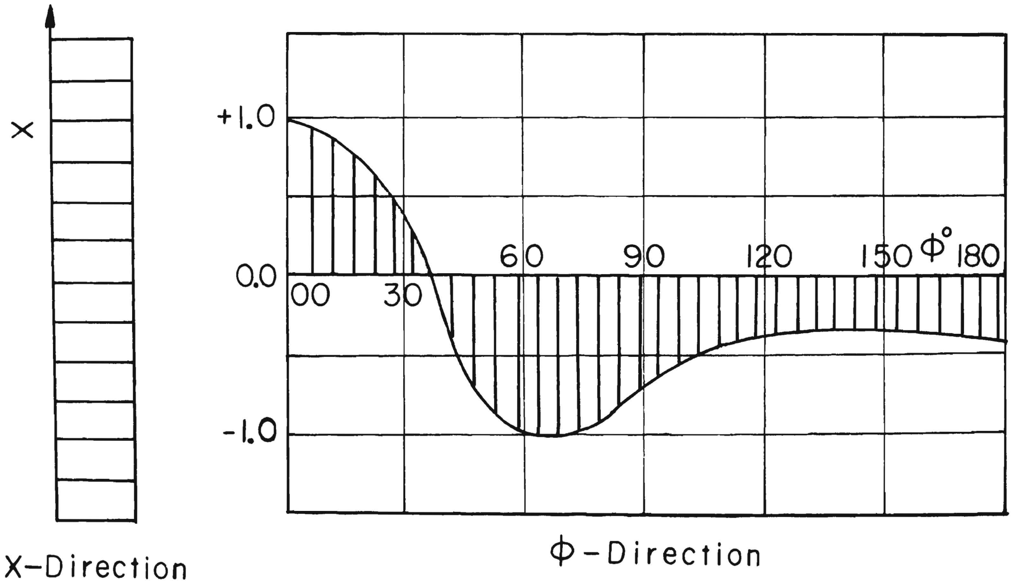

Figure (3) WIND LOAD DISTRIBUTION

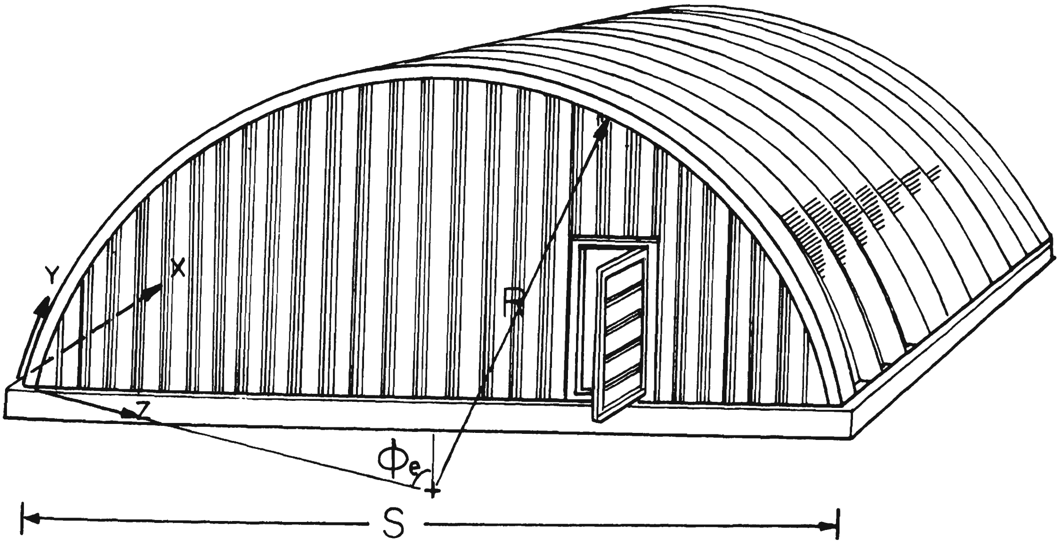

Figure (4) BARREL SHELLS MADE OF COLD-FORMED STEEL PANELS

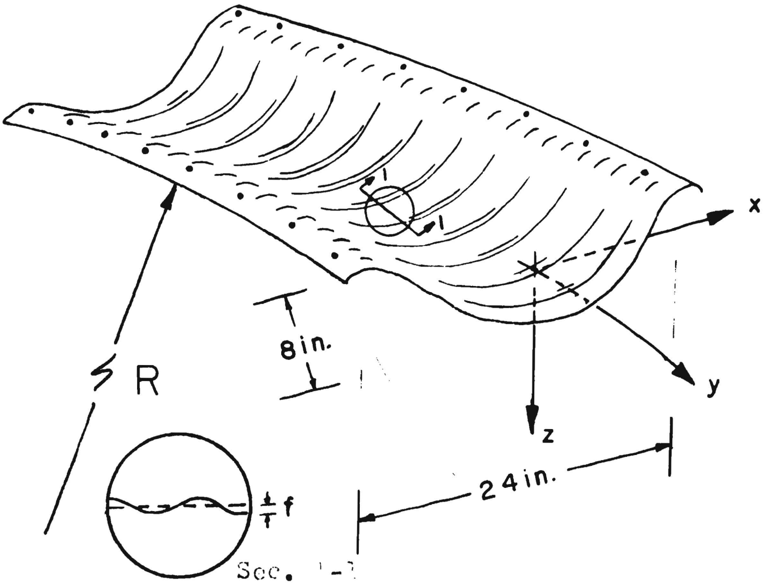

Figure (5a) DOUBLY CORRUGATED CURVED PANEL

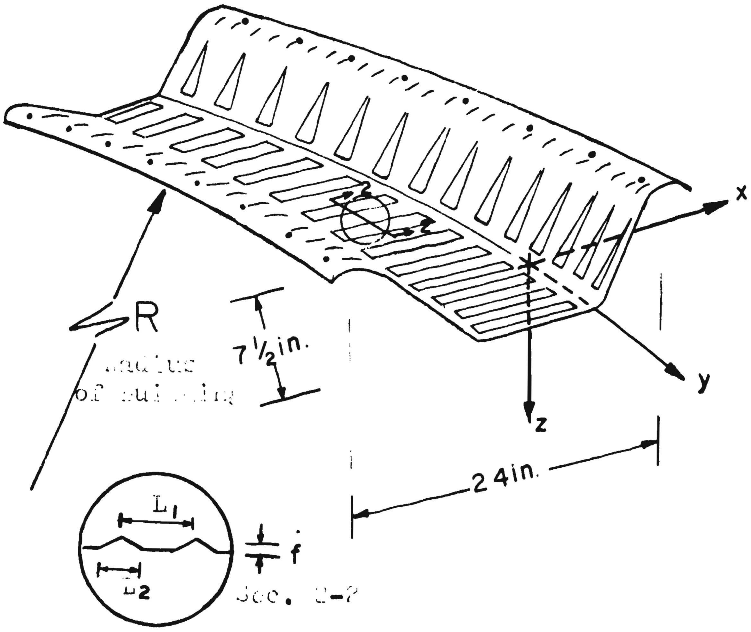

Figure (5b) CRIMPED CURVED PANEL

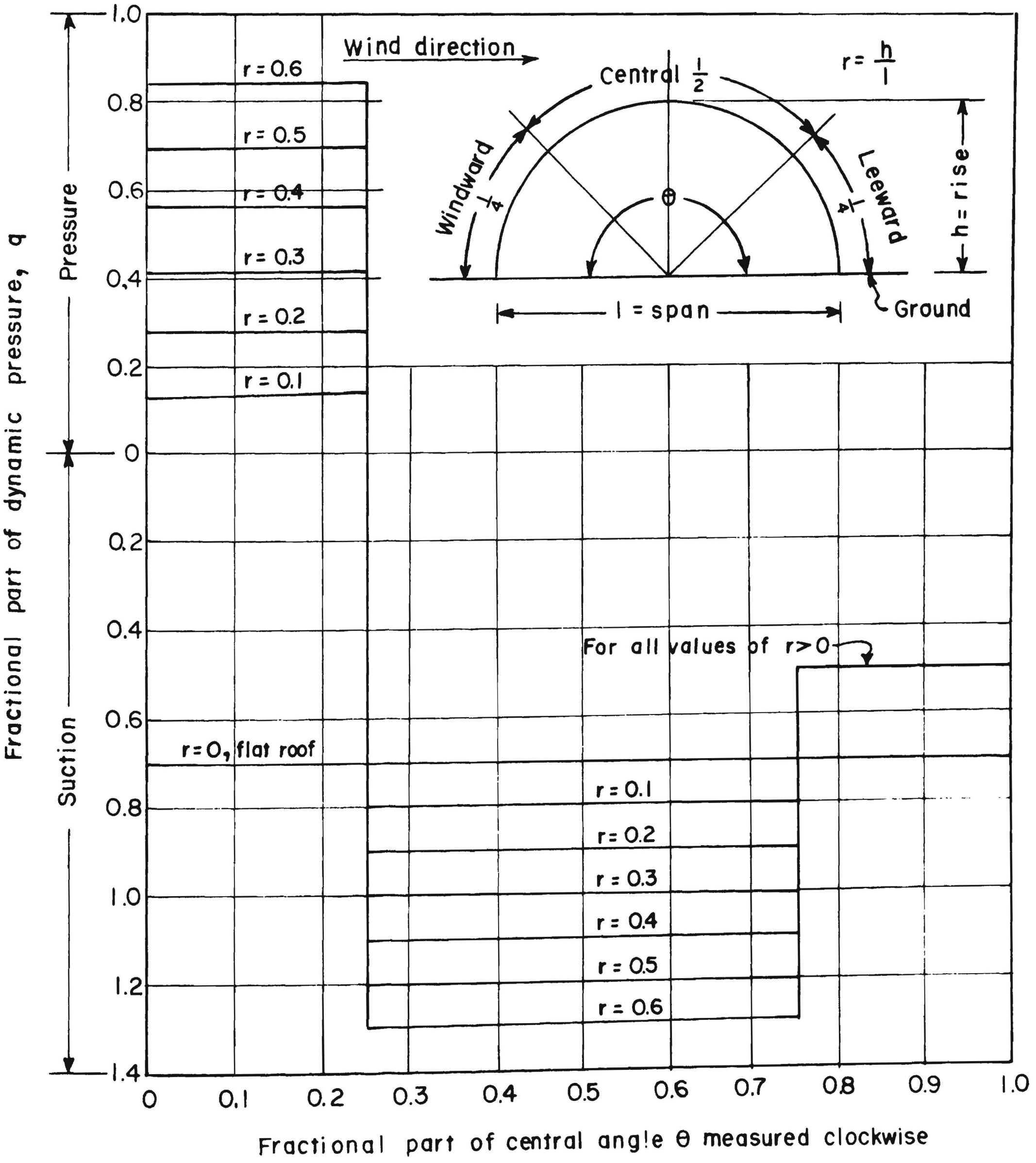

Figure (6) WIND PRESSURE DISTRIBUTION ON ROUNDED ROOFS STARTING FROM GROUND LEVEL - Ref. (30)