Study of Ferrocement Silo used for Bulk Material Storage
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ABSTRACT
Silos are the tall structures which are used for the storage of different powdery or granular materials. Reinforced Cement Concrete and Steel are the materials which are commonly used for the construction of Silos. In this paper, an attempt has been made to use ferrocement as an alternative material for the construction of Silos, especially for grain storage. Here, the ferrocement silo wall has been analysed for its various Height to diameter ratios with minimum reinforcement percentage and maximum possible horizontal pressure, hoop tension and vertical pressure carried due to its friction with the stored material. This analytical approach is based on Janssen’s Theory as per I.S. 4995 – 1974.
Keywords: Silo, Ferrocement, Stored material, Pressure.

1. INTRODUCTION
Silo, also known as a deep bin, is a bulk storage structure. It is used for the handling and storage of grains, chemicals and mining operations which is usually constructed of concrete or steel. In developing countries like India, farms and villages have inadequate grain storage facility which results into wastage in bulk quantity of food grains at post – harvest stage. Therefore, to meet the grain storage requirements an economically feasible alternative is required to be explored.

Ferrocement is a strong, versatile, light weight, durable building material which is simple in composition, requires almost no formwork, labour intensive with minimum skill and of low cost of construction. It is made from a wire reinforced mixture of sand, water, and cement which was first discovered in France by Jospeh Lambot in 1848 and patented by him in 1852. He is the first, who introduced applications of ferrocement in civil engineering field. A ferrocement structure is a much thinner and lighter structure and consists of closely, but uniformly distributed layers of wire meshes which provide greater tensile strength, flexibility and better crack resistance than ordinary concrete. It is effectively used in fabrication of boats, silos, water tanks, roofs, miscellaneous building components like sun – breakers, pergola, as a lost formwork, etc. [1].

2. DESIGN GUIDELINES FOR FERROCEMENT ELEMENTS
The design criteria for ferrocement elements follow same philosophy as that of reinforced cement concrete. In the design of a ferrocement element, thickness of the element and number of layers of the required area of mesh are required to be ascertained. In ferrocement construction, minimum thickness of an element is taken at least equal to the size of the opening in the mesh to be provided. To characterize the reinforcement in ferrocement, following three reinforcing parameters are commonly used:

2.1 Volume Fraction of reinforcement (V_f): It is defined as the volume of reinforcement divided by the total volume of the composite (matrix and reinforcement), expressed in percent. For a ferrocement element which is reinforced with meshes having square openings, V_f is equally divided into V_0 and V_4 for the longitudinal and transverse direction respectively.

2.2 Specific surface of Reinforcement (S_r): It is defined as the ratio of the total area of the reinforcing mesh which is in contact with mortar and total volume of the composite. It is expressed in terms of cm²/cm³ or cm⁻¹. It is different from that of surface area of the wire mesh. Similar to Volume fraction, it is equally divided into longitudinal (S_o) and transverse (S_t) direction for a square aperture mesh.

The relation between V_f and S_r for a square grid mesh is given by:

\[ S_r = 4 V_f / d_b \] (1)
For non-pre-stressed, non water retaining structures, the total volume fraction of steel mesh reinforcement should not be less than about 1.8 % and the total specific surface of reinforcement should not be less than about 0.80 cm$^2$/cm$^3$ [2]. It is tentatively recommended that for a given ferrocement element, without skeleton reinforcement, the number of layers of mesh should preferably be such that

$$\begin{align*}
n \geq 4 \ t \text{ (t in inches)} \\
n \geq 0.16 \ t \text{ (t in mm)}
\end{align*}$$

(2) \quad \text{Or}

(3)

In case, if skeleton steel is used in ferrocement, it is recommended that it should not occupy more than 50% of the thickness of the element. Thus, if $t'$ is the thickness of the ferrocement element in which the mesh layers are distributed, the number of layers of mesh should preferably be such that

$$\begin{align*}
n \geq 4 \ t' \text{ (t' in inches)} \\
n \geq 0.16 \ t' \text{ (t' in mm)}
\end{align*}$$

(4) \quad \text{Or}

(5)

In the design of ferrocement elements, there are two approaches which are followed:

1) Ultimate Stress Design (USD) or Limit State Design (LSD) or Load & Resistance Factor Design (LRFD),

2) Working Stress Design (WSD) or Allowable Stress Design (ASD).

When the mesh wires are drawn from steel, the maximum allowable tension in the reinforcement under bending and axial loads shall be $0.60f_y$ or 400 MPa, whichever is smaller, whereas maximum allowable compressive strength in the mortar matrix shall be $0.45f'_c$ [2]. Also, the maximum permissible crack width is 0.005 cm [1]

3. **DESIGN GUIDELINES FOR SILOS**

For the design of silos, IS: 4995 (I):1974 & IS: 4995 (II):1974 which are based on Janssen’s theory have been referred. There are three different kinds of loads which are caused by a material stored in a silo [3]

- 3.1 Horizontal load or horizontal pressure ($P_h$) acting on the side walls of a silo.
- 3.2 Vertical load or vertical pressure ($P_v$) acting on the cross-sectional area of the bin filling,
- 3.3 Friction wall load or frictional wall pressure ($P_w$) introduced into silo walls through wall friction.

![Figure 1 Bin Loads](image-url)

The maximum horizontal pressure on the silo walls, vertical pressure on the plan area of the circular silo and the vertical pressure transferred to the walls through friction have been calculated using the following expressions as mentioned in Janssen’s theory.

Horizontal pressure during Filling, $P_h = \frac{wr}{\mu_f}[1 - e^{-(\mu_f \lambda f H/r)}]$

(6)

Horizontal pressure during emptying, $P_h = \frac{wr}{\mu_e}[1 - e^{-(\mu_e \lambda e H/r)}]$

(7)

Maximum Vertical pressure on horizontal silo plane, $P_v = \frac{P_h}{\lambda}$

(8)

Maximum Vertical pressure carried by the wall due to friction,

$P_w = r(w.H - P_v)$

(9)

Hoop tension in the silo walls has been calculated by

$T = P_h \cdot (D/2)$

(10)
4. ILLUSTRATION

Here, ferrocement silo walls have been studied for their various H/D ratios by considering minimum reinforcement criteria. Therefore, according to Ferrocement Model Code, minimum specific surface of reinforcement i.e. 0.80 cm²/cm³ has been considered. Using relation in equation 1, volume fraction has been calculated which gives \( V_t \) as 2 \% (greater than the minimum value 1.8\%). For this minimum reinforcement, the ferrocement silo walls have been studied using following methodology:

4.1 Horizontal pressure consideration for silo filling condition
4.2 Crack width criteria consideration for silo filling condition
4.3 Horizontal pressure consideration for silo emptying condition
4.4 Crack width criteria consideration for silo emptying condition

After obtaining the maximum possible dimensions of the ferrocement silo for various H/D ratios, the silo walls have been checked for the vertical pressure carried due to friction by the stored material. For the study, following specifications and geometry details for a cylindrical ferrocement silo have been considered:

- Thickness of ferrocement silo wall = 25 mm
- Type of mesh = Square welded mesh [1]
  - Mesh wire diameter = 1.00 mm
  - Spacing of the wires in mesh = 13 mm
  - Number of layers of the mesh = 04 nos.

Wheat has been considered as the material to be stored. It has unit weight of 8338.5 N/m³, angle of internal friction is 28°, angle of wall friction, while filling is 0.75 \( \phi \) and while emptying is 0.60 \( \phi \). Pressure ratio, for filling, is 0.50 and for emptying is 1.00.

Using the permissible axial tension in the wire mesh and minimum reinforcement parameters, its capacity to carry hoop tension in the walls of cylindrical silo has been determined. Thereafter, using Janssen’s theory, maximum allowable horizontal, vertical and frictional loads have been calculated for both filling and emptying conditions of the ferrocement silo. This calculation is repeated for different H/D ratios of the ferrocement silo wall varying from 1.00 to 3.00 with increment of 0.20. Also, using crack width formula as applicable to concrete silos, maximum crack width has been checked. [4].

According to the methodology stated above, the pressure calculation on a silo wall for filling and emptying condition have been done. Then using minimum reinforcement parameters, area of mesh reinforcement resisting tensile stresses has been calculated. Amount of square mesh area which resists the hoop tension in the silo wall is practically half of the total mesh reinforcement area provided, therefore, by introducing efficiency factor for a square mesh, effective area of reinforcement has been calculated. Now, using permissible tensile stresses, permissible hoop tension has been calculated. Thereby, maximum permissible horizontal pressure (\( P_{ah} \)) in the silo wall in terms of diameter of the silo has been calculated and equated with the expression for horizontal pressure in the silo wall by Janssen’s theory in filling condition of silo (eq. 6). Here, value of hydraulic radius (\( r \)) has been mentioned in terms of D and finally relation has been simplified in terms of H and D only. Therein different values of H/D ratio, which varies from 1.00 to 3.00 with the rate of increment as 0.20 have been substituted and values of H and D for ferrocement silo have been obtained (table no.1).

The ferrocement is basically well known for its crack resistance characteristic, but cement mortar (i.e. matrix) as an individual material, is very strong in compression and weak in tension and may result into cracks on the outer face of the silo wall due to hoop tension. Therefore, to predict the crack width, calculation has been done according to IS: 4995 (II) – 1974 which is employed for reinforced concrete bins.

\[
\sigma_{cr} = 10^6 \times [4 + (d_v/p_0)](\sigma_{um}[1-6/(p_0 \sigma_{um})])
\]

Here, \( p_0 = 1 \% \), \( \sigma_{um} = 207 \text{ MPa} = 2110 \text{ Kg/cm}^2 \), \( \rho = 0.09 \) and \( \phi’ = 0.10 \text{ cm} \) and thus, crack width came out to be 0.0084 cm which is greater than the permissible i.e. 0.005 cm. Therefore, by this crack width criterion the ferrocement silo is unsafe and required to be reanalyzed for permissible crack width. Thus, permissible actual stresses (\( \sigma_{um} \)), maximum permissible hoop tension & horizontal pressure on the silo wall have been calculated in the reverse manner. These calculations have given revised dimensions of the silo for filling condition (table no.1).

Similarly, for emptying condition of the ferrocement silo, the \( P_{ah} \) value so calculated earlier in filling condition has been equated to the horizontal pressure expression of Janssen’s theory (eq. 7) for emptying condition and new H and D have been obtained (table no.1). Again checking the ferrocement silo walls for maximum crack width, the previously mentioned steps have been followed and details as tabulated in table 1 have been obtained.
Table 1: Diameter, Height and capacity of a ferrocement silo for different H/D values for filling & emptying condition from P disruptions & Crack width consideration

<table>
<thead>
<tr>
<th>S. No.</th>
<th>H/D</th>
<th>A - Filling condition</th>
<th>B - Emptying condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A1 - Pdisruption Criteria</td>
<td>A2 - Crack width criteria</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>H</td>
<td>Capacity (m^3)</td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>5.964</td>
<td>5.964</td>
</tr>
<tr>
<td>2</td>
<td>1.20</td>
<td>5.627</td>
<td>6.752</td>
</tr>
<tr>
<td>3</td>
<td>1.40</td>
<td>5.379</td>
<td>7.531</td>
</tr>
<tr>
<td>4</td>
<td>1.60</td>
<td>5.191</td>
<td>8.306</td>
</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>5.045</td>
<td>9.081</td>
</tr>
<tr>
<td>6</td>
<td>2.00</td>
<td>4.929</td>
<td>9.859</td>
</tr>
</tbody>
</table>

5. DISCUSSION

In condition - A1, it has been observed that as H/D ratio varies from 1.00 to 3.00, diameter of the silo reduces from 5.964 m to 4.620 m i.e. by 22.84 %. Height of the silo increases from 5.964 m to 13.506 m i.e. by 2.265 times and capacity of the silo increases from 166.61 m^3 to 229.642 m^3 i.e. by 1.378 times. As per permissible crack width criterion condition – A2 is concerned, the dimensions obtained for condition - A1 prove to be unsafe and hence, after reanalyzing, the revised dimensions have been obtained. It has been observed that from permissible crack width criterion, reduction in the diameter and height of the ferrocement silo is 23.12 % and decrease in its capacity is 54.57 %. Also the self weight of the ferrocement silo wall has been calculated taking unit weight of the ferrocement material as 25 kN/m^3. Then, the ratio of capacity of the ferrocement silo in terms of tons of wheat to the self weight of the silo wall on an average is found to be 13.14. This ratio decreases with the increase in H/D ratio. In this way, it is observed that crack width criterion governs the dimensions of the ferrocement silo in filling condition. Now, in case of emptying condition of the ferrocement silo, reduction in the dimensions has been observed as compared to filling condition for the same magnitude of horizontal pressure. This reduction, on an average has been found to be 18.04% and decrease in capacity has been observed to be on an average 44.82 %. Thus, emptying condition of ferrocement silo governs the dimensions of the ferrocement silo from the horizontal pressure or hoop tension consideration (condition - B1). Thereafter, the ferrocement silo has been checked for crack width and the final dimensions of the ferrocement silo (condition – B2) have been obtained. Thus, for the ferrocement silo, emptying condition with the maximum crack width criterion has become the governing criterion. After obtaining the dimensions of the ferrocement silo for various H/D ratio, its feasibility for vertical or compressive stresses due to friction of stored material and self weight have been checked. For this, for emptying condition of the silo considering various H/D ratio, full height of the silo wall has been divided into ten equal segments and maximum horizontal and vertical pressure along with maximum vertical stress carried by the wall due to friction have been calculated which are as shown in table no. 2. It has been observed that in emptying condition, more than 50 % of the weight of the stored material is carried by the wall due to friction between H/D ratios 1.2 to 1.4 and goes up to 73.14 % for H/D ratio equals to 3. The contribution of wall friction irrespective of H/D ratio has been found to be more than 50 % for the depths ranging between 3.3m to 4.7m from the top of the silo wall. This range may vary not only with the coefficient friction between the wall and the stored material, but also with the internal friction between the grains of the stored material. From table no. 3, it is quite evident that the maximum compressive stress induced in the ferrocement silo wall is for H/D ratio equals to 3.0 i.e. 1.878 N/mm^2 which is far less than the permissible compressive stress 15.75 N/mm^2.

Further, the quantities of material required for the construction of a ferrocement (C.M:1:5) silo wall for H/D = 2.00 has been calculated (table no. 4). Here, the diameter and height of the cylindrical silo wall have been taken as per table no. 1 condition 2b (i.e. D = 3.118 m and H = 6.236 m).

6. RESULT AND CONCLUSION

Thus, it can be concluded that as the hoop tension in the cylindrical silo walls is completely taken care by the wire meshes of high tensile strength, for the minimum reinforcement area and such a small thickness of the walls, large dimensions (i.e. H & D) for silos have been obtained. Also, the ferrocement silo wall design is governed by the crack width criterion in...
emptying condition (condition-B2). As the ferrocement is a rich mix of cement and sand, it has high compressive strength and safely carries vertical pressure due to friction and self weight.

**Table 2** Maximum total vertical pressures and the weights of the stored material carried by the wall for different H/D ratio.

<table>
<thead>
<tr>
<th>H/D</th>
<th>Ph or Pv (N)</th>
<th>Pw (N)</th>
<th>Total weight of the stored material (N)</th>
<th>% Weight carried by the wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>170818</td>
<td>123419</td>
<td>294237</td>
<td>41.95</td>
</tr>
<tr>
<td>1.2</td>
<td>163544</td>
<td>146189</td>
<td>309733</td>
<td>47.20</td>
</tr>
<tr>
<td>1.4</td>
<td>158227</td>
<td>169771</td>
<td>327998</td>
<td>51.76</td>
</tr>
<tr>
<td>1.6</td>
<td>154682</td>
<td>194802</td>
<td>349484</td>
<td>55.74</td>
</tr>
<tr>
<td>1.8</td>
<td>151944</td>
<td>220762</td>
<td>372706</td>
<td>59.23</td>
</tr>
<tr>
<td>2.0</td>
<td>149698</td>
<td>247344</td>
<td>397042</td>
<td>62.30</td>
</tr>
<tr>
<td>2.2</td>
<td>152552</td>
<td>280017</td>
<td>432569</td>
<td>64.73</td>
</tr>
<tr>
<td>2.4</td>
<td>147102</td>
<td>304086</td>
<td>451188</td>
<td>67.40</td>
</tr>
<tr>
<td>2.6</td>
<td>146188</td>
<td>333560</td>
<td>479748</td>
<td>69.53</td>
</tr>
<tr>
<td>2.8</td>
<td>145440</td>
<td>363756</td>
<td>509196</td>
<td>71.44</td>
</tr>
<tr>
<td>3.0</td>
<td>144947</td>
<td>394714</td>
<td>539661</td>
<td>73.14</td>
</tr>
</tbody>
</table>

**Table 3** Weight of the stored material carried by the silo wall for different H/D ratio, Self weight of the ferrocement silo and Maximum compressive stress induced in the silo wall.

<table>
<thead>
<tr>
<th>H/D</th>
<th>Pw (N)</th>
<th>Self weight of the silo (N)</th>
<th>Compressive Stress (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>123419</td>
<td>24989</td>
<td>0.528</td>
</tr>
<tr>
<td>1.2</td>
<td>146189</td>
<td>27489</td>
<td>0.645</td>
</tr>
<tr>
<td>1.4</td>
<td>169771</td>
<td>30071</td>
<td>0.766</td>
</tr>
<tr>
<td>1.6</td>
<td>194802</td>
<td>32803</td>
<td>0.893</td>
</tr>
<tr>
<td>1.8</td>
<td>220762</td>
<td>35619</td>
<td>1.024</td>
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<td>2.0</td>
<td>247344</td>
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<td>333560</td>
<td>47656</td>
<td>1.582</td>
</tr>
<tr>
<td>2.8</td>
<td>363756</td>
<td>50834</td>
<td>1.729</td>
</tr>
<tr>
<td>3.0</td>
<td>394714</td>
<td>54073</td>
<td>1.878</td>
</tr>
</tbody>
</table>
7. NOTATIONS

\( D \) = Internal diameter of the cylindrical silo in metres

\( d_b \) = Diameter of the wire of mesh in cm

\( \eta_f \) = Efficiency factor for wire mesh

\( f_c' \) = Compressive strength of the matrix mix obtained from the cylinders in MPa.

\( f_y \) = Yield strength of the reinforcing steel in MPa

\( \phi \) = Angle of internal friction of the material

\( \phi_f \) = Angle of internal friction of the material while filling

\( \phi_e \) = Angle of internal friction of the material while emptying

\( H \) = Height of the silo wall in metres

\( \lambda_f \) = Pressure ratio for silo filling condition,

\( \lambda_e \) = Pressure ratio for silo emptying condition,

\( \mu_f \) = Coefficient of wall friction during filling,

\( \mu_e \) = Coefficient of wall friction during emptying.

\( n \) = Number of layers of wires mesh

\( P_h \) = Horizontal load or horizontal pressure acting on the side walls of a silo.

\( P_v \) = Vertical load or vertical pressure acting on the cross-sectional area of the bin filling

\( P_w \) = Friction wall load or frictional wall pressure due to stored material

\( r \) = Hydraulic mean depth in metres

\( \rho \) = a factor depending on the bond characteristics of steel (0.09 for plain bars & 0.05 for deformed bars),

\( S_s \) = Specific surface of wire mesh reinforcement in \( \text{cm}^2/cm^3 \)

\( S_l \) = Longitudinal specific surface of wire mesh reinforcement in \( \text{cm}^2/cm^3 \)

\( S_t \) = Transverse specific surface of wire mesh reinforcement in \( \text{cm}^2/cm^3 \)

\( T \) = Hoop tension in the silo wall in Newtons

\( t \) = Thickness of a ferrocement element in inches or millimeters (as applicable)

\( t' \) = Effective thickness of a ferrocement element in inches or millimeters (as applicable) when skeleton steel is used

\( V_f \) = Volume Fraction of reinforcement in percent

\( V_{fl} \) = Volume Fraction of reinforcement in percent in longitudinal direction

\( V_{ft} \) = Volume Fraction of reinforcement in percent in transverse direction

\( w \) = Unit weight of the stored material in \( \text{N/m}^3 \)

\( w_{cr} \) = maximum crack width in cm.

\( p_0 \) = geometric percentage of the tensile reinforcement with respect to the concrete area in tension,

\( \sigma_{nt} \) = actual stress under permanently acting loads in Kg/cm²

8. REFERENCES


AUTHOR:

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