A DESIGN STUDY ON REINFORCED CONCRETE SILOS FOR REHABILITATION AND RETROFITTING

FINAL YEAR DESIGN PROJECT UG 2020

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CERTIFICATION

This is to certify that the

Final Year Project Titled

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Abstract

Thermal stresses are regularly experienced by silos due to the temperature of their stored material clashing with the atmospheric temperature on site. This is most prominent in the case of hot stored material conflicting with cold winter temperatures. In Reinforced Concrete (R.C) silos these stresses are experienced as tensile stresses in a circular outwards direction and are to be resisted by the vertically placed steel reinforcement bars.

Thermal stresses are however, rarely discussed and brought up in discussion regarding R.C silos unlike the more known stresses due to weight of stored material, wind, and seismic action. This leads them to often be neglected leading to silos being under designed and issues such as cracking begin to emerge during the silo's operation phase. The need for retrofitting arises to keep the silo operational and to prevent future damages that might cause complete structural failure. Depending on the retrofitting technique selected however this can lead to high costs, notable additional load being placed on the silo, large time periods where the silo cannot be operated, and the reduction of the silos maximum storage capacity.

Carbon Fiber Reinforced Polymers (CFRP) are composite materials consisting of carbon fibers that have proven to be an efficient and lightweight solution for the repair of deteriorated structures in the construction industry. For silos specifically they can be attached externally leading to minimum disturbance of operations and no reduction in storage capacity. Their high strength and light weight have led to them being widely used in developing countries but they find themselves being underutilized in Pakistan.

This project highlights the significance of thermal stresses on the design of an R.C silo by using commonly used design codes as well as showcases the capability of CFRP to act as a competent retrofitting technique that is sufficient to deal with said thermal stresses.

Key Words: *Thermal Stresses, R.C Silos, Carbon Fiber Reinforced Polymer, Retrofitting*

Declaration

I confirm that this study entitled "A Design study on Reinforced Concrete Silos for Rehabilitation and retrofitting.*"* is my original work. It has not been submitted elsewhere for evaluation. All material used from other sources has been properly cited and acknowledged.

G.L. MUHAMMAD ABDULLAH
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Key to Symbols and Abbreviations

R.C = Reinforced Concrete

CF = Controlled Flow Silo

qy = Lateral Pressure due to Stored Material

V = Density of Stored Material

R = Hydraulic Radius of Silo

y = Depth from top of Silo

$\boldsymbol{\mu'}$ = Tangent of Angle of Internal Friction of Stored Material

k = Lateral Pressure Coefficient

Mt = Moment due to Thermal Effects

Ec = Young's Modulus of Concrete

h = Thickness of Silo Wall

$\boldsymbol{\alpha c}$ = Thermal Coefficient of Expansion of Concrete

$\Delta \boldsymbol{T}$ = Thermal Differential

$\boldsymbol{\nu}$ = Poisson's ratio of Concrete

CFRP = Carbon fiber reinforced polymer

EB = Externally Bonded

NSM = Near Surface Mounted

Nn = Design Tensile Force for CFRP

$\boldsymbol{As}$ = Area of Steel Reinforcement

$\boldsymbol{fy}$ = Yield Strength of Reinforcement Steel

$\boldsymbol{Afrp}$ = Area of CFRP

$\boldsymbol{fu}$ = Ultimate Tensile Strength of CFRP

CHAPTER 1. INTRODUCTION

1.1 General

A RC silo is a structure whose primary purpose is to serve as a storage unit for large amounts of bulk material like grain, coal, fly ash, and cement. The most common types of Silos in regards to their construction material are Steel Silos and R.C silos with said R.C silos having become more favored recently because of quality of structure and maintenance. Adding on to this, the slip form method of construction can allow for more effective construction for R.C silos, as it involves casting tall cylindrical structures out of reinforced concrete. The vertical walls of a silo are much greater in height compared to the dimensions in lateral directions, making the overall structure possess a relatively tall figure. Due to this shape, the silos opposite sides will be intersected by the plane of rupture of the stored material. Additionally, a good chunk of the load is supported by the friction between the stored material and the silo's floor because of the previously mentioned tall height to lateral dimension ratio.

1.2 Background

The Silo that is taken as the case study for this project is owned by Pakistan's 2nd largest cement manufacturer Bestway Cement Limited and is located at its operating plant site at Kallar Kahar setup in 2014. Said Silo is a Controlled Flow (CF) Silo that stores Raw Meal and has a total height of around 81 meters. The Silo has two levels, level 1 is of a height of 32 meters and is not used for storage rather it is a housing compartment for the associated plant and level 2, which starts above 32 meters and lasts till 81 meters and is used for Storage of bulk material. Cracking phenomenon was observed at the upper 1/3rd portions of silo above the slab level at level 2. The services of NUST institute of Civil Engineering (Structural Engineering Department) were hired for crack depth measurement of the CF silo. The Team mobilized for site testing on 2nd June, 2021 and around 11 cracks which were identified and examined using Ultrasonic Pulse Velocity Testing apparatus by following Bungey et al (2006) approach. PUNDIT (Ultrasonic Pulse

Velocity Tests) was also performed over the uncracked silo wall sections at ground level and along height to 60 meters. The cause of the cracking phenomenon was unable to be identified at that time.

1.3 Scope of Study

The first part of this Project will consist of analysis of the Level 2 of the Silo where the cracking Phenomenon was observed in accordance with the Codes BS8110 and ACI 313-16 to mathematically determine the cause of said cracking phenomenon. SAP 2000 will also be used alongside these Codes for computer modelling and analysis as a further check on the design of the Silo. The second part of this Project will be the design of a potential retrofitting solution against the identified cause of the cracking phenomenon with the focus on not hindering the silos available storage capacity along with placing as minimum extra loading as possible. For this project only the walls of the second level of the Silo will be considered and the rest of the Silo is considered to be adequately designed.

1.4 Study Objectives

1. Analyze the Silo using BS8110, SAP 2000, and ACI 313-16.
2. Identify the most probable cause of the cracking phenomenon.
3. Design a light weight retrofitting solution that does not hinder storage capacity.
4. Suggest measures to prevent similar phenomenon from occurring in other Silos both already constructed and to be constructed.

CHAPTER 2. LITERATURE REVIEW

2.1 Silos in Pakistan

Silos are a mainstay in many industries within the country of Pakistan to allow for efficient storage of bulk material. Some of these uses include; DG Khan Cement which employs silos for the storage of raw materials like gypsum and clinker, Engro Foods which uses silos for storing dairy feed and grain, Sitara Chemical Industries which uses Silos for storing various chemicals that are used in their manufacturing processes, Ashraf Flour Mills which utilizes silos for storing wheat and other grains before processing them into flour, and Hub Power Company which employs silos for storage of the coal that is to be used as fuel for power generation. These examples illustrate the vast scope of Silo usage within the country but with this high level usage comes cases of Silo failure, the most prominent being the failure of the Fauji Cement Company Silo in 2016. This 25,000-ton capacity raw material silo was located at the company's Jhang Bahtar cement plant in Attock District, Punjab and failed at 29th May 2016. This failure thankfully did not result in any casualties but did lead to the complete shutdown of the plant's 7200-ton/day second production line for approximately five to six months. The failure serves to highlight the presence of potential inadequacies within the design of Silos within the country and the need to reassess these designs against modern international standards.

2.2 Loads on Silos

The walls of a Silo that is filled and is not currently subject to material filling and removal experiences the expected gravity, wind and earthquake loadings but there are 2 Types of experienced loadings that are unconventional for regular R.C buildings but are critical for Silos.

2.2.1 Pressure due to Stored Material

The weight of the material stored within the silo exerts itself on the walls of the silo in two forms. First vertical loading that acts in tandem with the already present gravity loadings and second a Hoop Stress that is a function of the material weight and exerts itself circumferentially outwards in all directions. This lateral pressure is tensile in nature and is resisted by steel reinforcement bars that are given in a vertical direction throughout the height of the silo.

2.2.2 Thermal Stresses

The temperature of the material stored within silos is often different from the atmospheric temperature of the site of the Silo. This creates a thermal differential between the inside and outside of the Silo resulting in an additional Hoop Stress. The magnitude of this stress is correlated to the amount of difference between the inside and outside of the silo while the direction is dependent on which side is hotter. This Thermal Stress is taken as a lateral Pressure and is also resisted by the vertical steel reinforcement bars.

2.3 Causes of Failures

Some of the most notable causes of failures and collapse in silos are discussed below.

2.3.1 Explosions and Bursting

Bursting failures or internal explosion are frequent occurrences in the silo structures as compared to the traditionally framed structures which are not exposed to such loads usually. Analyzing the theoretical opposite actions on silo walls, it can be inferred that very high “switch” pressures on a limited part of the wall are the most probable cause of the bursting failure. Methane is also responsible for explosions in certain silos resulting from fermentation of the stored forage or fodder.

2.3.2 Soil Conditions

Silos are, rather specific, thin-stemmed constructions that may either have a small area on the floor or diameter as compared to the height. Consequently, substantially bigger axial stress is induced at the bottom of the silo due to the resultant load formed by weight of the bulk material and structure. The supporting soil is usually subjected to the uniform compressive pressure and/or gravity loads. If the vertical load created by the weight of the stored material is off center, then the pressure bulb under the silo will be affected correspondingly. Vibrations resulting from other forces such as earthquakes, lateral loads also owing to strong winds can also cause a similar effect. This may result in tilting, relative settlement and even collapse of the structure because of the localized overstressing of the soil beneath the foundation. The most common cases of foundation failure in clay soils are observed when a silo is rapidly filled for its first use.

2.3.3 Corrosion

In case preventive measures are not observed, corrosion leads to failure of the metal parts of structures. Out of all silo types, steel ones are most vulnerable to corrosion, which in turn leads to more cases of corrosion failure within this type.

2.3.4 Deterioration

Poor maintenance can cause deterioration in concrete Silos. Most of this deterioration when it comes to conventional cast-in-place and precast concrete silos is due to presence silage acids. The rate of deterioration and its severity is influenced among other things by the size of the silo, the moisture content of the material to be ensiled and the degree of protection afforded over the concrete. Silos with large capacities are also more susceptible to the effect of acid deterioration than the small ones due to the increase in horizontal pressure. When moist plant material is stored in a silo it undergoes the process known as ensiling and as a result the silage acids; lactic and acetic are formed. When these acids make contact with the concrete silo walls they dissolve the Portland cement matrix which acts as binder to the reinforcements aggregates and with time the strength reduction increases further and further. When highly moist material is stored, its ensiling results in a higher level of fermentation and consequentially more acid production. This leads to a faster rate of concrete decay. These acids can reduce the silo’s strength to such a degree that the vertical load on the silo wall would result in the wall being crushed.

2.3.5 Thermal Ratcheting

The walls of silos are called upon to expand during the day and shrink as night approaches because of the changes in temperature. When there is no discharge occurring and the material stored in the silo is of a free flowing type, the material will settle as the available space in the silo grows larger. However, the material is unable to be pushed back during the contraction phase and results in tensile stresses on the structure’s walls. This effect occurs daily and accumulates to produce the failure of the wall. This effect is particularly noticeable in cases of steel silos.

CHAPTER 3. METHODOLOGY FOR ANALYSIS

3.1 Data Collection

Information on the physical structure of the silo including its dimensions along with the detailing of the Steel Reinforcement provided was derived from the Technical Report of the NUST team mentioned in Section 1.3. Due to effective unavailability of information beyond that mentioned in the report most other values required for checks were assumed based on Industry Standards and statements provided in the two design codes being used for this project. Data such as atmospheric temperature was taken from the publically available information on the relevant department’s website.

3.2 BS 8110

BS 8110 is the withdrawn British Standard for the design and construction of reinforced and prestressed concrete structures that is based on limit state design principles. It was used for most civil engineering and building structures. This standard was chosen to check the Silo against old design codes incase those were used for its design as well as providing a comparison point between it and more updated design codes.

The most important equation in the code relevant to silo design is the Janssen's formula for granular material used to calculate the hoop stresses due to loaded material:

$$\boldsymbol{qy = \frac{V.R}{\mu'}\left[1 - e^{-\frac{-y.k.\mu'}{R}}\right]}$$

Calculated stresses were then compared to the Steel Reinforcement provided in the Silo.

3.3 SAP2000

CSI SAP2000 Structural Analysis Program is an engineering software especially useful for beams, columns, slabs, trusses, cables & shells. SAP2000 is very easy to use as well as very powerful. Newer versions of it can perform basic analysis such as shear and moment calculations and advanced analysis such as time history and dynamic analysis which leads to it being a common program used for structural analysis. For the purposes of this project the Silo was modelled as a thick shelled element and the design was checked using the program's built-in structural checks.

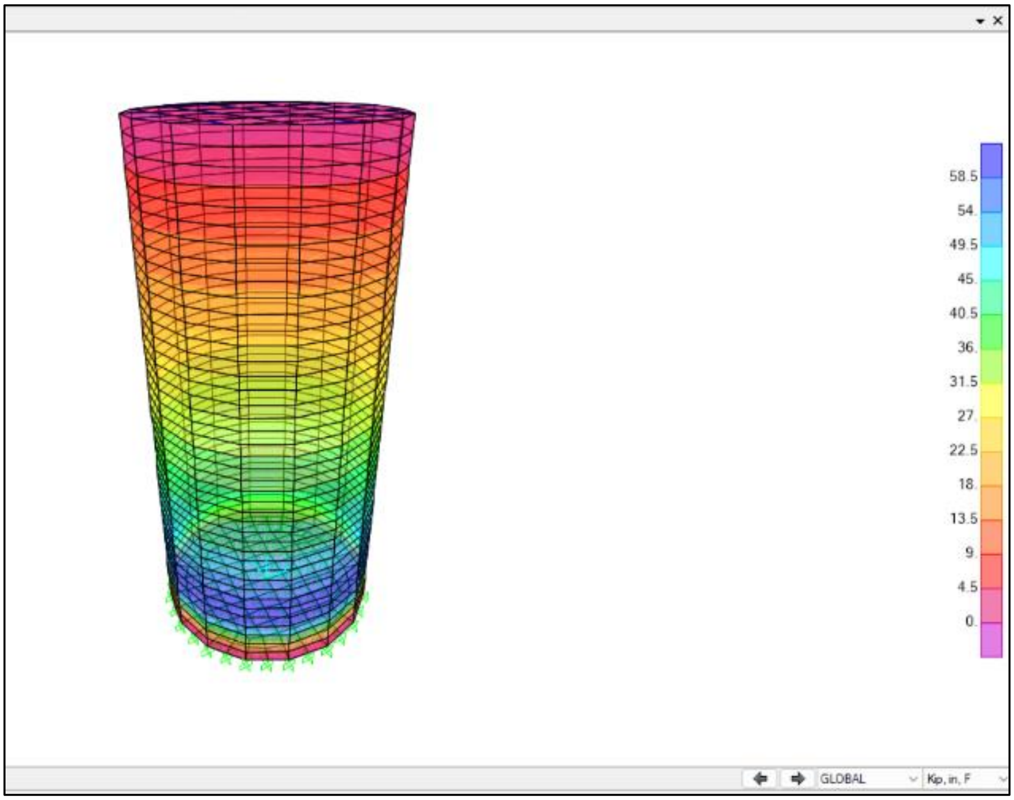


Figure 1: The Kallar Kahar silo as modelled in SAP2000

3.4 ACI 313

The ACI 313 code covers material, design, and construction of concrete silos, stave silos, stacking tubes for storage of bulk solid materials and fabrication and construction of the cast-in-place or precast or conventionally reinforced or post-tensioned silos. This makes it the ideal code for this analysis as well as providing a newer code to compare to the previously mentioned BS 8110. Specifically, the 2016 version with commentary was used for this project. Alongside having its own version of the Janssen's formula for granular material it also provides an equation for the calculation of moments generated due to thermal differentials:

$$\boldsymbol{Mt = Ec.h^2.\alpha c.\Delta T/12(1 - \nu)}$$

Calculated stresses were then compared to the Steel Reinforcement provided in the Silo.

3.5 Steel Reinforcement

The provided steel reinforcement was based on the NUST technical report. The steel was assumed to be as conservative as possible and a depth of 7 meters from the top of the Silo was chosen to be the point where the steel reinforcement would be checked against the applied loadings. This depth was specifically chosen due to being a point where it would be likely that there would not be much steel provided as well as being a point where all applied loadings would be acting.

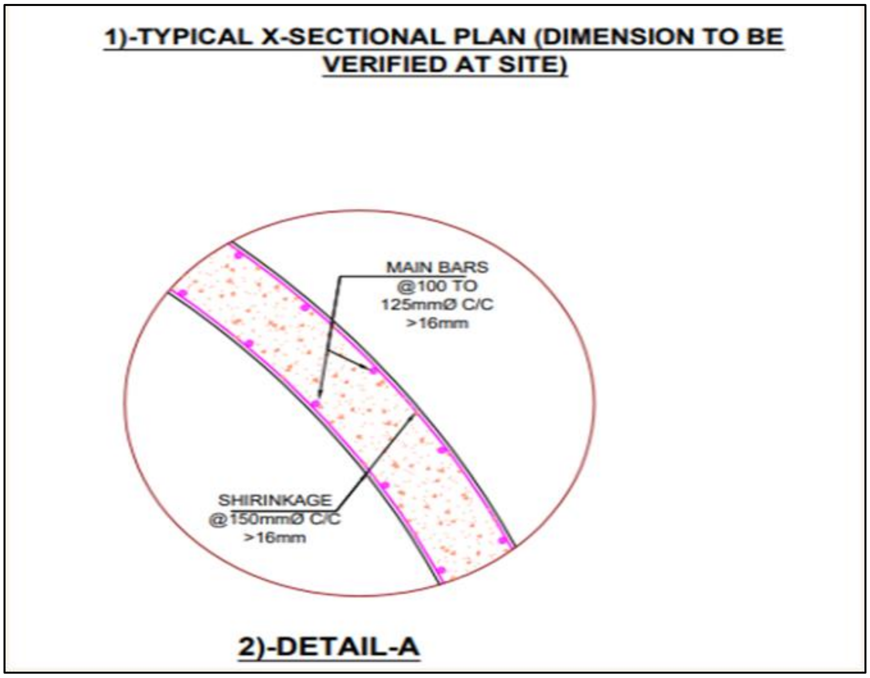


Figure 2: Silo steel reinforcement details from the NUST report

3.6 Qualitative Checks

Due to the numerical nature of the analysis it was possible that if an issue was identified it could be attributed to the wrong cause. Hence a qualitative check was done where the observed cracking in the analyzed silo was compared to the cracking found in other silo failures to supplement the calculated values.

CHAPTER 4. ANALYSIS RESULTS

4.1 Numerical Comparison

The table below shows the results from the methodologies stated in sections 3.2-3.4. Steel Reinforcement present in Silo was calculated to be approximately **2280 mm^2/m**

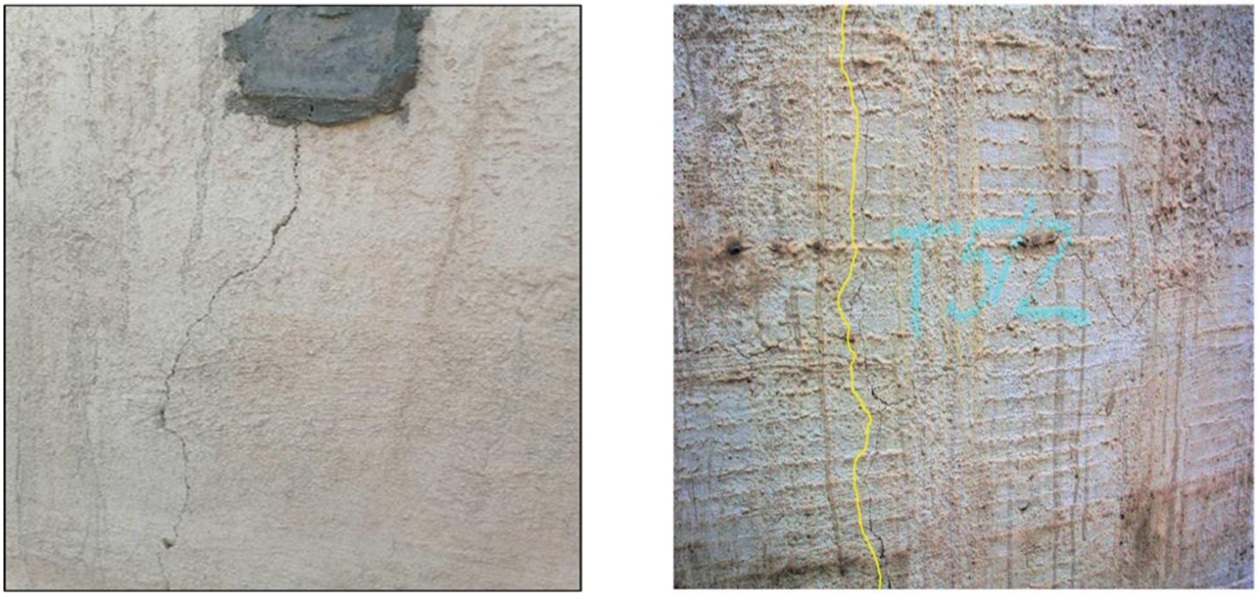
Table 1: Comparison of Analysis Results

Method	Area of Steel required (mm^2/m)	Result
BS8110	2276	No Failure
ACI 313-16 (No thermal)	2189	No Failure
ACI 313-16 (Thermal)	2349	**Failure**
SAP2000	-	No Failure

From this table it can be inferred that the combined action of loadings including thermal stresses, as calculated by ACI 313 results in the overloading of the given steel reinforcement.

4.2 Qualitative Check Result

To narrow down the exact cause of the failure as identified in section 4.1 literature review was conducted to find other cracking observed in silos that was similar in form to the one observed in Kallar Kahar.



(a) (b)

Figure 3: View of: (a) Cracking at Kallar Kahar; (b) Silo cracking after filling with hot material

From the comparison of the two figures shown above it can be concluded with reasonable certainty that the cause of the cracking in this case was due to thermal stresses.

CHAPTER 5. RETROFITTING DESIGN

For this project the Retrofitting solution chosen for the silo was based on Carbon Fiber Reinforced Polymer (CFRP) technology

5.1 Carbon Fiber Reinforced Polymer (CFRP)

Carbon Fiber Reinforced Polymer is a composite material and thus a combination of two materials, namely a fiber which is carbon and matrix which maybe a thermoset, thermoplastic or an elastomer with carbon providing good strength to weight ratio. It is said to replace conventional materials such as metals due to its low density, light weight, higher corrosion resistance, better stiffness and improved fatigue performance. For retrofitting purposes CFRP can be divided into the following two types:

5.1.1 Externally Bonded (EB)

In this technique the fibers are attached to the outside surface of the structure by a combination of epoxies and steel anchorage, either bolts or plates. This method is simpler, faster and commonly used for structures as not much preparation work is required before installation.

5.1.2 Near Surface Mounted (NSM)

In this method CFRP bars are inserted and anchored into pre-cut grooves. Advantages of this method include the possibility of anchoring the reinforcement into adjacent members, and the generally better strength and durability. However, the necessity for grooves to be made increases the effort needed for installation especially for larger structures.

For this project the design will be based on the simpler to install EB method.

5.2 Methodology for Design

For the design of the CFRP retrofitting, the additional force beyond the capacity of the present steel reinforcement was used as the design value for the retrofitting specifically. For properties of CFRP the product range of the company Sika Pakistan was used as reference for a design that would be feasible to do within the country. The equation used for determining of CFRP area is as listed below:

$$\boldsymbol{Nn = As.fy + Afrp.fu}$$

The design parameters used and the resultant design are as shown below:

Table 2: Parameters of Retrofitting Design

Design Force	71 KN/m
Product	SikaWrap®-300 C
Design Tensile Strength	3200 N/mm^2
Nominal Thickness	0.167 mm
Strip Width	600 mm
Strip Spacing	2.5 m
Total Number of Strips	20
Weight of Retrofitting	269 Kg

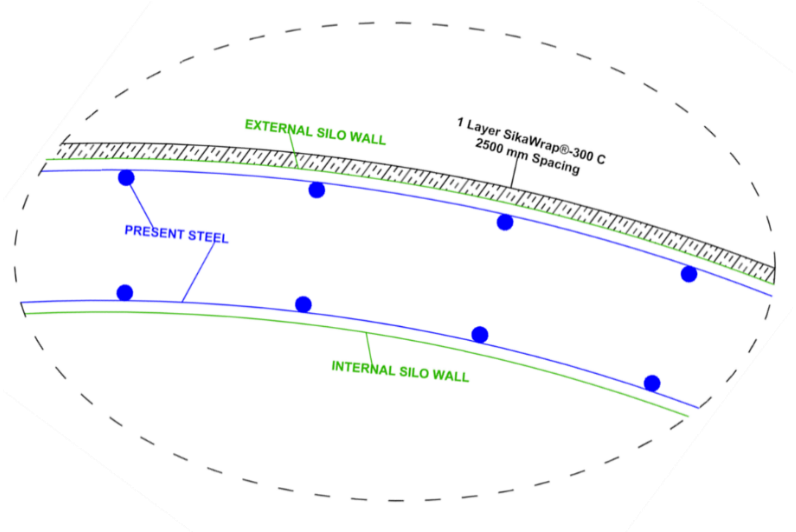


Figure 4: Segment of silo top view showcasing the retrofitted design

5.3 Retrofitting Process

The following figure represents the steps that will be taken for the installment of the CFRP retrofitting:

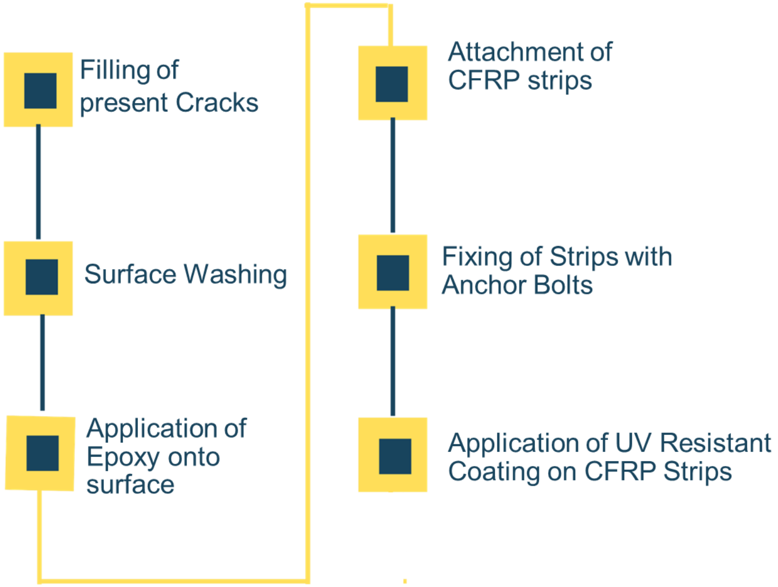


Figure 5: Flow chart of retrofitting process

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

On the basis of the results derived from this project the following conclusions were drawn:

1. The Kallar Kahar Silo most likely experienced its cracking phenomenon due to thermal stresses caused by the thermal differential created by the hot material inside clashing with the cold atmospheric temperatures of winter outside.
2. From experience in finding design information on silos it was noticed that calculations regarding thermal stresses were much rarer than those of wind and seismic loadings. This suggests that this maybe a factor that gets ignored during design leading to future cracking phenomenon.
3. A look into the properties and use cases of CFRP suggests that it would be most suitable for the Retrofitting of this Silo increasing its Hoop while not compromising its capacity or placing much additional load on it.

6.2 Recommendations

From both the experience of carrying out the project, the hurdles faced and the final results the following recommendations are made:

1. For design of Silos it is absolutely crucial that attention be paid to thermal stresses. From noting the temperatures that are to be encountered by the silo during its operation to adding the extra steel required to compensate for them. This is the best precautionary measure to be taken for it saves resources by preventing future structural defects from occurring.
2. It is best to use the commentary inclusive version of a design code for such projects, as some equations and terms are left vague in the original and assumptions about them can lead to significant over/underestimation in resultant values.
3. For silos that have already been constructed it is best to do a review of their design to see if they comply with modern design codes including passing thermal stress checks and act accordingly.
4. For silos that are compromised but still functional using CFRP as a retrofitting technique will provide a light weight, strong and lasting solution.

APPENDIX

Table of lateral pressure against depth from top using BS8110

y (m)	qc (KN/m2)	Fult (KN/m)	As (mm2/m)
7	26.47	495.02	2276
14	48.35	904.07	4157
16	53.87	1007.31	4631
21	66.42	1242.08	5711
28	81.36	1521.38	6995
35	93.70	1752.18	8056
42	103.90	1942.89	8933
49	112.32	2100.48	9657

Table of material lateral pressure against depth from top using ACI 313-16

y (m)	q (KN/m2)	k	p (KN/m2)	p(des) (KN/m2)
7	9.67	0.5	4.83	7.73
14	16.81	0.5	8.41	13.45
16	18.49	0.5	9.24	14.79
21	22.10	0.5	11.05	17.68
28	26.00	0.5	13.00	20.80
35	28.89	0.5	14.45	23.11
42	31.03	0.5	15.51	24.82
49	32.61	0.5	16.30	26.08

Table showing additional stresses acting at 7 m depth from top as per ACI 313-16

Loading Type	**Stress (KN/m^2)**
Wind	13.97
Seismic	3.56
Thermal	1.75

Table showing the properties of the various Sika Pakistan products

Product Name	**Tensile Strength (N/mm^2)**	**Nominal Thickness (mm)**	**Strip Width (mm)**	**Density (g/cm^3)**
SikaWrap®-300 C	3200	0.167	600	1.82
SikaWrap®-530 C	3200	0.29	300	1.82
SikaWrap®-600 C	2400	0.331	300	1.81
SikaWrap®-900 C	2400	0.478	300	1.81

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