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Grain Silo Strengthening – South Dakota

Prepared for Vector Construction Group

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General

The following design is in compliance with ACI 313-97, ACI 313R-97, ACI 318-99, and ACI 440.1R-01.

Three different types of silos have been identified as shown in Figure 1. They differ because of the strengthening scheme to be adopted: Type *A* needs to be strengthened for its entire perimeter; type *B* for three quarters of its perimeter, and type *C* for half of its perimeter.

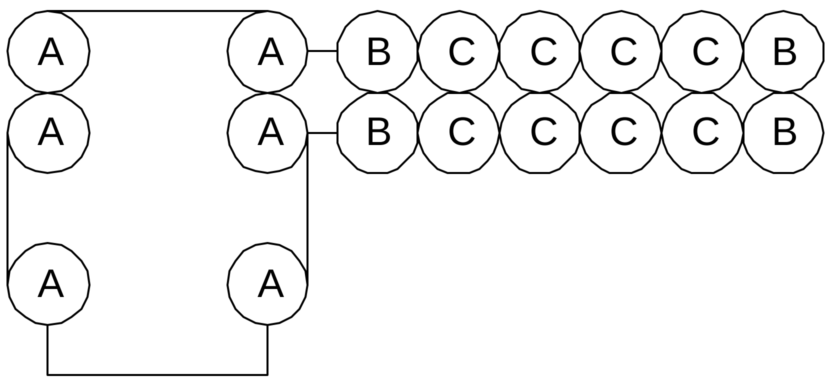

Figure 1 - Silos to be strengthened.

All silos dimensions and material properties used are provided by the contractor (Vector Construction Group) as follows: overall height $h=130\ ft$, inside diameter $d=19\ ft$, wall thickness $t=6\ in$; concrete compressive strength $f'_c=3000\ psi$, and steel yield strength $f_y=60,000\ psi$.

Number 4 steel bars are used as horizontal reinforcement with the following spacing:

- *10 in* on center for the first *50 ft*;
- *11 in* on center for the next *40 ft*;
- *12 in* on center for the last *40 ft*.

Number 4 steel bars *18 in* on center are used as vertical reinforcement.

ACI 313R-97, Table 4-A, suggests stored material properties. When the stored material is grain, its design properties are reported in Table 1:

Table 1 - Grain Material Properties.

	Weight per unit volume of stored material, *g [pcf]*	Coefficient of friction between stored material and wall surface, *m [-]*	Angle of internal friction, *f [degree]*
ACI 313R-97, Table 4-A	44-62	0.29-0.47	20-37
Assumed in this Design	48	0.29	20

To be noted that the worst conditions are attained for the smallest values of both the coefficient of friction between stored material and wall surface, and the angle of internal friction. Hence, their smallest values will be assumed in the design. The weight of the stored material has been assumed equal to *48 pcf* as suggested by the contractor. The height of the stored material is assumed to be *H=119.3 ft*.

Analysis

Structural analysis is carried out according to ACI 313-97, "Design and Construction of Concrete Silos and Stacking Tubes".

Vertical Reinforcement

The actual vertical steel reinforcement (#4 bars at *18 in* on center) does not meet the requirement for the minimum reinforcement indicated in Equation (1):

$$A_{s-vertical} \geq 0.002 A_g = 0.002(6")(12") = 0.144\ in^2/ft \qquad (1)$$

where A_g is the gross concrete area. The actual $A_{s\text{-}vertical}$ is given in Equation (2):

$$A_{s-vertical} = \frac{12"}{s} A_s = \frac{12"}{18"}(0.20) = 0.133\ in^2/ft \qquad (2)$$

where $s=18\ in$ represents the steel spacing.

Horizontal Reinforcement

The initial vertical pressure at depth y below the surface of the stored material is given as (see Figure 2):

$$q = \frac{g R}{m(1-\sin f)}\left[1 - e^{-m(1-\sin f)y/R}\right] \qquad (3)$$

where R is the ratio of area to perimeter of horizontal cross-section of storage space, expressed as $R=r/2$ for circular silo.
Initial horizontal pressure at depth y below the surface of the stored material can be expressed as:

$$p = (1-\sin f)q \qquad (4)$$

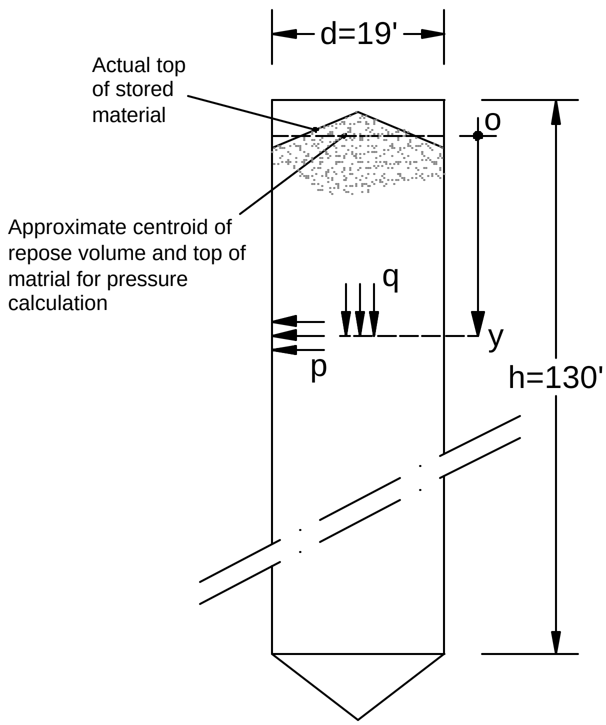

Figure 2 – Horizontal and Vertical Pressures for Wall Dimensioning.

The horizontal wall design pressure above the hopper for concentric flow patterns is obtained by multiplying the initial pressure *p* by a minimum overpressure factor of *1.5*. The required strength force per linear ft of height of the wall is given in Equation (5) (see Figure 3):

$$N = \frac{a}{f} pr \qquad (5)$$

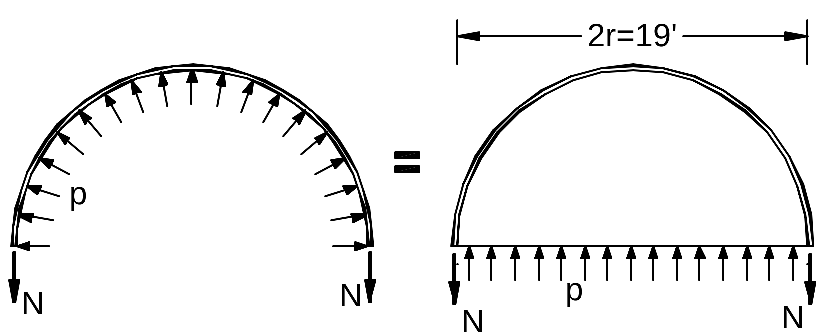

Figure 3 – Axial Force Used in the Design.

where, $a = 1.7$ is the coefficient multiplying the live load, and $f = 0.9$ is the strength reduction factor for axial tension as suggested by ACI 318-99. The wall is designed to have design strength at all sections at least equal to required strength, according to Equation (6):

$$N_n \geq \frac{N_u}{f} = N \tag{6}$$

Figure 4 shows a comparison between the required design horizontal axial force with the actual axial force as a function of the depth of the silo when only steel reinforcement is present. It is to be noted that only the last *30 ft* close to the top of the silo meet the requirement of the code, while the rest of the structure is under-reinforced.

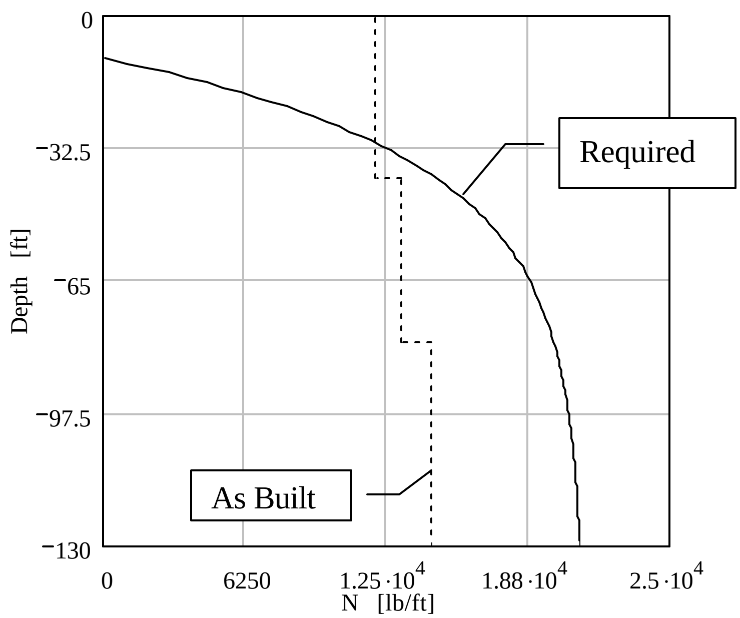

Figure 4 – Hoop Reinforcement as Built.

Crack Control

Wall thickness and reinforcement have to be so proportioned that, under initial pressure, the design crack width w computed using Equation (7) shall not exceed *0.01 in*:

$$w = 0.0001 f_s \sqrt[3]{d_c A} \leq 0.01\, in \tag{7}$$

where f_s (in *ksi*) represents the calculated stress in steel reinforcement at initial pressures, and d_c and A are expressed as follow:

$$d_c = 2.5 d_b$$
$$A = 2 d_c s \qquad (8)$$

where d_b is the horizontal steel reinforcement bar diameter.
Figure 5 shows crack width as a function of the depth of the silo. The actual design does not need to be improved since the maximum crack width is below the limit expressed by Equation (7).

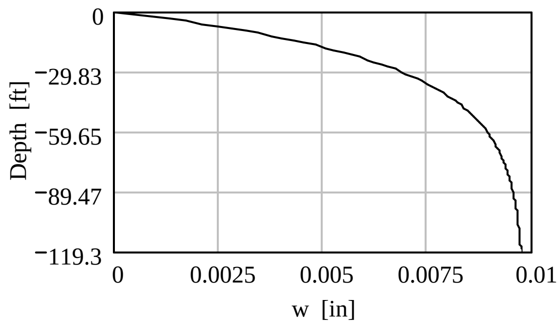

Figure 5 – Crack width Diagram.

Strengthening

Strengthening in both horizontal and vertical direction is carried out by using Near-Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) bars. FRP bars are bonded in place using compatible latex modified cement-based or an epoxy-based paste. This technique does not require any surface preparation work and, after groove cutting, requires minimal installation time. It also has the advantage of allowing anchorage of the bars into members adjacent to the one being strengthened.

Aslan 200 carbon FRP bars manufactured by Hughes Brothers are the material selected in the strengthening design. The minimum tensile strength and modulus of elasticity is $f^*_{fu}=300\ ksi$, and $E_f=18{,}000\ ksi$, respectively. The bar diameter used is *1/4 in* (#2). An epoxy based paste is proposed in the anchoring region where two silos merge. A cement-based grout is recommended for the rest of the application.

The strengthening design is carried out according to ACI 440.1R-01, "Guide for the Design and Construction of Concrete Reinforced with FRP Bars".
Ultimate design tensile strength is obtained from Equation (9):

$$f_{fu} = C_E f^*_{fu} = 0.9(300) = 270\ ksi \qquad (9)$$

where C_E is the environmental reduction factor taken equal to 0.9 as suggested in Table 7.1 (ACI 440.1R-01). The design modulus of elasticity will be the same as the value reported by the manufacturer.

Vertical Reinforcement

The vertical steel reinforcement is not in compliance with the requirement of ACI 313-97. By using a #2 CFRP bar ($A_{FRP}=0.05\ in^2$) at 18 in on center, the FRP contribution to the vertical capacity is given by Equation (10):

$$A_{FRP-vertical} = \frac{12"}{18"}(0.05) = 0.034\ in^2/\ ft \quad (10)$$

The total amount of vertical reinforcement is then given as:

$$A_{vertical} = A_{s-vertical} + A_{FRP-vertical} = 0.133 + 0.034 = 0.167 > 0.144 \quad (11)$$

which is larger than the minimum requirement expressed by Equation (1).

Horizontal Reinforcement

The horizontal design calls for #2 CFRP bars, at the maximum acceptable spacing of *3t=18 in* for the first *100.5 ft* of height. In the last *29.5 ft* of height up to the top of the silo, the existing steel reinforcement is sufficient, and no strengthening is needed. Figure 6 represents the existing, required, and strengthened capacity of the silo as a function of its height.
The proposed design is the minimum required to be in compliance with ACI 313-97.

When one silo merges into another one a hole is drilled in the common surface and the bar insert; an epoxy based resin is used because of its better mechanical characteristics compare to the cementitious grout. The hole's depth into the concrete is calculated using Equation (12), (ACI 440.1R-01):

$$\ell_{bf} = \frac{d_b f_{fu}}{2700} = \frac{(2/8")(270{,}000)}{2700} \simeq 25\ in \quad (12)$$

where $d_b=1/4\ in$ is the bar diameter.

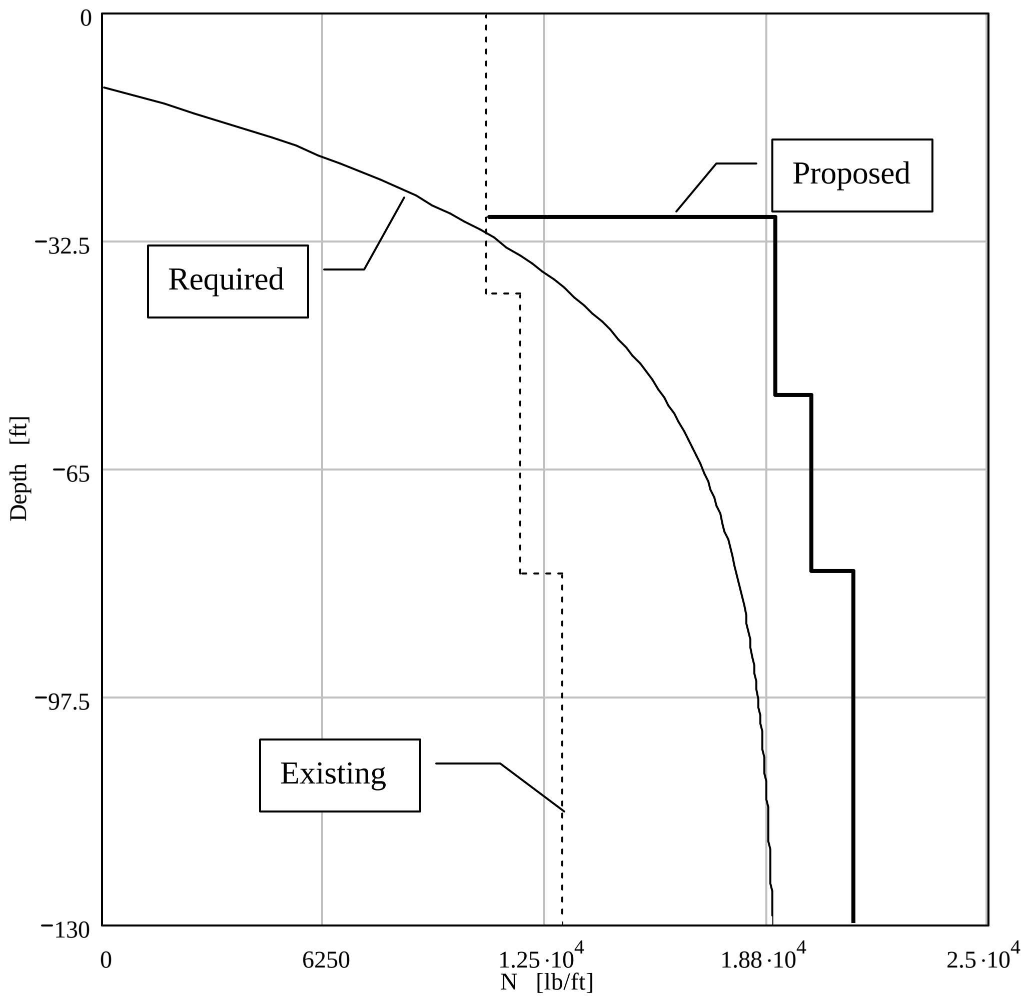

Figure 6 – Comparison between Required, Existing, and Proposed Design.

Crack Control

Crack width does not need to be improved since the existing steel reinforcement is able to meet code's requirements. However, the same horizontal CFRP bars used to strengthen the silo in the hoop direction can be taken into account to further decrease the crack width as depicted in Figure 7 showing a crack width diagram as a function of the silo's height for both existing and proposed design.

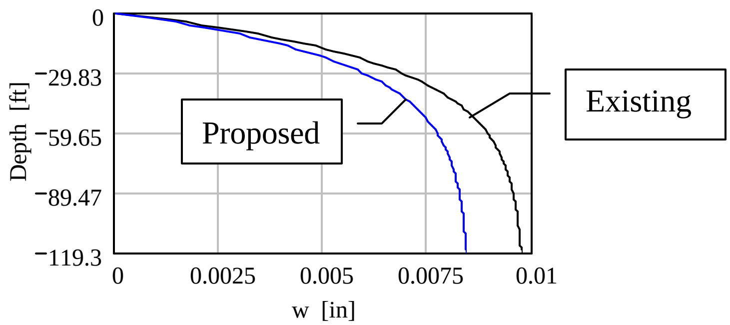

Figure 7 – Existing and Proposed Crack Width Diagram.

Figure 8 shows a sketch of the technique used for the silo's strengthening. The vertical bars are first inserted into the groove previously half-filled with the cementitious grout. A second layer of cementitious grout is then applied on top of the bars already in place. The horizontal bars are hence inserted and the groove completely filled and the surface leveled. The vertical groove is *0.75 in* deep, while the horizontal one in *0.5 in* deep.

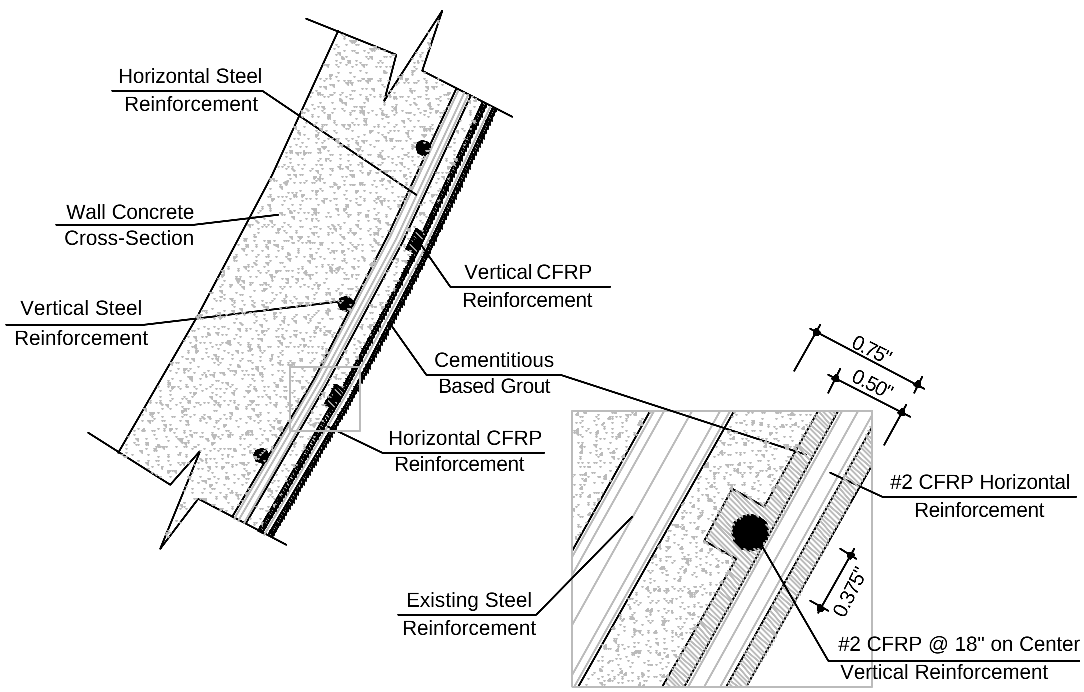

Figure 8 – Near-Surface Mounted (NSM) Technique.

Strengthening Material Quantity

Table 2 reports the total amount of FRP bars required for each silo identified in Figure 1. Table 3 summarizes the total amount of epoxy-based and cement-based paste needed to fill all grooves.

Table 2 – #2 Aslan 200 CFRP Bars.

Bars	Silo's Type	Total linear ft of bars/silo	Number of Silos	Total linear ft
Vertical	A	4340	6	26,041
	B	3201	4	12,805
	C	2187	8	17,497
Horizontal	A	5200	6	31,200
	B	4290	4	17,160
	C	3250	8	26,000
			Total (ft) =	130,703

Table 3 – Epoxy and Cement-Based Paste.

Paste	Silo's Type	Total cubic ft of paste/silo	Number of Silos	Total cubic ft
Cement-Based	A	8.30	6	49.79
	B	6.55	4	26.19
	C	4.55	8	36.40
			Total (ft^3) =	112.39
Epoxy-Based	A	0.217	6	1.30
	B	0.122	4	0.49
	C	0.122	8	0.97
			Total (ft^3) =	2.76

References

ACI Committee 313, "Design and Construction of Concrete Silos and Stacking Tubes", American Concrete Institute, Farmington Hills, Mich., 1997, 19 pp.

ACI Committee 313, "Commentary on Standard Practice for Design and construction of Concrete Silos and Stacking Tubes for Storing Granular Materials", American Concrete Institute, Farmington Hills, Mich., 1997, 20 pp.

ACI Committee 318, "Building Code Requirements for Structural Concrete (318-99) and Commentary (318R-99)", American Concrete Institute, Farmington Hills, Mich., 1999, 391 pp.

ACI Committee 440, "Guide for the Design and Construction of Concrete Reinforced with FRP Bars", American Concrete Institute, Farmington Hills, Mich., 2001, 41 pp.