Upgrade of RC Silos Using Near Surface Mounted FRP Composites

by

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Abstract

This paper describes a new technology for the repair and upgrade of reinforced concrete (RC) silos using Fiber Reinforced Polymer (FRP) composites. Reasons for strengthening silos are primarily lack of compliance with new code requirements, design and/or construction errors, and aging. An innovative strengthening technique based on the use of Near-Surface Mounted (NSM) FRP bars is herein presented by providing a detailed design example and a recently completed field application. It is envisioned that the use of NSM FRP reinforcement may become a highly effective solution to strengthening needs in silos and circular structures.

Key words

Design, fiber reinforced polymer (FRP), reinforced concrete, silo, strengthening.
Introduction

This section provides a brief review on the design and construction of reinforced concrete (RC) silos and describes their deficiencies. Traditional remedies are then presented and the principles of the new proposed technology are introduced.

Background

Reinforced concrete (RC) silos have been a widespread typology adopted in the US in the 1970’s for long-term storage of cement, coal and other materials. The dimensions of such structures can vary depending on the stored material. Cement or coal silos, which the present paper deals with, are usually characterized by a height-to-diameter ratio larger than two and by walls either on a continuous footing or on raft foundation (Safarian and Harris, 1985). In elevation, from the top to the bottom, the following elements can be identified in a typical structure: the roof, with one or more filling openings; the storing volume; the hopper, consisting of one or more discharging cones; and, the bottom space, sometimes configured as a tunnel, for collecting and transporting away the discharged material.

Depending on the thickness and the diameter of the silos wall, vertical and horizontal (hoop) steel reinforcement is placed in either one or two layers. When a single layer is prescribed, it is located near the outer face of the wall. Such internal steel reinforcement resists forces and bending moments due to the applied loads (i.e., dead loads, static material pressure, overpressures generated during filling or discharge, eccentric loadings due to the presence of multiple discharge openings, thermal stresses, and wind or earthquake). The reinforcement also plays an important role in maintaining concrete crack width within the allowed limits and in transferring local pressure concentrations to a greater surface of the wall (Safarian and Harris, 1985).

Design Guidelines for Steel Reinforcement

The applied forces and pressures are used for determining size and spacing of horizontal hoops to be in compliance with the minimum values suggested by the code specifications adopted at the time of design. In the US, the sequence of provisions covering the period of interest in this paper includes the following documents: ACI 313-68, ACI 313-75, ACI 313-77, revised in 1983, and ACI 313-97. At present, the horizontal reinforcement has to meet the following requirements: 1) minimum steel area of 0.25 percent of the gross concrete area per unit height, and 2) two layers of steel reinforcement for the silo wall equal to or larger than 9 in. (23 cm).

The vertical reinforcement is generally placed based on minimum size and amount as prescribed by the specifications. In particular, the minimum amount varies slightly as the specifications were updated over the years. Current provisions require: 1) minimum steel area of 0.20 per cent of the gross concrete area per unit height, 2) two layers of steel for silo walls equal to or larger than 9 in. (23 cm), 3) a #4 (12-mm diameter) steel bar or
larger, and 4) maximum horizontal spacing not to exceed 18 in. (45 cm) for exterior walls and 24 in. (60 cm) for interior walls.

Deficiencies
Many silos have shown signals of distress inducing owners to require technical investigations to determine their causes and to develop repair strategies. Spalling of concrete cover, appearance of differently shaped cracks and falling of dust from the walls are the most common warnings of silos distress. In the majority of the cases, engineers’ investigations underline that the distressed conditions could be attributed to both design and construction deficiencies as described below:

- The current code (ACI 313-97) suggests two layers of reinforcement for walls thicker than 9 in. (230 mm) and discourages engineers from using thinner walls as that makes it difficult to accommodate a double layer of reinforcement. The presence of a single layer of reinforcement is then one of the most common deficiencies that engineers may observe.
- The thickness of the wall is at times under-dimensioned in comparison to the silo diameter.
- The spacing of the reinforcing bars could be too large when the minimum amount of reinforcement drives the design, without accounting for the possible deformations of the walls under non-uniform loading, withdrawal or temperature effects (Safarian and Harris, 1985).
- Since designers did not typically specify in the drawings that the hoops be tied to the vertical bars, hoop reinforcement may have shifted very close to the outer face of the wall and rust over time without proper concrete cover protection. Hoop reinforcement corrosion decreases the effective steel area and produces horizontal cracks along the circumference of the wall.
- Poor concrete quality may have been a main factor in causing local delamination problems. The lack of quality control during placement has resulted in poor consolidation and caused spalling of the weak concrete and honeycombing.

Traditional Remedies
A number of different repair methods have been implemented for the upgrade of deficient silos. These traditional methods include: post-tensioning with external cables, building of new RC walls within the existing silo (e.g., new interior sleeves), and adding RC to the outside of the exterior walls (e.g., by shotcreting). Of particular interest is external shotcreting as it allows the construction of a barrier for protection of the existing silo, resolving at once all related durability concerns (Collins et al., 1997). This technique requires that the exterior surface of the silo walls be sandblasted to remove the deteriorated concrete in order to ensure good bond between the shotcrete and substrate material. Vertical and horizontal (hoop) steel is then added and tied to the existing walls by epoxy-grouted hook anchors. Finally, the shotcrete is placed, usually starting from the bottom of the silo, and horizontal construction joints are provided. The entire thickness of shotcrete is usually placed in a single pass.
In the following section, an innovative technique involving the use of non-metallic reinforcement applied to the external surface of the silo is presented, showing a design example and discussing a field application. This technology is an outgrowth of the use of externally-bonded fiber reinforced polymer (FRP) laminates, that has emerged as an accepted strengthening method worldwide.

**New Technology – Near Surface Mounted FRP Reinforcement**

Near-Surface Mounted (NSM) FRP reinforcing is an alternative to externally-bonded FRP laminates where a bar is inserted and anchored into a pre-cut groove. General advantages with respect to externally-bonded FRP laminates include the possibility of anchoring the reinforcement into adjacent members, and the opportunity of upgrading elements in their negative moment region with the reinforcement not exposed to potential mechanical damage typical of floor or deck systems (Nanni et al. 1999). The NSM FRP technique does not require extensive surface preparation work, and after groove cutting, requires minimal installation time compared to externally-bonded FRP laminates. Related to silo strengthening, the high speed of the grooving process, the non-corrosive nature and the low weight of the reinforcement, and the possibility of doweling into the wall ensuring proper development length, allow the NSM FRP solution to be highly competitive with traditional upgrade methods.

**Design Tools**

The present section deals with an example of analysis of an existing RC silo strengthened using FRP composites according to ACI 313-97, ACI 318-99, and ACI 440.1R-01.

Data selected for this example are summarized in Figure 1 and Table 1. A #4 (φ12-mm) horizontal steel hoop with the following spacing was used: 10 in. (250 mm) on centers (o.c.) for the first 50 ft (15 m), 11 in. (280 mm) o.c. for the next 40 ft (12 m), and 12 in. (300 mm) o.c. for the last 40 ft (12 m). The same #4 (φ12-mm) steel reinforcing bars were used as vertical reinforcement 18 in. (450 mm) o.c. spaced.

**Vertical Reinforcement**

The actual vertical steel reinforcement does not meet the ACI 313-97 requirement for minimum reinforcement as indicated in Equation (1) for both US Customary and SI Systems:

$$A_{s,\text{vertical}} \geq 0.002 A_g \begin{cases} 0.002(6\text{"})(12\text{"}) = 0.144 \text{ in}^2 / \text{ft} & \text{(US)} \\ 0.002(150 \text{ mm})(1000 \text{ mm}) = 300 \text{ mm}^2 / \text{m} & \text{(SI)} \end{cases}$$

(1)

where $A_g$ is the gross concrete area. The actual $A_{s,\text{vertical}_{\text{actual}}}$ is given in Equation (2):
where \( A_s \) is the steel area, and \( s \) represents the steel spacing.

In order to meet code requirements, strengthening with NSM Carbon FRP (CFRP) bars is adopted following the analysis described below.

The selected strengthening material has a minimum tensile strength and modulus of elasticity of \( f_{u}^* = 200 \text{ ksi (1380 MPa)} \), and \( E_f = 18,000 \text{ ksi (124 GPa)} \), respectively. The bar diameter used is 1/4 in. (φ6-mm).

The ultimate design tensile strength is obtained from Equation (3) (ACI 440.1R-01):

\[
f_u = C_E f_{u}^* = \begin{cases} 
0.9(200) = 180 \text{ ksi} \\
0.9(1380) = 1242 \text{ MPa} 
\end{cases}
\]

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 is the same as the value reported by the manufacturer.

By using a #2 (φ6-mm) CFRP bar (\( A_{FRP} = 0.05 \text{ in}^2, 32 \text{ mm}^2 \)) at 18 in. (450 mm) o.c., the FRP contribution to the vertical capacity is given by Equation (4):

\[
A_{FRP,vertical} = \begin{cases} 
\frac{12''}{18''} (0.05) = 0.034 \text{ in}^2 / \text{ ft} \\
\frac{1000 \text{ mm}}{450 \text{ mm}} (32) = 71 \text{ mm}^2 / \text{ m} 
\end{cases}
\]

The total amount of vertical reinforcement is then given as:

\[
A_{vertical} = A_{s,vertical_{asbuilt}} + A_{FRP,vertical} = \begin{cases} 
0.133 + 0.034 = 0.167 > 0.144 \text{ in}^2 / \text{ ft} \\
282 + 71 = 353 > 300 \text{ mm}^2 / \text{ m} 
\end{cases}
\]

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

**Horizontal Reinforcement**

The initial vertical pressure at depth \( y \) below the surface of the stored material is given as (see Figure 1):
\[ q = \frac{\gamma R}{\mu(1 - \sin \phi)} \left[ 1 - e^{-\mu(1 - \sin \phi) y / R} \right] \]  

where \( R \) is the ratio of area to perimeter of horizontal cross-section of storage space, expressed as \( R = 0.5d/2 \) for circular silos, \( \gamma \) represents the weight per unit volume of stored material, and \( \mu \) and \( \phi \) are the coefficient and the angle of friction between stored material and wall surface, respectively.

The initial horizontal pressure at depth \( y \) below the surface of the stored material can be expressed as:

\[ p = (1 - \sin \phi)q \]  

The horizontal wall design pressure for concentric flow patterns is obtained by multiplying the initial pressure \( p \) by a minimum overpressure factor of 1.5 (ACI 313-97).

The ultimate force per linear ft (or linear meter) of height of the wall is given in Equation (8) (See Figure 2) as follows:

\[ N_u = \alpha pr \]  

where \( \alpha = 1.7 \) is the coefficient amplifying the live load (ACI 318-99), and \( r \) is the silo radius. The wall is designed to achieve a design strength, \( \phi N_n \), at all sections, not less than the ultimate strength, \( N_u \), according to Equation (9):

\[ \phi N_n \geq N_u \]  

where \( \phi = 0.9 \) is the strength reduction factor for axial tension as suggested by ACI 318-99. The nominal strength, \( N_n \), can be written as follows:

\[ N_n = A_s f_y \]  

where \( A_s \) represent the steel area per linear ft (or linear meter) of horizontal reinforcement, and \( f_y \) is the yield stress of steel reinforcement.

Figure 3 shows a comparison between the required design horizontal axial force with the actual axial force (as built) as a function of the depth of the silo. It should be noted that only the top 30 ft (10 m) meet the requirement of the code, while the rest of the structure is under-reinforced.

The same technique used for vertical strengthening is adopted for the horizontal strengthening. When NSM bars are used, the contribution of the FRP needs to be added to the nominal strength, \( N_n \), reported in Equation (10). The final expression for \( N_n \) can be written as follows:
\[ N_n = A_s f_y + A_{FRP} f_{fu} \]  

(11)

where \( A_{FRP} \) is the area of the FRP reinforcement per linear ft (meter), and \( f_{fu} \) is the ultimate FRP design tensile strength as reported in Equation (3).

In order to achieve a satisfactory structural behavior, the following FRP reinforcement should be used: #2 (\( \phi 6 \)-mm) CFRP bars 16 in. (400 mm) o.c. applied for the first 75 ft (23 m) of height of the silo; #2 (\( \phi 6 \)-mm) at 3t=18 in. (460 mm) for the following 22.5 ft (7 m) of silo height (being 3t the maximum allowable spacing). The consequences of such CFRP contribution can be observed in Figure 3 representing the as-built, required, and strengthened capacity of the silo as a function of its height.

**Crack Width Control**

Wall thickness and reinforcement have to be so proportioned that, under initial pressure \( p \), the design crack width, \( w \), computed using Equation (12) (ACI 313-97) shall not exceed 0.01 in (0.25 mm):

\[
\begin{align*}
w &= 0.0001 f_s \sqrt[3]{d_c A} \leq 0.01 \text{ in (US)} \\
&
\quad w = 0.000014 f_s \sqrt[3]{d_c A} \leq 0.25 \text{ mm (SI)}
\end{align*}
\]

(12)

where \( f_s \) (in ksi or MPa) represents the calculated stress in steel reinforcement at initial pressures, and \( d_c \) and \( A \) are expressed as follows:

\[
\begin{align*}
d_c &= 2.5 d_p \\
A &= 2 d_c s
\end{align*}
\]

(13)

where \( d_p \) (in. or mm) is the horizontal steel reinforcement bar diameter.

Crack width resistance needs not be improved since the existing steel reinforcement is able to meet code requirements. However, the same horizontal CFRP bars used for the horizontal strengthening of the silo in the hoop direction can be taken into account to further decrease crack width as depicted in Figure 4 showing a crack width diagram as a function of the silo height for both existing and strengthened design.

Figure 5 shows a detail of the strengthening technique used to upgrade the silo.

**Case Study of Field Project**

A case study for the application of FRP composites on storage structures is represented by six RC silos, located in the Northeastern U.S. and used as load-out volumes for finished cement (ICRI 2001, Emmons et al. 2001). They are part of a larger complex, composed of structures built in different periods. In 1962, the cluster of four silos (1, 2, 3 and 4 in Figure 6) was constructed; each of them is 150 ft. (45.7 m) high, with a diameter equal to 22 ft. (6.7 m). In 1979, four (5, 6, 7 and 8) more were added, each standing 130 ft. (39.6 m) in height and 44 ft. (13.4 m) in diameter.
Background
The repair project concerned only silos 1, 2, 3, 4, 7 and 8. They are characterized by raft foundation and hopper independently supported by a ring beam and column system. Their wall thickness is equal to 8 in. (203 mm) for the first four silos and 10 in. (254 mm) for the other two; for all of them, a single layer of both vertical and horizontal steel reinforcement was placed on the outside surface of the walls. Initial signals of distress were observed in 1994 in the form of cracks and leakage of material through the silo walls (Figure 7).

Silos Upgrade with FRP Composites
Different upgrade techniques were proposed. All of them had the objective of proposing a repair methodology compatible with the peculiar cluster orientation of the silos, with common intersecting walls and then partial access around their perimeter. The main needs called for a solution: 1) fast in order to cause the shortest interruption of the normal use of the upgraded silos; 2) with high durability in order to prevent similar damages in the next future; 3) possibly integrated with advanced systems for the automatic management of charge/discharge operations; 4) able to provide an effective confinement of the silos despite the cluster configuration; 5) with low impact in terms of loss of interior volume as well as additional weight on the foundation; and 6) possibly realized on the external surface in order to avoid issues related to high temperatures during the cement production and to the need for cleaning the inner surfaces.

The evaluation based on such criteria along with a cost-benefit analysis induced the owner to select the technique based on the installation of NSM FRP bars in both horizontal and vertical directions of the exterior surface of the wall. As an additional benefit, the use of NSM bars transformed the cluster configuration into an advantageous feature for the upgrade by allowing the use of the common wall as anchorage of the circumferential bars.

The upgrade followed the steps outlined in the following list removing only one silo from service at a time in order to minimize the service interruption:

- Complete inspection of both exterior and interior walls in order to map all cracks and spalls. This was possible by using suspended swing stages. After inspection, cracks were epoxy injected and local patching of spalls was performed (Figure 8).
- Cutting of grooves (Figure 9). At the intersection of the groove with a common wall, a hole tangent to the silo curve and deep enough to ensure the development length (i.e., given by pull-out tests) was drilled. The vertical grooves were made deeper in order to have horizontal rings on the outer circumference and maximize their confinement action.
- After cutting and cleaning of all grooves, a two-component epoxy paste was gunned in the vertical grooves first; then the FRP bar was installed and a top bed of epoxy was applied. Horizontal NSM bars were then installed with the same procedure based on gunning a bottom epoxy layer (Figure 10), installing the bar...
(Figure 11) and applying a top bed of resin (Figure 12). As mentioned, all horizontal NSM bars were anchored into the common wall as shown in Figure 13.

- Finishing and painting of the surface.

Conclusions

This paper presented a design example and a field application to demonstrate the feasibility and the effectiveness of NSM FRP reinforcement for the repair and upgrade of RC silos.

The use of NSM FRP reinforcement has the advantage of involving the outer face of silo walls without the need for internal cleaning and loss of storage volume. In addition, the high strength of carbon FRP bars, their relatively high elastic modulus, and their high resistance to harsh environments ensure satisfactory performance in terms of both structural response and durability. The latter is generally of critical importance since these structures are often located close to commercial ports or rivers, and exposed to saline and moist environments.

By optimizing the grid of NSM FRP bars, it is possible to correct design or construction problems with spacing and amount of exiting steel vertical and hoop reinforcement or compensate for the loss of steel area due to corrosion. Along with structural aspects, easy and fast installation and minimized service interruption make the NSM FRP technique a competitive solution for the upgrade of RC silos. Further optimization of the costs could be achieved by installing the FRP bars in a latex-modified cement-based paste over the wall surface and keeping the epoxy resin only for the anchorage zones.

Acknowledgments

In 2000, the case study reported in this paper received the ICRI (International Concrete Repair Institute) Award of Excellence – Industrial Category. The following participants should be credited: Owner, Blue Circle Cement, Marietta, GA; Project Engineer/Designer, Co-Force America, Rolla, MO; Repair Contractor, Structural Preservation Systems, Baltimore, MD; Material Supplier, Master Builders, Inc., Cleveland, OH.

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Appendix A - Notations List

- $A_{FRP}$: horizontal area of the FRP reinforcement;
- $A_{FRP,vertical}$: area of FRP bars in vertical direction;
- $A_g$: gross concrete area;
- $A_s$: steel area of horizontal reinforcement;
- $A_{s,vertical}$: minimum vertical steel reinforcement as per ACI 313-97;
- $A_{s,vertical as built}$: actual vertical steel reinforcement;
- $A_{vertical}$: total area of vertical reinforcement;
- $C_E$: environmental strength reduction factor for FRP bars;
- $d_h$: horizontal steel reinforcement bar diameter;
- $E_f$: modulus of elasticity of FRP bars;
- $f_{fu}$: ultimate design tensile strength of FRP bars;
- $f^*_{fu}$: ultimate tensile strength of FRP bars given by the manufacturer;
- $f_s$: stress in steel reinforcement at initial pressures;
- $f_y$: yield stress of steel reinforcement;
- $p$: initial horizontal pressure at depth $y$ below the surface of stored material;
- $q$: initial vertical pressure at depth $y$ below the surface of stored material;
- $r$: silo radius;
- $R$: ratio of area to perimeter of horizontal cross-section of storage space;
- $s$: steel spacing;
- $w$: design crack width;
- $\gamma$: weight per unit volume of stored material;
- $\mu$: coefficient of friction between stored material and wall surface;
- $\phi$: strength reduction factor or angle of internal friction.
Figure 13 - Anchoring the NSM horizontal bar into the common wall. Error! Bookmark not defined.
Table 1 - Silo geometrical and mechanical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Overall Height $h$, ft/(m)</td>
<td>130/(39.00)</td>
</tr>
<tr>
<td>Inside Diameter $d$, ft/(m)</td>
<td>19/(5.80)</td>
</tr>
<tr>
<td>Wall Thickness $t$, in/(mm)</td>
<td>6/(152)</td>
</tr>
<tr>
<td>Concrete Compressive Strength $f_c$, psi/(MPa)</td>
<td>3,000/(20.7)</td>
</tr>
<tr>
<td>Steel Yield Strength $f_y$, psi/(MPa)</td>
<td>60,000/(414)</td>
</tr>
<tr>
<td>Weight per Unit Volume of Stored Material $\gamma$, pcf/(kN/m$^3$)</td>
<td>48/(7.54)</td>
</tr>
<tr>
<td>Coefficient of Friction between Stored Material and Wall Surface $\mu$</td>
<td>0.29</td>
</tr>
<tr>
<td>Angle of Internal friction $\rho$, degree</td>
<td>20</td>
</tr>
</tbody>
</table>
Actual top of stored material

Approximate centroid of repose volume and top of material for pressure calculation

Figure 1
Figure 2
Figure 3

- As Built (Come Costruito)
- Required (Richiesto)
- Strengthened (Rinforzato)
Figure 4

As Built
Come Costruito

Strengthened
Rinforzato

Depth [ft]

w [in]
Figure 7
Figure 11
Figure 12