To Study the Analysis, Design and Behavior of Corrugated Steel Silo

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Abstract— The paper deals with Analysis and Design of large cylindrical steel silos composed of horizontally corrugated sheets with vertical stiffeners. The 3D FE calculations were carried out with the commercial finite element code ‘‘STAAD Pro. software ’’. Usually in India, we are using IS and ACI codes for analysis and design of steel silo, but in no one they have describe about corrugated steel silo. It is important to know about the change in grain pressure and wall thickness, when we are using corrugated sheet instead of plain sheet during analyze and design the silo. In this paper we have calculated grain pressures and external load by using IS codes and other literature, then prepared geometry and analyzed it on STAAD Pro. Software to compare the result of hoop stress in vertical wall. Value of hoop stress in manual calculation and in STAAD Pro. are almost matching, except in the case of top and bottom plate. It shows that our assumptions while modeling the silos are correct.

Key words: "Steel Silo", "Corrugated Sheet", "Vertical Storage System", “Grain Storage System", "Steel Silo with Stiffner”

I. INTRODUCTION

A. *Definition & Classification:*

The terms "bin," "silo," and "bunker" have different meanings in different parts of the world and may vary from author to author. In India as per IS-4995 silo is a bin circular or polygonal in plan. Bunker is a bin whose cross section in plan would be square or rectangular. In the United State the term "bin" generally includes both silos and bunkers, silos being deep bins and bunkers shallow bins [10].

Metal silos are currently produced in a great variety of forms: circular, square and rectangular in plan-form; squat bunkers and tall cylinders; silos with smooth isotropic walls, stiffened walls, built from horizontally or vertically corrugated sheets with orthogonal stiffeners, or patented special wall forms; silos supported on the ground and silos elevated on skirts or columns.

Steel silos and bunkers can be classified as an either structural, made of structural steel plates, or the sheet metal type, made of either plain or corrugated light-gauge metal. Unless they are corrugated or have stiffeners attached, steel plates have little bending strength. Walls of circular units act horizontally as tension membranes. Vertically however, they may be subject to compressive stress and be prone to buckling.

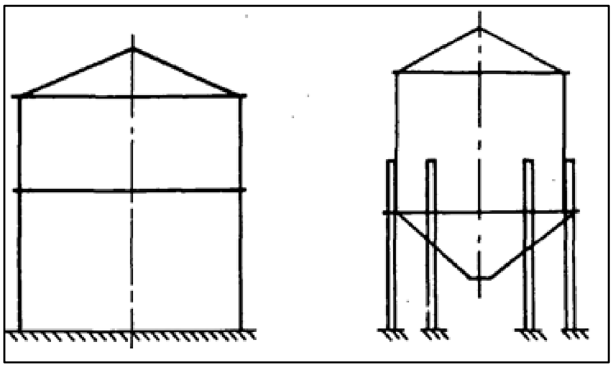

Fig. 1: Common circular metal silo forms

B. *Structural forms of Metal silos with Corrugated Sheeting:*

Small and medium size silos are often built from corrugated sheets. The commonest application involves corrugations running circumferentially around the silo. Unstjffened construction of this form is often used up to about 6m in height. Once vertical stiffeners are adopted, they must be assumed to carry the entire vertical load in the wall, as the difference in stiffness between a compressible corrugation and a vertical stiffener is such that the stiffener will collapse before the wall carries a significant part of the total load.

Fig. 2: Silos with corrugated sheet and vertical stiffener

Some large and very squat silos have been built in recent years from light corrugated sheets with the corrugations running vertically. External bands are required to support the internal pressures in the silo, but the required buckling strength in axial compression is easily achieved. For both forms of corrugated silo, the buckling resistance under wind is often critical, and should be determined from a calculation of the cylinder as an orthotropic eccentrically stiffened shell.

C. *Standards and Codes of Practice:*

– The only codes of practice on bins and silos which give guidance on structural design are the ACI code (ACI 313-77,1984) which relates only to concrete structures, the British code for the design of farm silage silos (BS 5061, 1974) and the Japanese code for small aluminum silos (JIS, 1987).

- Neither of these latter codes is helpful to the designers of large steel silos required at mines, railheads, power stations, port facilities and similar sites, for the storage of grain, coal, mineral ores and industrial chemicals.
- The best known tank design codes (AWWA D100-79,1979; API-620,1970) are relatively simple and appear to be quite satisfactory for simple fluid storage tanks.
- However, their provisions are less satisfactory for bulk solids storage structures, for which the loadings are much more complex, and the consequent structural behavior and failure criteria more involved.

II. Storage Facilities

Storing of bulk materials in silos and bunkers is essential to agricultural, mining, mineral processing, chemical, shipping, and other industries. Silos serve as long-term storage. It may serve as terminals for receiving and shipping. Such terminals usually involve multiple transportation modes; for example, material arriving by truck may be stored in the terminal temporarily and then discharged into train, barge, or ocean-going vessel for shipping elsewhere. Terminals usually have sophisticated systems for weighing materials being received and shipped. Methods of loading and unloading silos depend largely on the type of material to be handled and on economic and functional considerations.

A. Various Types Of Grain Storage Systems:

1) Plywood Bins
2) Hay Bales:
3) Silage Bags:
4) Commercially Available:
5) Concrete Blocks or Road Barriers:
6) Concrete Silos:

B. Advantages Of Vertical Storage Over The Horizontal Storage System:

- Simultaneous & continuous loading and unloading is possible.
- Moisture free storage is possible.
- Dust losses are reduced for powdery materials.
- Space is utilized more efficiently.

Very huge amount of cost is generally involved in construction of a single silo. So, it is required to concentrate in selection of alternate solution to optimize the cost before going for the design.

- Steel silos are wide spread around the world and are used for storing different materials, including Cement, Fertilizers, Grains and raw materials.
- It provides a fairly big storage capacity within a short period of time.

C. Stored Materials:

The physical properties of materials stored in silos and bunkers influence the flowability of the material and the forces that the material applies to the silo walls and bottom. Obviously those properties will vary from one material to another, but they may also vary within a supposedly uniform material. In materials of this latter type (coal is a good example) large variations of properties occur between materials from different sources or even in materials from a common source. The physical properties may also very with age of the material, degree of compaction, and changes of environment.

For pressure computation, the properties considered most important are unit weight (γ), angle of internal friction (Φ, approximately the same as angle of repose), and the coefficient of friction (μ) between the stored material and the bin wall. The coefficient of friction, μ, between stored material and the bin wall may also vary with age of the bin. Whether the wall is metal or concrete, it will probably become smoother with age, from abrasion by the sliding material.

III. Calculation of Pressure Due to Stored Materials

Early silo designers, not recognizing the importance of vertical friction between the stored material and the silo wall, assumed lateral pressures to vary hydrostatically. That assumption (even when reduced material densities were used) often gave wastefully conservative results. Subsequently, analytical methods were developed that consider wall friction. These methods provide means for computing: (1) Pressure of the stored material against vertical walls, sloping surfaces, and flat bottoms; (2) Friction forces and wall compression forces; and (3) Vertical pressures at various depths in the stored material itself.

Some of these methods give static pressures (pressures when material is at rest) only. During filling or emptying of the silo, pressures can be higher than static. Pressures may differ further if there is any lack of symmetry eccentrically located discharge openings, for example. The structural designer needs to know the final total pressure, or "design pressure." This design pressure can be estimated by modifying the computed static pressures to account for material movement, eccentric discharge, and other pressure-affecting conditions, or by using analytical methods intended to give design pressures directly.

A. Methods Of Computing Static Pressures Due To Granular Material:

These methods are based on equilibrium of the stored material in a static condition. Elastic interaction with the bin structure is not considered, nor is strain energy in either the stored material or the structure. These analytical methods correlate with test measurements with varying degrees of agreement.

Various methods use for calculating horizontal pressure due to storage materials are,

1) The JANSEEN method
2) The AIRY method
3) The REIMBERT method

IS code is follow JANSEEN method for calculating horizontal pressure. Derivation of this method describe below.

1) The Janssen Method for Computing Static Pressure:

The major breakthrough in computation of stored material pressures came in 1895 when H. A. Janssen developed equation for computing lateral and vertical pressures of granular material in deep bins. Janssen's method is based on equilibrium of a thin horizontal layer of stored material. Equating the vertical the vertical forces to zero gives:

$$qA + yAdy = A\,[q + dyx(dq/dy)\,] + \mu p(Udy)$$

In which:

q = static vertical pressure at depth Y

A = area of horizontal cross section through the silo

U = perimeter of horizontal cross section

p = pressure of stored material against walls at depth Y below surface of stored material

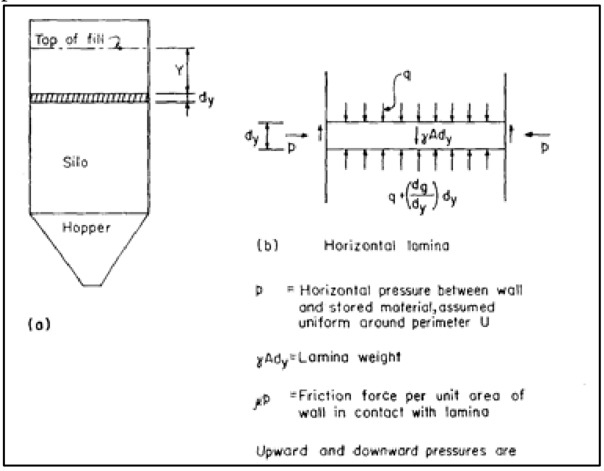

Fig. 5: Horizontal lamina for derivation of Janssen's equations

Substituting kq for p, and "hydraulic radius" R for A/U and rearranging, the differential equation of equilibrium becomes:

$$dq/dy = \gamma - (\mu kq/R) \qquad (2.1)$$

The solution to this differential equation is the Janssen formula for vertical pressure at depth Y:

$$q = (yR/\mu k)[1-e-\mu kY/R] \qquad (2.2)$$

Koenen improved Janssen's method by introducing the term $k = (1-\sin\Phi)/(1+\sin\Phi)$, or simply $k = \tan2(45° - \Phi/2)$, which is the Rankine coefficient for active earth pressure the ratio of horizontal pressure to vertical. Hence, to compute the horizontal pressure p, eq. (2-1) is multiplied by k. Thus, the Janssen equation for horizontal pressure is:

$$p = (yR/\mu) \times [1-e-\mu kY/R] \qquad 2.3)$$

The term in brackets in eq. (2-2) may be easily calculated using a hand calculator. However, its values are given by Table A-l (Appendix A) for various values of µkY/R. The wall friction force is µp per unit area of wall at depth Y. Vertical friction forces cause vertical force in the wall: compression if the wall is supported from below, tension if suspended from above. Integrating from the top of the stored material to depth Y, the vertical force in the wall (per unit of wall perimeter) at depth Y is:

$$V_y = \mu' \int^{Y} p\,dy = \gamma R\left[Y - \frac{R}{\mu' k}(1 - e^{-\mu' kY/R}\right]$$

The above derivation makes no assumption as to shape of the silo cross section. If the cross section is circular, then the hydraulic radius is:

$$R = \text{area/perimeter} = (\pi D2/4)/(\pi D) = D/4$$

In which D is the inside diameter.

For a square silo of side length a, R = area/perimeter = a/4. For regular polygonal silos a slightly conservative approximation is R = D/4, where De is the diameter of a circle whose area equals that of the polygon.

A rectangular silo with side lengths a and b will have different pressures on short and long sides. A common procedure is to let R = a/4 when computing pressure on the short side a, and for the long side to assume R = a'/4, where:

$$a' = 2ab/(a + b) \qquad (2.4)$$

An alternate value of a' suggested by Reimbert is to use

$$a' = (2ab-a2)/ b \qquad (2.5)$$

The silo wall designer needs to know the total vertical force applied to the wall by friction from the stored material. This force, from materials above any depth Y, is equal to the weight of those materials minus the upward force from vertical pressure q. Per unit length of wall, the friction force from above is:

$$V = R(yY-q) \qquad (2.6)$$

B. Flow Patterns:

Flow of stored material from silos is of two main patterns, funnel flow (core flow) and mass flow. In mass flow, all of the stored material is in motion during discharge. In funnel flow, movement occurs only in a channel within the stored material, and this channel is surrounded by nonflowing material.

1) Mass-Flow Silos:

In mass-flow silos the hopper is sufficiently steep and smooth to cause flow of all the solids without stagnant regions whenever any solid is withdrawn. Mass-flow silos are usually recommended for cohesive materials (coal, for example), materials that degrade with time, powders (unless means of withdrawal such as aeration are used), and materials in which segregation needs to be minimized. Mass flow will occur if three conditions are met:

1) The outlet must be large enough for the material to flow without arching.
2) The flow-control device must permit material to flow through the entire opening area.
3) The hopper walls must be smooth enough and steep enough to allow the material to slide, thus expanding the flow channel upward until it meets the vertical walls of the silo.

2) Funnel-Flow Silos:

Funnel flow occurs when the hopper is not sufficiently steep and smooth to force material to slide along the walls, or when the outlet of a mass-flow bin is not fully effective. In a funnel-flow silo, solid flows toward the outlet through a channel that forms within stagnant material. Usually, funnel-flow bins are suitable only for coarse, free-flowing or slightly cohesive, nondegrading solids in which segregation is unimportant. Yet, at the time of this writing, funnel-flow silos are the more prevalent type.

3) Expanded Flow:

Besides the two main flow patterns, there is an intermediate type called "expanded flow." Expanded flow is a combination of mass flow and funnel flow. The lower portion of the hopper operates in mass flow and the upper in funnel flow. To prevent ratholing in the upper, funnel-flow portion of the mass-flow hopper, the flow channel should expand to a diagonal or diameter equal to or greater than the critical rathole diameter determined for the material to be stored.

IV. Analysis of Corrugated Steel Silo

A. Problem Selection:

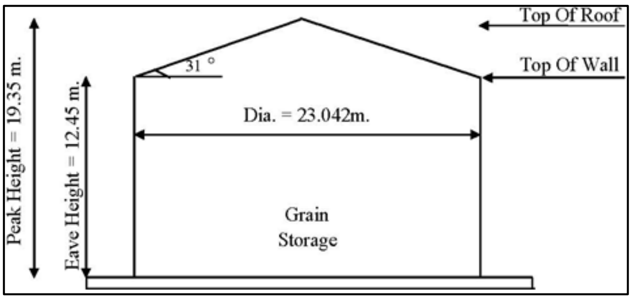

Fig. 6: Line sketch of corrugated steel silo

Data:
Internal Diameter of Silo = m23.0
Type of Silo = FBS
Eave Height of Silo = 12.45 mtr.
Peak Height of Silo = 19.35
Angle of Roof with Vertical = 31.0°
Material to Be Stored = Wheat

B. Calculation Of All Design Parameters As Per Is: 4995 (Part-1) -1974 Table-1.2:

Density of wheat W = 7.50 kN/m3
Hydraulic radius R = 5.76 m
Pressure ratio during filling λf = 0.50
Pressure ratio during emptying λe = 1.00
Angle of internal friction Φ = 28.0°
Angle of wall friction during filling δ = 21.0°
Angle of wall friction during emptying δ = 16.8°
Co-efficient of wall friction during filling µf = 0.38
Co-efficient of wall friction during emptying µe = 0.30

C. Evaluation of the Effective Wall Friction Coefficient for Corrugated Sheet:

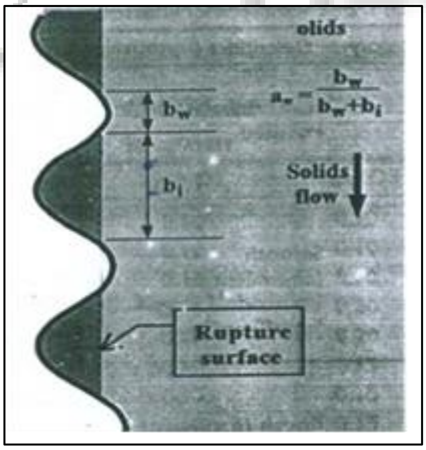

Fig. 7: Corrugated Sheet Profile.

For wall (corrugated or profile steel sheeting or walls with horizontal ribs), the effective wall friction is a function of the material's internal friction, friction against a flat wall, and the profile of the sheeting.
The effective wall friction may be taken as:

$$\mu_{eff} = (1-a_w) \tan\Phi_i + a_w \mu_w$$

Where:
µeff is the effective wall friction coefficient;
tanΦi is the internal friction coefficient;
µw is the wall friction coefficient (acting against a flat wall surface);
aw is the wall contact factor.

aw = bw / (bw + bi) = 0.25
µeff (During Filling) = 0.49
µeff (During Emptying) = 0.47

Name of Pressure	During Filling in kN/m2		During Emptying kN/m2	
Max Pw	WxR =	43.20	WxR =	43.20
Max Ph	WxR/µf =	87.37	WxR/µe =	91.14
Max Pv	(WxR)/(µfxλf) =	174.73	(WxR)/(µexλe) =	91.14

Table 1: Calculate max design pressures as per IS 4995 (Part I) 1974.

Variation of pressure along depth: Pi (z) = Pi max x (1-e-z/z0)
Note: Where P stands for pressure & suffix i stand for w, h or v corresponding to the pressure Pw, Ph or Pv respectively
During filling Zof = R/ (µfxλf) = 23.30
During emptying Zoe = R/ (µexλe) = 12.15

Shell Ring No.	Ht. of C.G. of ring from Leveled surface	z/z0f	e-z/zof	Xf = 1-e-z/zof	Pressure at the C.G. of ring from level surface: Ph x Xf kN/m2	Pv x Xf kN/m2	Pw x Xf kN/m2
15	2.46	0.11	0.90	0.10	8.75	17.50	4.33
14	3.29	0.14	0.87	0.13	11.50	23.00	5.69
13	4.12	0.18	0.84	0.16	14.15	28.31	7.00
12	4.95	0.21	0.81	0.19	16.72	33.43	8.27
11	5.78	0.25	0.78	0.22	19.19	38.38	9.49
10	6.61	0.28	0.75	0.25	21.57	43.14	10.67
9	7.44	0.32	0.73	0.27	23.87	47.75	11.81
8	8.27	0.35	0.70	0.30	26.10	52.20	12.91
7	9.10	0.39	0.68	0.32	28.24	56.49	13.97
6	9.93	0.43	0.65	0.35	30.31	60.63	14.99
5	10.76	0.46	0.63	0.37	32.31	64.62	15.98
4	11.59	0.50	0.61	0.39	34.24	68.48	16.93
3	12.42	0.53	0.59	0.41	36.10	72.19	17.85
2	13.25	0.57	0.57	0.43	37.89	75.78	18.74
1	14.08	0.60	0.55	0.45	39.62	79.25	19.59

Table 2: During filling pressure at the C.G. of ring from level surface.

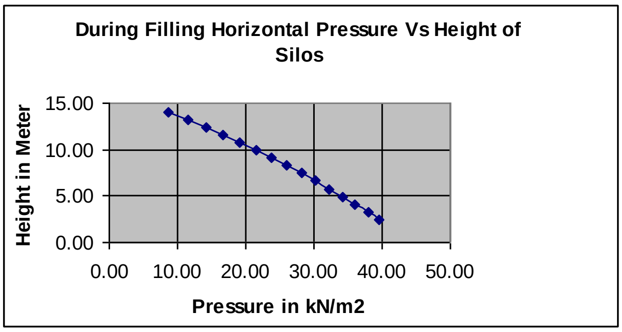

Chart 1: Horizontal pressure during filling Vs height of silo.

Shell Ring No.	Ht. of C.G. of ring from Leveled surface	z/z0f	e-z/zof	Xf = 1-e-z/zof	Pressure at the C.G. of ring from level surface		
					Ph x Xf kN/m2	Pv x Xf kN/m2	Pw x Xf kN/m2
15	2.46	0.20	0.82	0.18	16.69	16.69	7.91
14	3.29	0.27	0.76	0.24	21.61	21.61	10.24
13	4.12	0.34	0.71	0.29	26.20	26.20	12.42
12	4.95	0.41	0.67	0.33	30.48	30.48	14.45
11	5.78	0.48	0.62	0.38	34.49	34.49	16.35
10	6.61	0.54	0.58	0.42	38.22	38.22	18.12
9	7.44	0.61	0.54	0.46	41.71	41.71	19.77
8	8.27	0.68	0.51	0.49	44.98	44.98	21.32
7	9.10	0.75	0.47	0.53	48.03	48.03	22.77
6	9.93	0.82	0.44	0.56	50.88	50.88	24.12
5	10.76	0.89	0.41	0.59	53.54	53.54	25.38
4	11.59	0.95	0.39	0.61	56.03	56.03	26.56
3	12.42	1.02	0.36	0.64	58.34	58.34	27.65
2	13.25	1.09	0.34	0.66	60.50	60.50	28.68
1	14.08	1.16	0.31	0.69	62.53	62.53	29.64

Table 3: During emptying pressure at the C.G. of ring from level surface

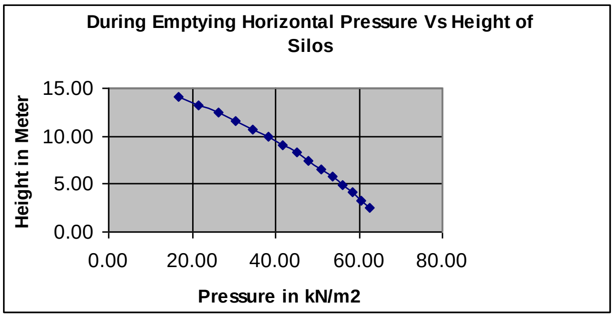

Chart 2: Horizontal pressure during emptying Vs height of silo.

D. Application Of Horizontal Pressure And Vertical Friction Force On The Vertical Wall In Staad Pro.:

Horizontal pressure is increase when height goes increase from level surface. So, we have calculated horizontal pressure at bottom of the plate and top of the plate. Then apply this pressure as trapezoidal pressure on each plate at each level. Vertical friction forces apply on each plate by using a uniform pressure option.

Fig. 8: Application of Horizontal Pressure in STAAD Pro.

V. RESULTS & CONCLUSION

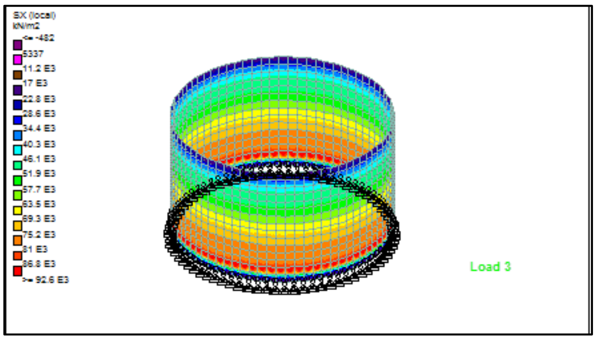

Figure 9: Stress Sx in silo wall with stiffener due to horizontal

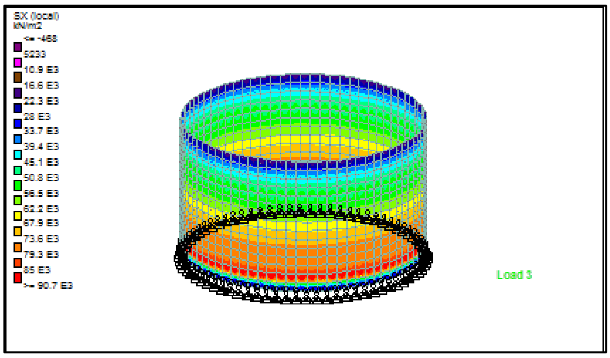

Figure 10: Stress Sx in silo wall without stiffener due to horizontal

Shell Ring No.	Ht. of C.G. of ring from Leveled surface	Phx Xf in kN./m2	Hoop Tension In kN.	Provided Thk. of Corrugated Plate In mm	Equivalent Thk. of Rect. Plate In mm	Hoop Stress Manually in kN./m2
15	2.46	16.69	192.27	2.00	6.72	28611
14	3.29	21.61	248.90	2.00	6.72	37038
13	4.12	26.20	301.78	2.00	6.72	44908
12	4.95	30.48	351.18	2.00	6.72	52258
11	5.78	34.49	397.31	3.20	8.00	49664
10	6.61	38.22	440.30	3.20	8.00	55037
9	7.44	41.71	480.55	3.20	8.00	60068
8	8.27	44.98	518.23	3.20	8.00	64778
7	9.10	48.03	553.33	3.20	8.00	69166
6	9.93	50.88	586.12	3.20	8.00	73265
5	10.76	53.54	616.74	3.20	8.00	77093
4	11.59	56.03	645.41	4.00	8.63	74787
3	12.42	58.34	672.06	4.00	8.63	77874
2	13.25	60.50	697.00	4.00	8.63	80765
1	14.08	62.53	720.35	4.00	8.63	83470

Table 4: Hoop stress applied on plate due to horizontal pressure during emptying

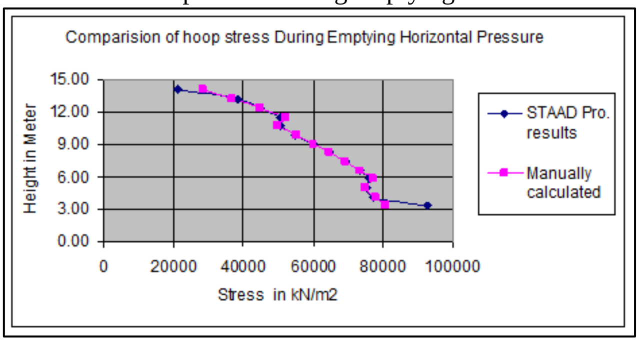

Chart. 3: Comparison of hoop stress results from STAAD Pro. and Manual calculation

A. Following observation can be made from the above stress diagrams due to Horizontal pressure during filling and emptying condition.

[1] We have use equivalent thickness of the corrugated sheet while modeling of the silo in STAAD Pro. Because of this equivalent thickness of the corrugated sheet it reduces the value of hoop stress and ultimately it reduces the thickness of the vertical wall.

[2] Stiffness of vertical stiffener use in the modeling of silo wall is very small so, there is not considerable difference in the value of Sx (Hoop Stress), when we are modeling silo with stiffener or without stiffener.

[3] Where, Sx = Hoop tension force per unit length per unit thickness

[4] Stiffness of vertical stiffener is very small so, it can not restraint the corrugated sheet from both the ends. Value of hoop stress in manual calculation and in STAAD Pro. are almost matching, except in the case of top and bottom plate. It shows that our assumptions while modeling the silos are correct.

REFERENCES

[1] John W. Carson, Ph.D., M.ASCE1 "Limits of Silo Design Codes" 2014 American Society of Civil Engineers.

[2] M. Esther Magdalene Sharon, C.V.Kavitha Abirami and K.Alagusundaram "Grain Storage Management in India" Journal of Postharvest Technology 02 (01): 012-024, January' 2014

[3] M.Wojcik, P.Iwicki, J.Tejchman "3D buckling analysis of a cylindrical metal bin composed of corrugated sheets strengthened by vertical stiffeners" Science Direct/Thin-Walled Structures 49 (2011) 947–963.

[4] E.Gallego, C.González-Montellano, A.Ramírez, F.Ayuga, E.Gallego et al. "A simplified analytical procedure for assessing the worst patch load location on circular steel silos with corrugated walls" Science Direct / Engineering Structures 33 (2011) 1940–1954.

[5] P.Iwicki, M.Wójcik, J.Tejchman "Failure of cylindrical steel silos composed of corrugated sheets and columns and repair methods using a sensitivity analysis" Science Direct/Engineering Failure Analysis 18 (2011) 2064–2083.

[6] Rotter J.M. "Guide for the economic design of circular metal silos" Spon Press; 2001.

[7] Adem Dogangun1; Zeki Karaca2; Ahmet Durmus3; and Halil Sezen, M.ASCE4. "Cause of Damage and Failures in Silo Structures" Journal Of Performance Of Constructed Facilities © ASCE / March /April 2009 / 65

[8] Adam J. Sadowski1 and J. Michael Rotter, F.ASCE2. "Buckling in Eccentrically Discharged Silos and the Assumed Pressure Distribution" 858 / Journal Of Engineering Mechanics © ASCE/July 2013

[9] Y.M. Cheng1; K. T. Chau2; L. J. Xiao3; and N. Li4. "Flow Pattern for a Silo with Two Layers of Materials with Single or Double Openings" 1278/Journal Of Geotechnical and Geoenvironmental Engineering © ASCE / September 2010

[10] IS-4995(Part-1&2) – 1974 "Code of practice for RCC bins", Bureau of Indian Standards, New Delhi.

[11] IS-875 (Part-1,2&3) – 1987 "Indian code of practice for loads for buildings and structures", Bureau of Indian Standards, New Delhi.

[12] IS-1893 (Part-1) 2002 "Indian standard criteria for earthquake resistant design of structure", Bureau of Indian Standards, New Delhi.

[13] IS-9178 (Part-1) – 1979 "Criteria for design of steel bins for storage of bulk materials", Bureau of Indian Standards, New Delhi.
[14] ACI – 313R91 "Commentary on standard practice for design and construction of concrete silos and stacking tubes for storing granular materials", American Concrete Institute
[15] IS-277 – 2003 "Galvanized steel sheet (plain and corrugated) specification", Bureau of Indian Standards, New Delhi.
[16] IS-800 – 2007 "Code of practice for general construction in steel", Bureau of Indian Standards, New Delhi.