Structural Behavior of Grain Bin Steel Silo

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STRUCTURAL BEHAVIOUR OF GRAIN BIN STEEL SILO

By

Yu Xie

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at the University of Windsor

Windsor, Ontario, Canada

2015

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STRUCTURAL BEHAVIOUR OF GRAIN BIN STEEL SILO

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14 May 2015
DECLARATION OF ORIGINALITY

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ABSTRACT

Steel silo is a farm storage structure which is widely used for storing grains. Currently, corrugated galvanized steel sheets are widely used as the side wall of the silo structure. Only a few studies on prototype silo were conducted to determine the grain load on the silo wall. However, no study was conducted to determine the structural behavior of silo structure and lateral displacement of the corrugated sheet under grain load. Therefore, this study was carried out using both experimental tests and finite element analyses to determine the structural behavior of the silo made of corrugated steel side wall. The finite element model developed in this study can be used to optimize the silo structure. The grain load equation (Janssen’s Equation) was also validated using a field full-scale silo structure in this study.
DEDICATION

To my parents, who have given me meticulous care and tremendous encouragement.
ACKNOWLEDGEMENTS

I would like to thank all of those who have helped me in completing this study. My sincere thanks to my advisor, Dr. S. Das for his continuous support during the master’s program and his useful guidance throughout my graduate studies. I would also like to acknowledge the assistance of my other committee members, Dr. J. Sokolowski and Dr. R. Carriveau. I would like to sincerely thank Mr. Jamshid Zohreh Heydariha and Dr. Hossein Ghaednia, without who I would not be able to complete the challenging field work and I acknowledge that the instrumentation and collection of data were primarily done by them. I would also like to thank the technicians at the University of Windsor, Mr. Lucian Pop and Mr. Matthew St Louis for helping me in the lab with chariness and responsibility, in spite of their busy schedule.

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Lastly, I express my sincere gratitude towards my parents who have given me meticulous care in my life and tremendous encouragement for the study along the way.
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>D</td>
<td>Inside diameter of silo bin</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity for the material of the silo wall</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$I_{x(22)}$</td>
<td>Moment of inertia of x (22) axis</td>
</tr>
<tr>
<td>$I_{y(33)}$</td>
<td>Moment of inertia of y (33) axis</td>
</tr>
<tr>
<td>$K_j$</td>
<td>Janssen ratio of horizontal to vertical pressure</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture content of the grains inside of the silo</td>
</tr>
<tr>
<td>$M_s$</td>
<td>Modulus of compressibility of the silo filling for horizontal radial compression</td>
</tr>
<tr>
<td>$p_h$</td>
<td>Normal pressure acting perpendicularly to silo wall surface</td>
</tr>
<tr>
<td>$p_v$</td>
<td>Shear stress acting along wall surface</td>
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<tr>
<td>$t$</td>
<td>Wall thickness</td>
</tr>
<tr>
<td>z</td>
<td>Vertical coordinate (the depth of bulk inside of silo)</td>
</tr>
<tr>
<td>$\Delta \theta_i$</td>
<td>Inside temperature change</td>
</tr>
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<td>$\Delta \theta_o$</td>
<td>Outside temperature change</td>
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<tr>
<td>$\alpha$</td>
<td>Coefficient of thermal contraction of the wall</td>
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<tr>
<td>$\gamma$</td>
<td>Specific weight of grain bulk = $\rho \times g$</td>
</tr>
<tr>
<td>$\gamma_{popcorn}$</td>
<td>Bulk density of popcorn</td>
</tr>
<tr>
<td>$\varepsilon_f$</td>
<td>Mean free thermal strain in the wall</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Coefficient of sliding friction between bulk solid and wall surface</td>
</tr>
<tr>
<td>$\mu_c$</td>
<td>Coefficient of friction of wheat on corrugated sheet surface</td>
</tr>
<tr>
<td>$\mu_d$</td>
<td>Dynamic coefficient of friction between the grains and the silo side wall surface</td>
</tr>
</tbody>
</table>
$\mu_f$  Coefficient of friction of wheat on flat (smooth) sheet surface

$\mu_{int}$  Coefficient of internal friction between bulk solids

$\mu_s$  Static coefficient of friction of corn on galvanized steel

$\rho$  Bulk density of grains

$\Theta$  Angle of wall friction between bulk solid and wall surface

$\Theta'$  Angle of internal friction between bulk solids

$\Theta_{pop}$  Angle of internal friction between popcorn bulk solids
CHAPTER 1

INTRODUCTION

1.1 GENERAL

A grain silo is a farm structure built to store grains in bulk. Grain silos are generally built as tall and cylindrical bins. They can also be constructed in the form of warehouses, domes, and large elongated bags. Currently, tall steel cylindrical silos are widely chosen by farmers and grain conveyor companies. Grain silos primarily store grain, seed, or silage. In the late 1970s, the food industry grew rapidly around the world as the demand of grain storage increased as a consequence. Recently, 95% of the grain bin structures in the U.S.A are large steel storage silos. The construction of bin silo wall can be either corrugated or flat. Corrugated wall silos are more economical and have larger capacity and higher stability than flat (smooth) wall silos.

In the past, most failure cases in silo structures were caused by insufficient design against the unexpected load conditions such as eccentric discharging, thermal ratcheting, strong wind, and earthquake.

1.2 PROBLEM STATEMENT

The price of steel silos has been climbing over the last ten years. In Alberta, the grain bin prices increased from $2.50 per bushel (total price of the silo divided by the maximum volume capacity) in 2004 to $4.00 per bushel in March, 2015 (Alberta Agriculture and Rural Development, 2015). The price of steel silo is influenced by its demand and price of steel. Hence, dimension analyses and optimization of steel silos became important and necessary. On the other hand, full-scale test on field silo structure for its analysis is very expensive, time consuming, and difficult. Hence, help of numerical model and analysis is
the best alternative tool for analysis and optimization of structural elements of silo. Since there is no validated numerical model to analyze the entire steel silo structures on certain dimensions, it is necessary to develop a validated finite element model to assess the structural behavior and dimension control of steel silos.

1.3 OBJECTIVES

The major objectives of this study are listed below.

1. Undertake full-scale field tests for understanding the complex structural behavior of silo subject to grain loading.
2. Develop and validate the finite element model (FEM).

1.4 SCOPE OF WORK

The scope of this research are as follows.

1. Undertaking a detailed literature review.
2. Building referential support for instrumentations.
3. Preparing the test setup, including the installation of loadcell, strain gauges for hoop (circumferential) and vertical (longitudinal) strains, weather station, and linear variable displacement transducers (LVDT) for lateral wall displacements.
4. Acquiring test data from the silo with the filling of corns.
5. Preparing of standard coupon specimens for material tests and testing the coupons of specimens.
6. Analyzing the test data.
7. Determining the behavior of the test silo based on the result of the tests.
8. Developing and validating finite element model using test data.
1.5 METHODOLOGY

The research methodology of this project comprises of both experimental and numerical studies. Lateral displacements, hoop (circumferential) strains, vertical (longitudinal) strains, and internal lateral load of the side wall at certain height were measured in the experimental work. Finite element model (FEM) of the silo structure was developed and validated using test data.

1.6 ORGANIZATION OF THESIS

This thesis is organized as following chapters.

Chapter 1 – Introduction: providing general information about steel silo structures and the objectives of this study
Chapter 2 – Literature review: summarizing the findings of the past studies on silo structures
Chapter 3 – Experimental program: presenting detailed information on silo dimensions and the methodology of the experimental study
Chapter 4 – Experimental results: providing the experimental results and discussions
Chapter 5 – Finite element model simulation: giving the details of modelling and validation followed by discussion on comparison between test result and analysis data
Chapter 6 –Conclusion and recommendation: summarizing the finding in this study and providing the future recommendations
CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Silo is a special farm structure used for the purpose of storing grain. In the past, silo structures were damaged or collapsed due to the insufficient design of complicated natural hazards and catastrophe. However, Canada is a large grain exporter in the world and hence, the grain industry takes an important role in the GDP (Gross Domestic Product). The ability of storing grain safely becomes necessary and critical for Canada. A better understanding of structural behavior of silo in the complicated natural environment should be acknowledged to prevent the accident and failure in silo structures. The mechanical characteristics of silo structure should be determined accurately to analyze the structural behavior of the silo structure. A silo structure experiences the major load from the lateral pressure and surface friction on the side wall caused by the grain load. The objective of this chapter is to review past studies on the silo structure, summarize the method of load calculations, and understanding of the structural behavior of grain bin silo.

2.2 PAST STUDIES ON INTERNAL GRAIN LOAD OF SILO

2.2.1 INTRODUCTION

According to the China Steel Silo Code, European Code, Australian Standard and (GB50322-2011, EN1993-4-1:2007, AS3774-96), Janssen’s Equations (Janssen, 1895) with some modification in the depth of the grain bulk can be used to determine the grain load. Janssen’s equation (Janssen, 1895) requires a series of coefficients and parameters of the grain inside the silo. These are bulk density of the grain, moisture content of the grain, coefficient of the friction between grain particle and wall surface, and angle of internal friction between bulk solids.
2.2.2 JANSSEN'S EQUATION

Janssen’s equation was presented by Janssen in 1895 for predicting the static lateral bin pressure and internal wall surface friction due to grain load. According to Jose et al. (2013), three international silo building standards (ASAE EP 433-2000, AS 3774-96, ISO 11697-95) adopt the same theory and equation for predicting the horizontal (lateral) pressures \( p_h \) on the silo wall. However, these three standards differ in determining the unloading effect since use different coefficients of overpressure. According to these three standards and codes, the horizontal \( p_h \) and vertical \( p_v \) pressure forces on the side wall can be determined using the Janssen Equation (Janssen, 1895) as follows.

\[
p_h = \frac{\gamma D}{4\mu} \left( 1 - e^{-\frac{4\mu K_j z}{D}} \right) \tag{2.1}
\]

\[
\mu = \tan \varphi' \tag{2.2}
\]

\[
K_j = 1 - \sin(\varphi) \tag{2.3}
\]

\[
p_v = \mu p_h \tag{2.4}
\]

where,

\( p_h \) = Normal pressure acting perpendicularly to silo wall surface

\( p_v \) = Shear stress (vertical stress) acting on wall surface

\( \gamma \) = Specific weight of grain bulk = \( \rho \times g \)

\( \rho \) = Bulk density of grains

\( g \) = Acceleration due to gravity

\( D \) = Inside diameter of silo bin

\( \mu \) = Coefficient of sliding friction between bulk solid and wall surface

\( K_j \) = Janssen ratio of horizontal to vertical pressure

\( z \) = Vertical coordinate = the depth of bulk inside the silo
\( \phi' \) = Angle of wall friction between bulk solid and wall surface
\( \phi \) = Angle of internal friction between bulk solids

**2.2.3 COEFFICIENT AND PARAMETERS OF GRAIN**

The constants such as the coefficient of friction of corn on the galvanized steel bin wall \( (\mu) \), Janssen ratio of horizontal to vertical pressure \( (K_J) \), and the grain moisture content \( (MC) \) need to be determined for predicting of the silo internal lateral wall pressure and surface friction on the silo wall. According to the past study (Bucklin et al., 1993), the coefficient of friction of grain on wall material \( (\phi') \) has the highest effect on the magnitude of the lateral wall pressure.

Several experimental studies were completed by Bucklin et al. (1993) to study sources of fluctuation in the dynamic coefficient of friction of corn on galvanized steel. A set of trial tests was conducted by pulling a 32-mm wide, 1.3-mm thick blade through the test apparatus for a distance of 51 mm at the speed of 0.21 mm/s. In these tests, three major variables (grain moisture content, grain pressure, and number of trials) were taken into account. Bucklin et al. (1993) undertook these experiments at the Agricultural Engineering Department of the University of Florida and the University of Georgia under four different grain pressures and these are 13.8 kPa, 34.5 kPa, 55.2 kPa, and 69.7 kPa. The tests were also conducted at two different moisture contents (w.b.) of 12\% (± 0.5\%) and 16\% (± 0.5\%). Bucklin et al. (1993) based on the test data made following conclusions.

1. Dynamic coefficient of friction did not change consistently with the change in the pressure.
2. The value of coefficient of friction decreases with prolonged time and as number of filling cycles increases. This was also found by Thompson et al. (1988) and Thomson and Ross (1983).
3. The lateral pressure on the side wall in the Janssen Equation increases as the coefficient
of friction between the corn and steel wall decreases.

Thompson et al. (1988) and Bucklin et al. (1989) found that the value of the coefficient of friction decreased when wheat repeatedly passed over a galvanized surface which is due to the deposit of organic material from the wheat particles on the metal surface.

Bucklin et al. (1989) found that as the grain movement occurred on the bin wall, which is smaller than the static value of the coefficient of friction changed from a static value to dynamic value. The dynamic coefficient of friction is defined as the coefficient of friction between the steel surface and the grains along the steel surface when grains move and slide. The static coefficient of friction is determined when the grains start moving on the steel surface. The dynamic value of coefficient of friction decreased with the time as greater amounts of grain move over the bin wall surface. Moreover, the study found that as the pressure increased the dynamic coefficient of friction of wheat on steel wall decreased which was also observed by Zhang et al. (1988). Further, Bucklin et al. (1989) concluded that the dynamic coefficient of friction varied with pressure and type of silo wall material. This study also found that repeated sliding contact with the grain decreased the coefficient of friction.

Regression equations for the dynamic coefficient of friction ($\mu_d$) of corn on cold rolled steel were developed and presented in the studies completed by Bickert and Buelow (1966) as follows.

For $10 \leq MC \leq 17.5$; 

$$\mu_d = 0.256 + (1.34 \times 10^{-3}) \text{MC}$$

(2.5)

For $20 \leq MC \leq 22$; 

$$\mu_d = 0.153 + (6.67 \times 10^{-3}) \text{MC}$$

(2.6)

where, MC is the moisture content measured as the percentage of wet bulb (w.b., %) and $\mu_d$ is the dynamic coefficient of friction.
Turgut and Bilge (2013) conducted a test to study physical and mechanical properties of corn to determine the parameters of structural design for storage silos. In this study, bulk density, true density, angle of internal friction, static coefficient of friction were chosen as dependent variables and moisture content (MC) was considered as an independent variable. Thus, regression equations of each parameter related to the independent variable which was moisture content (MC) were found in this study. Accordingly, a regression equation of bulk density of popcorn ($\gamma_{popcorn}$) which was presented by Turgut and Bilge (2013) as follows.

$$\gamma_{popcorn} = 895.77 - 5.10 \text{MC} \quad (R^2 = 0.98)$$

where, MC is moisture content measured as the percentage of dry bulb (d.b., %).

Turgut and Bilge (2013) also developed and presented a regression equation for the static coefficient ($\mu_s$) of friction of corn on the galvanized steel as follows.

$$\mu_s = 0.110 + 0.0272 \text{MC} \quad (R^2 = 0.93)$$

where, MC is the moisture content measured as the percentage of wet bulb (w.b., %) and $\mu_s$ is static coefficient of friction of corn on galvanized steel.

A regression equation for the angle of internal friction ($\phi_{pop}$) between popcorns was presented (Turgut and Bilge, 2013) as well and as follows.

$$\phi_{pop} = 19.31 + 0.97 \text{MC} \quad (R^2 = 0.97)$$

where, MC is moisture content measured as the percentage of dry bulb (d.b., %) and $\phi_{pop}$ is angle of internal friction between bulk solids.

### 2.2.4 Comparison Between Flat and Corrugated Wall

Most steel silo are made of two kinds of side walls and there are flat (smooth) and
corrugated steel sheets. However, the corrugated sheets take the overwhelming majority in the recently constructed silos due to its excellent property of stiffness in the longitudinal and vertical directions. Molenda et al. (1996) conducted a test to compare the different deformable behavior between flat side wall sheets and another silo made of corrugated steel sheets with similar dimensions and loading condition. One 7.3 m high and 2.44 m wide prototype silo with corrugated side wall was constructed and filled with wheat. Then the results were compared with earlier test data of silo made with flat side walls (Molenda et al., 1996). The side walls and the bin floor were separately supported on three load cells to isolate wall and floor loads. Load cells were mounted at an angular spacing of 120° around circumference of the silo underneath the wall. The silo was tested with two series of centric filling, 14 series of eccentric discharge, six series of centric discharge to investigate the behavior of wear-in effect (the wall surface condition and geometry changed with internal grain) and the effect of the eccentric discharge.

Molenda et al. (2000) compared the coefficient of friction between the grain and the side wall to analyze the different behavior in these two silos. Both smooth-wall bin and corrugated-wall bin were filled with same soft red winter wheat. The frictional properties, such as the coefficient of internal friction ($\mu_{\text{int}}$), the coefficient of friction (COF) against corrugated steel ($\mu_{c}$), and the coefficient of friction against flat (smooth) steel ($\mu_{f}$), of the wheat were determined. The values of these frictional properties are shown in Table 2.1.

<table>
<thead>
<tr>
<th></th>
<th>Smooth Wall Bin</th>
<th>Corrugated Wall Bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{int}}$</td>
<td>Initial 0.47 (+0.02)</td>
<td>After 23 tests 0.41 (+0.02)</td>
</tr>
<tr>
<td>$\mu_{c}$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>$\mu_{f}$</td>
<td>0.45</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Note: $\mu_{\text{int}}$, coefficient of internal friction between bulk solids; $\mu_{c}$, COF on corrugated sheet; and $\mu_{f}$, COF on flat (smooth) sheet.
Table 2.1 shows that all frictional properties decreased after repeated tests (23 and 21 tests, respectively). The reduction in coefficient of friction against smooth wall was larger than that of against corrugated wall. A sample of wheat was tested on the flat rolled sheet before it was corrugated. This coefficient of friction of this sample decreased from 0.150 to 0.135. After completing of these tests, Molenda et al. (1996) made several conclusions as follows.

1. The dynamic-to-static wall pressure ratio on the corrugated wall was lower than that on the flat wall.
2. The corrugated wall has the slip-stick frictional effects (the spontaneous jerking motion that can occur while two objects are sliding over each other).
3. The corrugated wall has the upward frictional force which was not observed in the flat wall.
4. Only flat (smooth) wall silo showed the wear-in effect.

### 2.3 FACTORS OF INFLUENCE ON THE STRUCTURE BEHAVIOR OF SILO

#### 2.3.1 DISCHARGING

Numerous tests and investigations were completed in last few decades to understand the effect of different factors causing the non-uniform pressure and strain along the perimeter and also along the height of the silo. Blight (1992) summarized several findings from those experiments.

1. Blight (1992) indicated that most design codes and guidelines recommends using the Janssen’s equation (Janssen, 1895) for the prediction of lateral wall pressures.
2. Blight (1992) also summarized that the lateral pressure increases when silo begins discharging. This happens because coefficient of friction changes from its static value to smaller dynamic value (see Equations 2.1 and 2.4).

Additionally, most design codes and articles consider two critical loading cases: end of
filling and start of discharging. Blight (1992) concentrated on these two loading cases with a third condition applied was the daily temperature cycles into static analysis to determine the structural behavior under temperature change.

### 2.3.2 TEMPERATURE CHANGE

Blight (1985) undertook an experiment to determine the relationship between the strain of silo structure and temperature changes. In this test, strain gauges were installed on the silo wall in the hoop direction in the longitudinal direction on the stiffener to measure the hoop strains of the wall and longitudinal strains of stiffener. The temperature was measured and recorded all day. The data showed that the temperature rose rapidly in the late morning at around 8 AM and fell gradually in the afternoon. The hoop strain maintained the same trend as the temperature changed. However, the strain of the stiffener did not change as much as the hoop strain on the wall changed. The variation of hoop strain, stiffener strain, and temperature over a period of 24 hours are shown in Figure 2.1.

![Figure 2.1 Variation in Hoop Strain, and Stiffener Strain in Corrugated Steel Grain Silo over 24-Hour Period of Temperature (Blight, 1985)](image-url)
Blight (1992) concluded that steel silo wall sheets expand due to the increase of temperature. As a result, the silo bin experiences reduction in internal pressure. Simultaneously, filling flow of grains occurred inside of the wall due to the void space caused by expansion of the steel wall. The restraining pressure develops inside of the silo due to the contraction of the silo wall once the temperature decreases in the night. This restraining pressure accumulates every day gradually to a peak value until the contraction stress of the side wall reaches the value of the lateral grain pressure. This phenomenon is known as thermal ratcheting effect. Generally, the restraining pressure inside the silo accumulates to a peak value over a period of three to five days. This ratcheting behavior in the silo has been demonstrated by Blight (1985). This additional pressure on silo wall occurred by temperature fluctuation is known as the “temperature surcharge pressure”.

Puri et al. (1986) mentioned that the temperature surcharge pressure has been recognized as a significant component of the load carried by silo walls. However, only American Society of Agricultural Engineers (ASAE, 2000) and the guidelines for the assessment of loads on bulk solids containers (Gorenc and Hogan, 1986) include temperature surcharge pressures as part of the load design for silo structures.

Blight (1992) developed an equation for determining the temperature surcharge (TS) of a cylindrical silo as follows.

\[
TS = \frac{2M_sEt \varepsilon_f}{M_s D + 2Et}
\]  

(2.10)

where,

- \(M_s\) = modulus of compressibility of the silo filling for horizontal radial compression
- \(E\) = modulus of elasticity for the material of the silo wall
- \(D\) = mean diameter of the silo
- \(t\) = wall thickness
\( \varepsilon_f = \) mean free thermal strain in the wall

An equation was presented by Blight (1992) for determining the difference of temperature change between inside and outside of the wall as follows.

\[
\varepsilon_f = \frac{\alpha}{2} (\Delta \theta_0 + \Delta \theta_i)
\] (2.11)

where,

\( \alpha = \) coefficient of thermal contraction of the wall
\( \Delta \theta_0 = \) outside temperature change
\( \Delta \theta_i = \) inside temperature change

Blight (1992) found that the lateral pressure and frictional wall loads may both vary considerably along the perimeter of a silo. This fluctuation may be multiplied or reduced. However, it is not easy for precise analysis and prediction. Most of the variation was caused by thermal effects.

Moran et al. (2006) developed a finite element model (FEM) using commercially available finite element program ANSYS to analyze pressure distributions on silo wall subjected to thermal effect. In this study, the action of the grain, friction, and wall were simulated. The finite element model was developed with a height of 9 m, a diameter of 6 m. The cylindrical flat (smooth) steel wall with a thickness of two mm was developed in this FEM as shown in Figure 2.2. Flexible shell elements (SHELL63) were used to model the silo wall. The grains in silo were simulated by employing the solid elements (SOLID45) with a granular material property. The friction generated between the grains and the wall surface was modelled using a pair of contact (CONTA173 and TARGET170) which allow the pressure transmission between the silo wall and the grains.
Parameters such as wall thickness (2.0 mm), modulus of elasticity of the grain (500 GPa), Poisson’s ratio of the grain (0.3) and coefficient of friction between the grain and wall (0.25) were considered in this FEM. The following conclusions were made.

1. Decreasing temperature causes a significant increase in the lateral pressure (see Equation 2.10), which should be considered in the calculation and design of the silo structure. It should be noted that a 24 m diameter bolted steel silo made of corrugated sheets collapsed due to thermal ratcheting in 1996 in southwestern of U.S. which was reported by Carson (2000).

2. The increase of lateral pressure is not proportional to the reduction in the temperature.

3. Based on their parametric study, they found that the increase in lateral pressure due to temperature reduction is more pronounced with increments of the wall thickness, modulus of elasticity of the grain, and Poisson’s ratio of the grain. However, the lateral pressure is scarcely influenced by differentiation of friction angle between grain and wall material.
2.3.3 WIND FORCE

Zhang and Shu (2007) used commercially available finite element program, ANSYS to study the structural behavior of vertical stiffened steel corrugated-wall silo behavior under wind pressure. The silo has diameter of 27.43 m, height of 34.01 m, and 90 vertical stiffeners arranged along the periphery of the side wall. In this study, the orthotropic shell element was used to simulate corrugated-sheet of the silo wall. The results of displacements, inner forces, and stresses under wind pressure were obtained. Finally, nonlinear analysis was undertaken using the first critical mode in eigenvalue buckling analysis as the imperfection and the imperfection sensitivity of the structure was investigated. The analysis was based on the wind pressure factors and distribution diagram along the circumference of silo structure as shown in the Table 2.2. In this table, α denotes the angle to the reference direction (negative direction of the wind towards the silo) in the angular coordinate system of the silo. The $\mu_s$ stands for the wind pressure form (distribution) factor which varies from +1.0 to -0.17 along the half perimeter of the silo wall. The positive value of $\mu_s$ indicates the compression pressure on the side wall and the negative value of $\mu_s$ represents the suction pressure on the side wall. The wind height factor ($\mu_z$) is used to calculate the wind pressure at different heights ($h$) of the silo wall.

Table 2.2 Wind pressure form factor and height factor (Zhang and Shu, 2007)

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\mu_s$</th>
<th>$h$</th>
<th>$\mu_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>+1.0</td>
<td>5</td>
<td>1.17</td>
</tr>
<tr>
<td>15°</td>
<td>+0.8</td>
<td>10</td>
<td>1.38</td>
</tr>
<tr>
<td>30°</td>
<td>+0.1</td>
<td>15</td>
<td>1.52</td>
</tr>
<tr>
<td>45°</td>
<td>-0.7</td>
<td>20</td>
<td>1.63</td>
</tr>
<tr>
<td>60°</td>
<td>-1.2</td>
<td>30</td>
<td>1.80</td>
</tr>
<tr>
<td>75°</td>
<td>-1.5</td>
<td>40</td>
<td>1.92</td>
</tr>
<tr>
<td>90°</td>
<td>-1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>105°</td>
<td>-1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120°</td>
<td>-0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>135°</td>
<td>-0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150°</td>
<td>-0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>165°</td>
<td>-0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180°</td>
<td>-0.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The study found that the maximum radial displacement is near the top of the silo wall because of the maximum wind pressure in this area. The radial displacements distribution patterns at two different heights (h = 5.283 m and 23.77 m as shown in Figure 2.3) of the silo wall are almost the same. The maximum negative and positive displacements occurred at 15° and 90° of circumferential direction which respected to the reference direction (opposite wind direction) as shown in Figure 2.3.

![Figure 2.3 Radial displacements of specific heights (5.283 m and 23.7735 m) over half perimeter of silo surface (Zhang and Shu, 2007)](image)

Zhang and Shu (2007) summarized the findings of the investigation of the wind pressure on silo structure as follows.

1. The radial displacement caused by wind pressure is larger than displacement in the vertical direction.
2. The maximum radial displacement occurred near to the top of the silo and at about 90° in circumferential direction to the wind.
3. The maximum wind pressure increases as the roof rigidity increases and also as the depth of corrugation of silo wall increases or pitch decreases. However, the rigidity of vertical stiffener and boundary restraint conditions have a little influence on the
maximum wind load on the silo structure.

2.3.4 MOISTURE CONTENT

Bucklin et al. (1985) conducted experimental test to study the buckling stresses of model (prototype) grain bins with varying radius to wall thickness ratios (r/t) and various levels of internal pressure. The radius to thickness ratio (r/t) was controlled by changing wall thicknesses for the test section from 0.23 mm to 0.74 mm, giving radius to thickness ratios between 1000 and 3300. The diameter of the test silo was 1.52 m and the height of this silo was 2.44 m. The prototype silo consisted of two circular sections for instrumentation and data acquisition purposes and one test section in between the two instrumented sections along the vertical direction as shown in Figure 2.4. The test section was made of thinner (thickness ranged from 0.23 mm to 0.74 mm) steel sheet than the instrumented sections (thickness of 6.4 mm) to ensure that the buckling always occurred first in the test section. The upper and lower instrumented sections were mounted with foil strain gages to measure circumferential and axial strains on the silo wall.

Figure 2.4 View and cross-section of loading frame (Bucklin et al., 1985)
The study made the following conclusions based on the test result.

1. Buckling load increases with the increasing in the internal pressure.
2. Grain solids behave like a semi-fluid with elastic-plastic properties when compressed.
3. The modulus of elasticity of wheat increases with increasing grain pressure and decreases with increasing moisture content.

Kebeli et al. (2000) conducted tests on the one meter high and 0.6 m diameter model grain bin made of 0.4 mm thick smooth galvanized steel sheet to study the moisture-induced pressures and loads in silo structure (see Figure 2.5). The test silo bin was filled with red spring wheat which was chosen because it has high bulk density.

Six strain gauges were installed at three different heights and located 180° apart along the perimeter of silo wall. These strain gauges were used to measure the strains and then the strain data was used to calculate lateral pressures. The side wall of this test silo was supported by a ring-shaped steel base (thickness of 6.4 mm) which had an outside diameter of 0.68 m and inside diameter of 0.60 m. Three load cells were installed under the side wall steel base located 120° apart. These load cells were used to measure the vertical loads of the side wall steel base (vertical friction force). Another three load cells were installed at 120° apart under the base table which supported the entire silo structure to measure the vertical load of the bin base table (total weight of the grains). The average moisture content was calculated by total weight changes based on the known initial moisture content of the grains.
Based on the test data, the following conclusions were made (Kebeli et al., 2000).

1. Vertical floor loads increased as the moisture content of the grains increased and the load on the bin floor reached a slightly higher value than the total weight when bin previously filled with drier grains.

2. The vertical wall forces (frictional force) on the bin wall decreased as the grains were wetted, that is, as moisture content increased. This occurred because of the forces in the upward direction due to grain expansion.

3. Change in grain moisture content has a significant effect on the lateral pressure. As the moisture content increases the value of lateral pressure increases significantly.

4. Janssen’s Equation was found to be able to predict the static pressures on the wall with the appropriate value of constants such as coefficient of friction between grains and wall surface ($\mu$) and Janssen ratio of horizontal to vertical pressure ($K_J$).

### 2.4 FAILURE CASE STUDIES

A field silo located in Poland failed due to buckling failure was investigated by Iwicki et al. (2011). Linear buckling and non-linear analyses were undertaken using 3D Finite
Element (FE) model. This FE model were developed using commercially available finite element code, ABAQUS.

The failure of silo structure which was studied by Iwicki et al. (2011) is as a steel silo consisted of corrugated wall sheets with vertical stiffener columns with the height and diameter of 20.13 m and 12.48 m, respectively. The bin wall consisted of 24 rings along the vertical direction which made from horizontal corrugated sheets. Each sheet was 890 mm wide (high) and 2940 mm long. The thickness of the corrugated sheets varies from 0.75 mm (22 gauges) up to 1.75 mm (15 gauges). The sheet corrugation had pitch of 119 mm and depth of 10 mm. The FE analysis found that several vertical stiffener columns were buckled severely during an initial continuous filling and discharging process of the silo (the wall pressure reached the maximum value). The maximum lateral displacement of the stiffener column was found to be about 0.5 m and this displacement reduced to 0.15 m when the silo was emptied completely (see Figure 2.6).

![Figure 2.6 View on buckled vertical column of empty silo (Iwicki et al., 2011)](image)

The corrugated wall sheets were mounted to the stiffener columns at a constant spacing of 119 mm (bolt connections were not modeled). The four-node thin shell element with a
reduced integration point were used in the model. At the top of the wall, a circumferential ring was defined with a thickness of 300 mm to simulate the roof. Hence, restraints provided by the FE model did not simulate actual roof. The material of the silo was assumed to be elastic or elastic-perfectly plastic. The steel properties were defined as follows: modulus of elasticity (E) of 210 GPa, Poisson’s ratio (ν) of 0.3, and yield stress (f_y) of 350 MPa.

Based on this study, Iwicki et al. (2011) finally made the following conclusions.

1. The failure of this silo was caused by buckling of vertical stiffener columns which occurred due to the insufficient buckling strength of stiffener columns. The buckling strength of the stiffener columns was two to four times lower than the recommended values by Euro-code 3 EN1993-4-1 (2007).

2. The buckling capacity of vertical stiffener columns recommended by Euro-code 3 EN1993-4-1 (2007) is very conservative. In this code, the number of buckling half-waves along the circumference was assumed equal to the half of the column number.

3. The bending stiffness of stiffener columns should have been strengthened by two to three times by attaching additional stiffener column on the existed stiffener column at the height of five to nine meters to avoid buckling failure of the stiffeners.

Dogangun et al. (2009) summarized different types of damage and failures in silo structure. In this study, reasons for failure in silo were summarized as internal explosion and bursting, filling and discharging, soil condition, corrosion, deterioration, thermal ratcheting, and Earthquakes. Dogangun et al. (2009) reported a collapsed concrete grain storage facility which killed 11 people in France in 1997 as shown in Figure 2.7. This failure of silo structure was caused by internal explosion and bursting.
Dogangun et al. (2009) presented a silo failure due to discharging as shown in Figure 2.8. This silo had served for 16 years and busted at the interruption for a visual inspection during discharging process.

Dogangun et al. (2009) also reported two adjacent silo leaned to each other due to insufficient resist strength of soil under the foundation (see Figure 2.9). This twin silos
were built in the Red River Valley in Canada. These two silos were built so close that the overlapping area of pressure bulbs occurred between two silos and caused insufficient resistance as shown in Figure 2.9.

![Figure 2.9 Two Silos Leaned to Each Other (Dogangun et al., 2009)](image)

Dogangun et al. (2009) reported two failed silo due to corrosion as shown in Figure 2.10.

![Figure 2.10 Two Collapsed Silo Due to Corrosion (Dogangun et al., 2009)](image)

Dogangun et al. (2009) described a collapsed silo in southwestern United States due to thermal ratcheting (see Figure 2.11). The theory of thermal ratcheting was explained in Section 2.3.2.
Dogangun et al. (2009) explained that earthquake causes three seismic structural loads (one in vertical direction and two in horizontal directions) in silo structure. The vertical structural seismic load is relatively small than these two horizontal seismic loads. The effect of these two horizontal seismic loads becomes more significant in taller silo structures storing heavier grains. Dogangun et al. (2009) reported several collapsed cement silos in Turkey as shown in Figure 2.1. These cement silos collapsed in November 12, 1999 7.2 magnitude Duzce earthquake, but these cement silos might be damaged in earlier August 17, 1999 Kocaeli 7.4 magnitude earthquake.
2.5 SUMMERARY

Following summaries can be made based on the literature review.

1. The internal loads on the side wall of silo structure can be predicted by Janssen’s equation (1895).

2. The grain load is primarily affected by the physical properties of grain (bulk density, moisture content, and angle of friction between grain solids and wall surface). However, the bulk density and friction angle are controlled by the moisture content of the grain.

3. The lateral pressure increases significantly with the increase in the moisture content of the grain. Thus, controlling moisture content within a safe and economic range is important.

4. As the moisture contents increases the vertical frictional force on the wall decreases, however, increase in moisture content of grains result in significant increase in lateral pressure on the silo wall.

5. Corrugated side wall sheet was recommended by the past study to achieve a higher stiffness and stability.

6. When silo start discharging the grain, the internal wall pressure increase significantly. The increment in the pressure on the side wall due to discharging was inconsistent along the perimeter of the silo wall and it varied with unloading speed.

7. Change in temperature also influences the internal pressure on the side wall of the silo. Rise in temperature caused a decrease in lateral pressure and vice versa. Change in the lateral pressure on the wall is also affected by the wall thickness, young's modulus of elasticity of the grain, and Poisson’s ratio of the grain.

8. The wind pressure affects the displacements of the silo structure. The radial displacement is larger than the displacement in vertical directions and the maximum radial displacement occurs at the silo top of the silo and at about 90° in the
circumferential direction to the wind.

Based on the literature review, it is concluded that no study validated the finite element model by experimental data, no experimental test was conducted to measure the lateral displacement on the silo wall. No experimental test was completed in a full-scale large diameter steel silo structure and all previous experimental studies were undertaken on small model (prototype) silos. Hence, this research was designed and undertaken to obtain the behavior of lateral displacement of the silo wall from a filed large silo and then develop and validate FE model to enhance the understanding on the silo structure.
CHAPTER 3

EXPERIMENTAL STUDY

3.1 INTRODUCTION

In the past studies on the silo structure, most experimental researches were undertaken to determine the pressure magnitude and distribution on the side wall due to the load from grains. However, very limited numbers of studies concentrated on the behavior of lateral displacement on the side wall of steel silo structures. These studies include tests of prototype silos. Test on full-scale silo structure is not available in the literature. Thus, the objective of this project was to determine the behavior of lateral deformation of the side wall under the internal pressure caused by the bulk of whole kernel corns. The current study was undertaken on a large silo structure located in the field. Thus, many natural disturbances may have occurred in the test procedure, such as strong wind, heavy rain or snow fall, and large fluctuation of temperature. The test data were analyzed and then they were used to validate the numerical model. This model can be used to analyze the behavior of displacement of the side wall under different variables from both geometric and loading aspects.

3.2 GEOMETRY OF STRUCTURE AND STRUCTUREAL COMPONENTS

The silo cylinder was constructed on a circular concrete foundation with a side wall consist of corrugated steel sheets, vertical stiffener columns, and a roof. Inside the silo, the floor of the bin is a steel plate supported above the concrete foundation as shown in Figure 3.1. The discharging and conveyer systems are located under the steel bin floor. The floor is 467 mm above the concrete foundation (see Figure 3.2). In addition, there is a side discharge door at five meters above the concrete foundation.
According to the dimensional information provided by the Lambton Conveyer Ltd., the total height of the silo is 23.27 meters which includes an inclined roof which has an angle of 32°. The inside diameter of silo cylinder is 14.55 meters. All structural components of the silo are made of same material, ASTM A653 SS GR 50 Class 1 galvanized steel (ASTM, 2013), which specified minimum yield strength of 344 MPa, minimum tensile strength of 448 MPa, and 12% elongation on two inches (50.8 mm) gauge length.

![Figure 3.1 View of Test Silo](image)

![Figure 3.2 Location of the Bottom Floor](image)
The bottom floor inside of the silo bin is located 0.467 meters above the top of the concrete foundation. Thus, there are two constraints in the bottom area of the side wall. One is from the connection between the side wall and concrete foundation and another one is from the connection between the side wall and the bottom floor. Total weight of corn that could be stored in it is 2524 metric tons \((W = \text{area} \times \text{height} \times \text{density of grains} = 166.27 \text{ m}^2 \times 18.53 \text{ m} \times 819.27 \text{ kg/m}^3)\).

Side wall is made of corrugated galvanized steel. The corrugation of the sheet has the pitch of 101.6 mm and the depth of 19.2 mm. The side wall was built with 17 layers of ring. Each ring consists of 16 corrugated steel sheets. The total length of each sheet is 2.93 meters. The height of the each sheet is 1.16 meters. Two adjacent wall sheets of a ring were connected by two columns of bolts in the vertical direction. In the horizontal direction, however, only one row of bolts was used as the connection between two adjacent side wall rings (See Figures 3.3 to 3.5).

![Figure 3.3 Outside View of Bottom Side Wall](image-url)
As shown in Figure 3.5, there are four overlapping areas in each corrugated sheet, which are the bolt-connection areas located on both the vertical and horizontal edges of each sheet. Thus, the effect of double thickness occurs in these overlapping areas. Therefore, the thickness of overlapping area is doubled by two layers of side wall sheets. The diameter of the bolt used in the overlapping area is 9.525 mm. Bolts have a 1.5875 mm clearance to
the holes. That means a 9.525 mm bolt goes in the 11.11 mm hole which would cause the bin wall to open up when silo is filled with grains.

There are 32 stiffener columns along the periphery of the silo and they are attached to the side wall with bolts (see Figure 3.1). Each stiffener column consists of different single stiffeners which vary in cross-section and thickness along the height. Two adjacent stiffeners in a column are connected by a laminate stiffener and the connection is achieved through bolts as shown in Figure 3.7.

In the first ten layers of side wall rings, the stiffener column consists of two single stiffener sections (a) and (b) as shown in Figure 3.6. This two layer stiffener (c) includes a main stiffener (b) attached to the side wall and a laminate stiffener (a) bolted to the web of the main stiffener (b) (see Figures 3.6 and 3.7). Also, the thickness of stiffener decreases with the increase of height on each stiffener column.

![Figure 3.6 Sketch of Stiffener Combination](image)

**Figure 3.6 Sketch of Stiffener Combination**
Figure 3.7 View of combined stiffener

Lambton Conveyer Ltd. provided stiffener drawings as shown in Figure 3.8, the following explanations would help in understanding all the naming of the stiffeners.

1. Name of each stiffener starts with W2P which stands for a stiffener has 101.6 mm wide corrugation and length (tall) of two side wall rings’ height
2. Stiffener Base (B) Plate in Full Length (F) with a thickness of 8 gauges (4.37 mm): W2P-BF-08
3. Main (R) Stiffener in Full Length (F) with a thickness of 10 gauges (3.57 mm): W2PR-F-10, W2PR-F-12 (12 gauges, 2.78 mm) and W2PR-F-14 (14 gauges, 1.98 mm)
4. Laminate (L) in Full Length (F) Stiffener with a thickness of 8 gauges (4.37 mm): W2PL-F-08, W2PL-F-10 (10 gauges, 3.57 mm), W2PL-F-12 (12 gauges, 2.78 mm) and W2PL-F-14 (14 gauges, 1.98 mm)
5. Swaged (S) Main (R) in Full Length (F) with a thickness of 12 gauges: W2PSR-F-12 (12 gauges, 2.78 mm) and W2PSR-F-14 (14 gauges, 1.98 mm)
6. Top Stiffener in Half Length (HF) with a thickness of 14 gauges: W2P-HF-14 (14 gauges, 1.98 mm; half length: one side wall ring height)
Each vertical stiffener until beginning of 11th side wall ring level consists of two different stiffener sections as shown in Figure 3.6. The details of side wall and stiffeners are listed in the Table 3.1.

**Table 3.1 Dimensional List of Side Wall and Stiffeners**

<table>
<thead>
<tr>
<th>Side wall Ring number</th>
<th>Gauge Number of Side Wall (Gauges, mm)</th>
<th>STIFFENER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MAIN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gauge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number</td>
</tr>
<tr>
<td>17 (Top)</td>
<td>18 Gauges (1.27 mm)</td>
<td>14</td>
</tr>
<tr>
<td>15 &amp; 16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 &amp; 14</td>
<td>17 Gauges (1.43 mm)</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>15 Gauges (1.79 mm)</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>14 Gauges (1.98 mm)</td>
<td>10</td>
</tr>
<tr>
<td>7 &amp; 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>13 Gauges (2.38 mm)</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (Bottom)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: “MAIN” for main stiffener which attached on the side wall, “LAM” for laminate stiffener which attached on the main stiffener.
3.3 TEST VARIABLES AND LIMITATION

According to the Janssen’s equation (Janssen, 1895), the normal pressure \((p_h)\) and vertical stress \((p_v)\) are function of the diameter and height of the silo cylinder, density of corn bulk. Thus, moisture content and the depth of corn bulk inside of the silo bin are the major variables in the test. The wind force and the temperature change have little influence to the test result of hoop strain of the side wall.

It is not economically feasible to measure the lateral displacement on the entire height of the side wall because it is very expensive and time consuming. Furthermore, most deformation and highest strains are expected to occur at the bottom one-third height of the silo, as previous numerical study shows that the maximum pressure from grains occur close to the silo bin floor. Thus, the location of the measurement was determined to be in the range of seven-meter height from the top of the concrete foundation.

3.4 TEST SETUP

The position layout of LVDTs, load cell, bottom floor, and strain gauges is shown in Figure 3.9. High accuracy Linear Voltage Displacement Transducers (LVDT) were mounted and used to measure the lateral displacement of the side wall. These LVDTs were mounted on a standalone circular steel column which was isolated from the silo structure. The steel pole was erected beside the silo. The circular column was made of hollow steel tube of 400 mm diameter and 4 mm thick wall. The steel pole had its own concrete foundation (see Figures 3.9 and 3.10). This hollow pole was erected beside the concrete foundation of the silo, and the pole was strapped to the side of the concrete foundation by two steel clamps (see Figure 3.10). The pole was braced at 3.5 m height measured from top of the ground (see Figure 3.12) with steel angle member (∟ 70 mm × 70 mm × 5 mm) as shown in Figure 3.11. These two steel bracing members were anchored to the concrete foundation of the silo.
Figure 3.9 Position Layout of Instruments

Figure 3.10 Bottom Anchor of Pole
Figure 3.11 Middle Anchor of Pole

Silo

Corrugated sidewalls

Angle bracing

Silo concrete foundation

6000 mm

3500 mm

Ground surface

Concrete foundation of pole

Two steel ropes attached to other structure

Figure 3.12 Sketch of Hollow Pole
The height of the pole is nine meters to the ground surface. Since the pole was made of hollow section and it was slender, vibration and sway at the top of the pole due to wind are expected to occur beyond the top bracing point. To prevent shaking and vibration caused by wind and other unknown factors, the top of the pole was tied with two symmetric steel ropes and the ends of the rope were fastened to the bottom stiffeners of the other silo next to the test silo as shown in Figure 3.13.

![Figure 3.13 Top Anchor of Pole](image)

A load cell was mounted on the inside wall of the silo cylinder to obtain the pressure on the silo wall at 825 mm height from the top of the bottom steel floor to help validating Janssen’s equation (Janssen, 1895) and the numerical model. The load cell was mounted perpendicularly to the side wall by using four 9.5 mm diameter bolts (see Figure 3.14). A 90 mm diameter circular steel disk was installed on the load cell to measure the lateral grain load.
Nine linear voltage displacement transducers (LVDTs) were installed horizontally on the pole at different heights to measure the lateral displacement as shown in Figure 3.9. The LVDTs were bolted on horizontal steel angle members with clamps which were mounted on the vertical pole as shown in Figure 3.15. A circular disk made of polyethylene was used to secure LVDT located on the silo wall. The circular disk had very strong magnet which was used to mount the circular disk on the silo wall.

Four strain gauges were installed in the longitudinal and vertical directions on the outside
surface of the side wall at height of 500 mm and 1470 mm measured from the top of the concrete foundation (see Figure 3.16).

![Figure 3.16 Installation of Strain Gauges](image)

Another four strain gauges were installed on and around the entrance door of the silo as shown in Figures 3.17. Two of these strain gauges were attached just above upper and below the door to measure the strain concentrations beside the door frame. The last two strain gauges were attached on lower part of the door surface and web of the removable steel channel beam screwed in between of the door frame. These strain gauges in and around the entrance door were installed to determine if strains at and around the door are within the acceptable limit.

![Figure 3.17 Strain Gauges on the Entrance Door](image)

The strain-time plots of these four strain gauges were shown in the Appendix A (see Figures
A.1 to A.4). The maximum strains measured by these four strain gauges are presented in the Table 3.2. The minimum yield strains observed from the material tests is presented in this table to compare the level of these strains.

<table>
<thead>
<tr>
<th>Location</th>
<th>Door</th>
<th>Beam</th>
<th>Upper Wall</th>
<th>Lower Wall</th>
<th>Yield Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max micro strain (με)</td>
<td>435</td>
<td>-25 to +36.2</td>
<td>901</td>
<td>775</td>
<td>2000</td>
</tr>
</tbody>
</table>

From Table 3.2, it can be found that all the maximum strains in four locations are much less than the yield strain. Thus, only elastic deformation occurred in these four locations. The stain on the beam varied from -25 με to +36.2 με. The magnitude of the stain on the beam is very low. The variation is negligible.

3.5 INSTRUMENTATION

Instruments used in this experimental work include load cell, nine LVDTs (Linear Voltage Displacement Transducer), four strain gauges (not including those mounted on the entrance door), a weather station, and a data acquisition system. The load cell was used to measure the lateral force created on the side wall of the silo resulting from the corn. Lateral pressure was then calculated by dividing the lateral force with load cell contact area which was a circular steel disk of 90 mm diameter.

Ten channels of electrical resistance (350Ω) strain gauges of 5 mm gauge length were installed in hoop (circumferential) and vertical (longitudinal) directions on the side wall at heights of 500 mm and 1470 mm from the concrete foundation to determine the hoop strain and vertical (circumferential) strain of the side wall (see Figure 3.9). Nine spring loaded LVDTs were mounted on the steel pole along the vertical direction. The maximum displacement of these LVDTs varied from 50 mm to 100 mm. The weather station was installed around the steel pole to monitor the local weather condition such as wind speed,
rain fall, and temperature. Two analog output modules (Data Scan 7021) were used along with a laptop computer and Daylite software (test data collection and recording) in the field to acquire test data. Every module has eight channels. Before the installation of instruments, calibration processes were completed to ensure all the gauges were in working condition. Thus, load cell was calibrated on a standard MTS load testing machine in the structure engineering lab of University of Windsor. The LVDTs were calibrated by the distance gauge as shown in Figure 3.18. Computer and data acquisition system were secured in a steel storage shed as shown in Figure 3.19.

![Figure 3.18 Calibration of LVDT](image1.png)

![Figure 3.19 Steel Storage Shed](image2.png)
3.6 TEST PROCEDURE

The test was and could only be carried out during the window of one week in the month of November when the silo bin was being filled with corn. Two rounds of tests were completed once in November 2013 and next one in 2014. The layout of LVDTs were changed in 2014 test as the test data of 2013 suggested some minor changes.

The silo bin was gradually filled with corns and the drying system was working all the time to keep the moisture content at a target value of 15%. The lateral displacements and strains of the side wall were measured by the LVDTs and strain gauges. The internal lateral pressure was determined by the load cell. The moisture content and filling rate data were collected from the control room of the bin operator (a role of paper log recorded by the dryer system). The wind speed, wind direction, and temperature data were acquired through the weather station. Test data was recorded every 5 minutes by the Daylite software. Complete filling process took five days with several pauses in the filling process (depends on how grains are brought by farmers and weather condition) and intermittent discharges (depends on whether or not a buyer arrives to buy corns) in between through the side discharge door which was located at nine meters above the top of concrete foundation.

3.7 MATERIAL TENSILE TEST

Two tensile coupons specimens according to ASTM E 8/E 8M-13a specifications (ASTM, 2014) were cut in the longitudinal direction of the sample corrugated side wall sheet. These specimens were then tested by a standard MTS load testing machine (see Figure 3.20) in accordance with ASTM E 8/E 8M-13a (ASTM, 2014) specifications to determine complete stress-strain behavior.
The tension coupon specimens were cut from the side wall of corrugated grade 50 class 1 steel sheet with the thickness of 15 gauges (1.79 mm), prepared and tested according to ASTM E 8/E 8M-13a specifications (ASTM, 2014). Subsize tensile coupon was chosen based on the thickness of the corrugated sheet. Two subsize tension specimens with gauge length of 25 mm and width of 6 mm were made as shown in Figures 3.21 and 3.22.
The actual thickness of the two tensile coupons was 1.60 mm to 1.625 mm instead of the nominal thickness of 1.79 mm. A clip-on extensometer of 25 mm (1 in) gauge length (see Figure 3.20) was mounted at the mid length of the specimen to determine the strain data. The extensometer was removed from the coupon specimen once ultimate stress value reached. The load was applied gradually using displacement control method.

3.8 SUMMARY

The experiment of filling test on the silo structure was to identify the deformation behavior of the silo and to validate the numerical modelling. During the test, according to the record of the weather station, the wind speed never exceeded 6 m/s and usual wind speed was about 5 m/s, the amount of precipitation at the test site was almost zero which means that the test procedure was under minor natural influence, and the highest and lowest temperature were 1.7 °C and -13.2 °C, respectively.
CHAPTER 4

EXPERIMENTAL RESULTS

4.1 GENERAL

This chapter discusses the results obtained from the test and the discussions based on these test results. The experimental results include the lateral displacement of the side wall measured by the LVDTs, hoop (circumferential) and vertical (longitudinal) strains of the side wall, and internal lateral pressure on the side wall determined from the load cell. This chapter also presents the result of material tensile test is presented in this chapter.

4.2 MATERIAL PROPERTIES

This section provides the tensile stress-strain plots of two coupon specimens which were tested in accordance with the ASTM (American Society for Testing and Materials) E8 standard (ASTM, 2014). The stress-strain plot of one coupon specimen which has a lower yield strength is shown in Figures 4.1 and 4.2. The stress-strain behavior of another coupon specimen is presented in Figures B.1 and B.2 in Appendix B.

Figure 4.1 Stress-Strain Behavior of Specimen 1
According to results of these two tensile material tests, the yield strengths of specimen one and two are 375 MPa and 415 MPa, respectively. The ultimate strengths of these specimens are 450 MPa and 483 MPa, respectively. The modulus of elasticity are 206 GPa and 214 GPa, respectively (see Table 4.1).

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity</td>
<td>206 GPa</td>
<td>214 GPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>375 MPa</td>
<td>415 MPa</td>
</tr>
<tr>
<td>Ultimate Tensile Stress</td>
<td>450 MPa</td>
<td>483 MPa</td>
</tr>
<tr>
<td>Yield Strain</td>
<td>2000 με</td>
<td>2000 με</td>
</tr>
<tr>
<td>Ultimate Strain</td>
<td>17.1 %</td>
<td>19.2 %</td>
</tr>
<tr>
<td>Fracture Strain</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
</tbody>
</table>
4.3 LATERAL DISPLACEMENTS

This section presents the lateral displacements of the side wall when the silo was filled to various levels. The lateral displacement was recorded when the silo was filled to five different levels. Plots of lateral displacement with height at five different filling statuses (35%, 53%, 65%, 82%, and 100%) are shown in Figures 4.3 to 4.7. In these figures, the height of each LVDT is measured from the top of the concrete foundation as shown in Figure 3.9 of Chapter 3.

The percentage of filling (filling status) refers to the percent of current volume of grains based on maximum volume capacity of silo which is 12459 m³. The maximum volume capacity was calculated using the area of bin floor and the distance between the bin floor and the silo eave. Thus, the percentage of filling also refers to the percent of current depth of the grains based on the maximum depth of the grains which is the distance between the bin floor and the silo eave.

The test results of different filling statuses were selected based on the record of filling rate (volume of corn per minute, $F$) and filling time ($T$) which were provided by the staff in the control room located beside the silo bin. The time of different filling statuses was determined by calculating accumulated volume ($V$) of the grains in the silo bin. The accumulated volume ($V$) was calculated and summed by filling rate times the filling time ($\sum F \times T$) which were recorded continuously by the dryer system in the silo. The discussion of horizontal displacement is provided next.
Figure 4.3 shows that the lateral displacements of the side wall increases as the height of silo increases up to about 1.5 m from top of the concrete foundation. However, lateral displacements of the wall decreases above the height of 1.5 m. The trend of decreasing in lateral displacement with the increasing height is mainly caused by the decreasing internal lateral pressure from the grains. It should be noted that the maximum displacement is not at the bottom of the silo rather, it occurs at about 1470 mm above the top of the concrete foundation. This is because the side wall in the bottom area was restrained by the inner steel floor at 467 mm height and concrete foundation. It can also be observed that the slope of curve changes at around the heights of 1.25 m and 2.5 m (see Figure 4.3). The lateral displacement at these two heights are relatively lower values than the lateral displacement at upper and lower heights. The reduced displacements at heights of 1.25 m and 2.5 m and this is mainly caused by the increased stiffness offered by the overlapping area on the side wall sheets. The same behavior of the reduced displacements at the heights of 1.25 m and 2.5 m can be observed in other four filling statuses (53%, 65%, 82%, and 100%) as
shown in Figures 4.4 to 4.7.

Figure 4.4 Lateral Displacement of Wall at 53% Filled Condition

Figure 4.5 Lateral Displacement of Wall at 65% Filled Condition
Figure 4.6 Lateral Displacement of Wall at 82% Filled Condition

Figure 4.7 Lateral Displacement of Wall at 100% Filled Condition
From Figures 4.3 to 4.7, it can be found that all the maximum lateral displacements occurred at about 1.5 meter from the top of the concrete foundation in all five filling statuses. All the lateral displacements under each filing status increased as the percentage of filling increased from 35% to 100% as shown in Figure 4.8.

![Figure 4.8 Maximum Lateral Displacements at Five Filling Status](image)

**Figure 4.8 Maximum Lateral Displacements at Five Filling Status**

From Figure 4.8, it can be observed that the growth of maximum lateral displacement of the wall is not linear. The slope of the curve decreases as percentage of filling (height of filling) increases. It is because the lateral pressure increased with a decreasing slope as the depth of grains inside the silo increased (see Figure 4.13) and this follows the Janssen’s theory (Janssen, 1895).

**4.4 STRAINS ON SIDE WALL**

This section provides the result of the hoop (circumferential) and vertical strains on the side wall measured at two different heights (0.5 m and 1.47 m). The strain results for the five different filling statuses (35%, 53%, 65%, 82%, and 100%) of the grain bin are shown in Figures 4.9 to 4.12. Also, comparison of the strain results at these two different heights is provided at the end of this section.
As shown in Figure 4.9, the vertical strain at 0.5 m height, the magnitude is positive until the bin was filled to 75% capacity, and then it becomes negative. It is because that the vertical stress was composed of a positive tension stress due to constrains offered by floor and negative compression stress resulting from friction. These two stresses work against each other. This positive vertical stress is mainly caused by the vertical tension stress from the constraint at the connection between the side wall and the bottom floor (see Figure 3.2 in Chapter 3). This negative compression stress is caused by the vertical friction stress from the grains as suggested by Janssen. The vertical strains at height of 0.5 m present positive value due to the tension stresses is larger than the compression stress until silo bin is 75% filled. Hence, the overall vertical (longitudinal) strains at height of 0.5 m present negative value when silo is filled more than its 75% capacity. This is due to the vertical compression stresses becomes larger than the vertical tension stress at this stage.

Further, the magnitude of vertical strain at 0.5 m height is below 50 micro strain (με). It is because that the magnitudes of vertical (longitudinal) compression stress and tension stress are close to each other. Thus, the magnitude of vertical strain is smaller at the height of 0.5
m if compared to the vertical strain at 1.47 m height (see Figures 4.9 and 4.10). This is because as the height of silo increases the effect of the constraints from the silo floor and also concrete foundation reduces.

![Figure 4.10 Vertical (Longitudinal) Strain at 1.47 m Height](image)

The vertical strain at 1.47 m height presents negative values for all stages of filling as shown in Figure 4.10. This is because that the stress at height of 1.47 m composed of only the vertical friction stress caused by grains. Furthermore, the magnitude of vertical strain increases as percentage of filling increases. It is because of that the grain vertical friction stress increases as the depth of grains increases (Janssen, 1895).

However, lateral pressure from grains creates positive value in hoop strains for both 0.5 m and 1.47 m heights as shown in Figures 4.11 and 4.12.
Both hoop strains at two these two locations show an increasing trend with an increase in the percentage of filling. This is due to the hoop stress generated from the lateral pressure of grains increases with the increase in percentage of filling. The hoop strain values at 0.5 m height are less than the hoop strain at the height of 1.47 m. The smaller value of hoop
strain at height of 0.5 m height is because of the vertical and lateral constraint resulted from the connection between the silo floor and the silo wall and also between the silo wall and concrete foundation. Further, the maximum vertical strain (-300 με) and hoop strain (650 με) of the side wall at two different heights (0.5 m and 1.47 m) are much less than the yield strain (2000 με) which was observed from the material tensile tests (see Figure 4.2). This indicates that the test silo experienced only elastic deformations at these two heights.

4.5 INTERNAL LATERAL PRESSURE

This section presents the resulting internal lateral pressure at 825 mm height measured from the top of silo steel floor as the silo was being filled by corn. The pressure data was collected at 825 mm from the bottom floor (see Figure 3.14 in Chapter 3). Lateral pressure was calculated by dividing the lateral force (measured by the load cell) with load cell contact area which is a circular steel disk of 90 mm diameter (see Figures 3.9 and 3.14).

![Figure 4.13 Internal Lateral Pressure at 0.825 m Height](image)

The internal lateral pressure increased with the percentage of filling due to the increased grain load. There are some fluctuations in the slope of the lateral pressure curve. It is because of that the silo bin was not continuously filled. There were some pauses in the filling process and also intermittent partial discharging occurred during the test. Thus, the
increase in pressure may be caused by the discharging, and the pressure decreases after stop discharging. The internal lateral pressure at the same height of 0.83 m was calculated and compared by Janssen’s equation (Janssen, 1895) in next chapter (see Chapter 5, Section 5.6 and 5.10).

All the test results (lateral displacement, strain, and lateral force) at different percentages of filling were determined by taking average of 20 to 30 test data. A typical test result determination of maximum lateral displacement at 53% filled condition is shown in Figure 4.14. There are 27 test data, and the standard deviation of these data is 0.0347 which is very small.

![Figure 4.14 Determination of Test Result](image)

**4.6 SUMMARY**

This chapter presented and discussed the lateral displacement, internal pressure, and strain which increased with the increase in grain load. In the circumferential direction of the side wall, the wall sheet was always under tension. However, compression stress occurred in the vertical direction along the side wall. The overlapping area on the side wall increased the local stiffness, resulting in a decrease in lateral displacement.
5.1 INTRODUCTION

Numerical simulation using finite element method is necessary to be carried on to analyze the structural behavior of silo bin. The experimental result was used to validate the FE model. Future parametric study can be accomplished using the validated model. However, the scope of this research does not include any parametric study.

A commercially available general purpose finite element (FE) analysis software, ABAQUS (SIMULIA, 2011), was used to develop FE model. This chapter discusses the development and validation of finite element model. In reality, the geometry and cross-section of most structural components of the silo tested in this research are too complex to be simulated and analyzed using finite element model (FEM). Thus, simplification to complex structure was employed into the silo finite element model to make the simulation running effectively.

5.2 MODEL PARTS SIMULATION

In reality, the side wall, stiffener column, and roof of silo structure are all made of thin steel sheets. Thus, every structural component was modelled using general purpose quadrilateral shell elements (S4R).

5.2.1 STIFFENER

The major structural components of the field silo tested in this study are vertical stiffener columns, side wall, and roof. A stiffener in FE model is shown in Figure 5.1.
The stiffener columns are connected to the silo side wall and in the perpendicular direction to the ground. For the first ten bottom side wall rings, the stiffener column consists of two different cross-sections (see Figures 3.6 and 3.7). For the remaining side wall rings, the stiffener consists of only one single cross-section (see Table 3.1). The cross section of the stiffener varies as the height change. The variation is due to the complex combination of different cross-section shapes. Therefore, stiffeners used in the field silo structure are too complex to simulate and it poses more difficulty in the mesh generation of the finite element model (FEM). Hence, the cross-sectional geometry of the vertical stiffeners were simplified keeping the moment of inertia of the cross-section in both x and y axes unchanged using simplified channel section. Section Builder software (SCAD Soft, 2013) was used as to obtain equivalent cross-section (see Figure 5.2).

The original thickness of the combined stiffener (W2P-BF-08 combined with W2PL-F-08) at the bottom most two rings is eight gauges (4.37 mm), with the moment of inertia about x (22) and y (33) axes being $1.72 \times 10^6$ mm$^4$ and $5.06 \times 10^6$ mm$^4$, respectively. After the
conversion to simpler cross-sectional geometry, the stiffener cross-section is defined as 105.6 mm wide (including the thickness) and 75.6 mm high (including the thickness) U-shaped channel section with a uniform thickness of 14.2 mm. The details of cross-section and geometry are shown in Figure 5.2.

![Diagram of actual and simplified cross-sections](image)

(a) Actual Cross-section  
(b) Simplified Cross-section

**Figure 5.2 Conversion of combined Stiffener W2PR-BF-08 and W2PL-F-08**

Table 5.1 shows the dimensional parameters of actual stiffeners and the dimensional parameters of their equivalent simpler U-shaped channel cross-sections.
### Table 5.1 Dimensional List of True and Equivalent Stiffeners

<table>
<thead>
<tr>
<th>Section Name of Stiffener</th>
<th>Thickness (gauge, mm)</th>
<th>$I_x(22)$ (mm$^4$)</th>
<th>$I_y(33)$ (mm$^4$)</th>
<th>Width of U-shaped Section (mm)</th>
<th>Height of U-shaped Section (mm)</th>
<th>Thickness of U-shaped Section (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2PR-F-10 with W2PL-F-10</td>
<td>10 gauges (3.57 mm)</td>
<td>$1.39 \times 10^6$ mm$^4$</td>
<td>$4.19 \times 10^6$ mm$^4$</td>
<td>105.6 mm</td>
<td>75.6 mm</td>
<td>10.7 mm</td>
</tr>
<tr>
<td>W2PR-F-10 with W2PL-F-12</td>
<td>10 gauges (3.57 mm)</td>
<td>$1.32 \times 10^6$ mm$^4$</td>
<td>$3.99 \times 10^6$ mm$^4$</td>
<td>105.6 mm</td>
<td>75.6 mm</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>W2PR-F-12</td>
<td>12 gauges (2.78 mm)</td>
<td>$7.18 \times 10^5$ mm$^4$</td>
<td>$2.45 \times 10^6$ mm$^4$</td>
<td>105.6 mm</td>
<td>72.2 mm</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>W2PSR-F-12</td>
<td>12 gauges (2.78 mm)</td>
<td>$6.62 \times 10^5$ mm$^4$</td>
<td>$2.27 \times 10^6$ mm$^4$</td>
<td>105.6 mm</td>
<td>72.2 mm</td>
<td>5.2 mm</td>
</tr>
<tr>
<td>W2PSR-F-14</td>
<td>14 gauges (1.98 mm)</td>
<td>$4.86 \times 10^5$ mm$^4$</td>
<td>$1.68 \times 10^6$ mm$^4$</td>
<td>105.6 mm</td>
<td>72.2 mm</td>
<td>3.7 mm</td>
</tr>
<tr>
<td>W2P-HF-14</td>
<td>14 gauges (1.98 mm)</td>
<td>$4.74 \times 10^5$ mm$^4$</td>
<td>$1.64 \times 10^6$ mm$^4$</td>
<td>105.6 mm</td>
<td>72.2 mm</td>
<td>3.6 mm</td>
</tr>
</tbody>
</table>

Note: The naming of stiffener as shown in Table 5.1 is adopted as suggested by the industry collaborator of this project, Lambton Conveyor Ltd. The detail explanation was given in Section 3.2.

#### 5.2.2 SIDE WALL

The entire wall of the silo is consisted of 17 layers of horizontal rings with gradually decreasing thickness with increasing height. The adjacent two corrugated steel sheets of same ring are connected by two columns of bolts with an overlapping area and each column of bolts has 21 bolts in it. The connection between two wall sheets of two adjacent rings is made of one row of 25 bolts (see Figure 3.5).

Due to the symmetry of the side wall, by importing the sketch of the corrugated side wall sheet (see Figure 3.5), the part of the wall was simulated with the forming type of revolution
on 360°. The full view of side wall in the FEM is presented in Figure 5.3.

![Figure 5.3 Side Wall Simulation in FEM](image)

The silo bin in the field is anchored to concrete foundation. The bin has a bottom steel floor which is 467 mm above the top of concrete foundation (see Figure 3.2). The conveyer and cargo care system (humidity adjustor) are placed in between the concrete foundation and the bottom steel floor. The connection between the side wall sheets and silo bottom floor was simulated in the FEM to restrain certain area which was screwed with the bin bottom floor. The bin bottom floor is directly supported by the concrete foundation and hence, the bottom floor was not simulated in the FEM.

5.2.3 ROOF

The roof component, which consists of steel sheets and inner support beams, was simulated in the FEM. The radius of the roof is 7.27 m and gradient of roof is 32°. The roof of the silo was simulated using a flat sheet instead of corrugated sheet to simplify the finite element model. Roof structure is supported by inclined beams and these beams are
connected to the top of the side wall ring. The stiffness of the inner roof beams has negligible effect on the lateral deformation of the bottom side-wall. Therefore, the roof and its inner beams were simplified by ignoring the beams and increasing the thickness of the roof sheets. The view of roof is shown in Figure 5.4.

![Figure 5.4 Roof Simulation in FEM](image)

### 5.3 MATERIAL PROPERTY

The nominal dimensions and nominal material properties were provided by the industry partner, Lambton Conveyor Ltd. The material of all the steel structural components conform to ASTM A653 SS GR 50 Class 1 (ASTM A653, 2013), which specifies 50 ksi (344 MPa) minimum yield strength, 65 ksi (448 MPa) minimum tensile strength, and 12% elongation in two inches (50.8 mm) gauge length. All the structural components, such as side wall sheets, roof, and stiffeners are made of same material. Two material tensile tests were carried out to determine actual mechanical properties (see Table 4.1). The true stress-true plastic strain behavior is shown in Figure 5.5. For the FE model, the lower of the two yield strengths was used in the FEM. The Young’s Modulus and Poisson’s Ratio were assumed to be 206 GPa and 0.3, respectively. The plastic material property was also modeled based on the same test data which are the true stress-strain curve obtained from the material tensile test as listed in the following Table 5.2 and as shown in Figure 5.5.
Table 5.2 List of Nodes on the True Stress-True Plastic Strain Curve

<table>
<thead>
<tr>
<th>Stress (kN/m²)</th>
<th>Plastic Strain (%)</th>
<th>Stress (kN/m²)</th>
<th>Plastic Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>385259</td>
<td>0</td>
<td>441821</td>
<td>3.833</td>
</tr>
<tr>
<td>393524</td>
<td>0.47222</td>
<td>448652</td>
<td>4.46191</td>
</tr>
<tr>
<td>398317</td>
<td>0.74637</td>
<td>456260</td>
<td>5.20549</td>
</tr>
<tr>
<td>403332</td>
<td>1.0316</td>
<td>468824</td>
<td>6.55968</td>
</tr>
<tr>
<td>411667</td>
<td>1.54235</td>
<td>480707</td>
<td>8.02679</td>
</tr>
<tr>
<td>416900</td>
<td>1.89012</td>
<td>489652</td>
<td>9.25595</td>
</tr>
<tr>
<td>422590</td>
<td>2.28894</td>
<td>502476</td>
<td>11.221</td>
</tr>
<tr>
<td>428614</td>
<td>2.73954</td>
<td>513117</td>
<td>13.0735</td>
</tr>
<tr>
<td>435579</td>
<td>3.30021</td>
<td>700000</td>
<td>50</td>
</tr>
</tbody>
</table>

5.4 ASSEMBLING

The silo FEM model was created in the global coordinate system. The y-axis was defined as the central vertical axis of the entire model. The radius of the side-wall is 7.27 m and the top height of the side wall is 19.0 m. The full-scale view of assembled model is shown in Figure 5.6.
All the stiffener sections were merged together as a stiffener column to simplify the assemble process. Intersecting boundaries (geometric edge) between original stiffener sections were retained to separate different geometry in order to assign the corresponding property section. Thirty two stiffener columns are uniformly spaced along the periphery of the silo wall. The roof of the silo is mounted on the top edge of the side wall. View of all 32 stiffener columns is presented in Figure 5.7.
5.5 CONSTRAINT DEFINITION

As every stiffener column of the real silo is connected to side wall using bolts, the constraint in between of the side wall and the stiffener columns in the finite element model was defined as “tie”. A surface-based (surface-to-surface) tie constraint was used to make the translational and rotational motion as well as all degrees of freedom equal for a pair of surfaces. The tie constraint between side wall and stiffener was simulated by constraining all the translational and rotational motion and degrees of freedom \((\theta_x, \theta_y, \theta_z, u_x, u_y,\) and \(u_z\)) of the nodes in the slave surface of the stiffener equal to the nodes in the master surface of side wall. Hence, there was no sliding and rotation in between of the stiffener column and the side wall. The constraint between side wall and stiffeners is shown in Figure 5.8.

![Figure 5.8 Constraint between Side Wall and Stiffeners](image)

The primary functional structural component of a silo is the side wall. Thus, entire web surface (the contact surface between stiffener and side wall) of the stiffener column was
defined as tie constraint to surface of the side wall of the silo. Thus, the surface of the stiffener column was tied to the side wall to prevent all translational and rotational motion between the side wall and stiffener column. The web surface of stiffener column was chosen as slave surface whereas the master surface was the outside surface of the side wall. Furthermore, the nodes on the bottom edge of a roof component were tied to the nodes on the top edge of the side wall. The node-based tie constraint was used to make only the translational motion and degrees of freedom equal for a pair of nodes. The nodes on the top edge of the side wall were chosen as master nodes and hence, and the nodes on the roof edge were assigned as the slave nodes. The constraint between side wall and roof is shown in Figure 5.9.

![Figure 5.9 Constraint between Side Wall and Roof](image)

5.6 BOUNDARY CONDITION

In the finite element model of the silo structure, the boundaries are located on the bottom edge of the side wall ring and the bottom edges of the stiffeners. The bottom most wall ring is mounted to the concrete foundation by bolts. Hence, there are two separate boundary conditions on the bottom most side wall ring. The first one is the connection with the concrete foundation and the next one is the connection to bottom steel floor. The boundary condition between side wall and the concrete foundation was fully fixed and as presented
in Figure 5.10. Hence, at each node on the bottom edge of side wall, all translational and rotational degrees of freedom were constrained \((\theta_x = \theta_y = \theta_z = u_x = u_y = u_z = 0)\). The bottom most ring and bottom most surface of all stiffener columns were bolted to the concrete foundation.

![Figure 5.10 Boundary Constraint between Side Wall and Concrete Foundation](image)

The boundary condition between side wall and bottom floor is presented in Figure 5.11. The rotational degrees of freedom were kept free \((\theta_x = \theta_y = \theta_z = 1)\); however, the translational degrees of freedom were set to zero \((u_x = u_y = u_z = 0)\) at the connection nodes between the bottom most side wall ring and the inner bottom floor. This was chosen because the floor of the silo is connected to the inside wall of silo by bolts (diameter of 9.525 mm) at a spacing of 238 mm.

![Figure 5.11 Boundary Constraint between Side Wall and Internal Bottom Floor](image)

For the stiffener column, the boundary condition was set as clamped by restraining all the displacements and rotations \((\theta_x = \theta_y = \theta_z = u_x = u_y = u_z = 0)\) at the nodes on the bottom edge of the stiffener column. This was chosen because each stiffener is rigidly
connected to the rigid concrete foundation. The boundary condition of stiffener is shown in the Figure 5.12.

![Figure 5.12 Boundary Constraint between Stiffener and Concrete Foundation](image)

5.7 LOAD DEFINITION AND DISTRIBUTION

In this finite element model, the primary load applied are the horizontal pressure \( p_h \) and vertical shear stress \( p_v \) from the corns inside the silo. These values were determined from Janssen Equation (Janssen, 1895) as follows.

\[
p_h = \frac{\gamma D}{4 \mu} \left( 1 - e^{-\frac{4 \mu K_j z}{D}} \right) \tag{5.1}
\]

\[
\mu = \tan \phi' \tag{5.2}
\]

\[
K_j = 1 - \sin(\phi) \tag{5.3}
\]

\[
p_v = \mu p_h \tag{5.4}
\]

where,

\( p_h \) = Normal pressure acting perpendicularly to silo wall surface

\( p_v \) = Shear stress acting along wall surface

\( \gamma \) = Specific weight of grain bulk = \( \rho \times g \)

\( \rho \) = Bulk density of grains

\( g \) = Acceleration due to gravity
\( D \) = Inside diameter of silo bin

\( \mu \) = Coefficient of sliding friction between bulk solid and wall surface

\( K_j \) = Janssen ratio of horizontal pressure to vertical pressure

\( z \) = Vertical coordinate = the depth of bulk inside of silo

\( \phi' \) = Angle of wall friction between bulk solid and wall surface

\( \phi \) = Angle of internal friction between bulk solids

The bulk density of corn (\( \gamma \)) was determined using the regression equation of bulk density of popcorn presented by Turgut and Bilge (2013) as follows.

\[
\gamma_{\text{popcorn}} = 895.77 - 5.10 \text{MC} \quad (R^2 = 0.98) \tag{5.5}
\]

where, MC is the moisture content (\%, d.b. = dry bulb).

The acceleration of gravity (\( g \)) is 9.8 m/s\(^2\). The silo cylinder diameter (\( D \)) is 14.55 m.

The static coefficient of friction for the corn on the galvanized steel (\( \mu_s \)) was determined from the regression equation developed by Turgut and Bilge (2013) as follows.

\[
\mu_s = 0.110 + 0.0272 \text{MC} \quad (R^2 = 0.93) \tag{5.6}
\]

The dynamic coefficient of friction between corn and cold rolled steel (\( \mu_d \)) was determined using the regression equations proposed by Bickert and Buelow (1966) as follows.

For \( 10 \leq \text{MC} \leq 17.5 \); \( \mu_d = 0.256 + (1.34 \times 10^{-3}) \text{MC} \) \tag{5.7}

For \( 20 \leq \text{MC} \leq 22 \); \( \mu_d = 0.153 + (6.67 \times 10^{-3}) \text{MC} \) \tag{5.8}

The average moisture content recorded by the controller of the silo in the field was 15%. Thus, the initial static (\( \mu_s \)) and dynamic (\( \mu_d \)) coefficients of friction were calculated from Equations (5.6) and (5.7) and the value for \( \mu_s \) and \( \mu_d \) are 0.518 and 0.2761, respectively. Thompson and Ross (1983) and Thompson et al. (1988) found that the friction coefficient

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(\(\mu\)) decreases with the increasing number of filling cycle. Hence, the true coefficient of friction (\(\mu\)) was determined using the pressure data recorded from the load cell inside of the silo bin and using Janssen’s equation (1895) at 100% filled condition. The true coefficient of friction (\(\mu\)) was calculated to be 0.432 using Janssen’s equation (Equation 5.1) after other variables were determined. Hence, the value of 0.432 determined for \(\mu\) lies within the range of static coefficient of friction (\(\mu_s\)) and dynamic coefficient of friction (\(\mu_d\)) as suggested by Turgut and Bilge (2013) and Bickert and Buelow (1966), respectively.

The angle of internal friction of popcorn (\(\phi_{pop}\)) was determined form the regression equation proposed by Turgut and Bilge (2013) as follows. This relationship was used to determine \(K_j\) using Equation 5.3 in this study.

\[
\phi_{pop} = 19.31 + 0.97 \text{MC} \quad (R^2 = 0.97)
\]  

(5.9)

Since the moisture content (MC) of the silo was recorded as 15%, the angle of internal friction of corn solids (\(\phi_{pop}\)) was calculated at 33.86 ° using Equation (5.9). Therefore, the Janssen ratio (\(K_j\)) was then determined using Equation (5.3) and the value is 0.44283. The load distribution and magnitude of internal pressure and frictional force are shown in Figures 5.13 and 5.14.

![Figure 5.13 Load Distribution on Side Wall](image)
5.8 Mesh Generation

General purpose quadrilateral shell elements with reduced integration (S4R) were used in this FE model. It is because the silo structure was made of thin steel sheets and the side wall and their symmetric geometry. The general-purpose shell element provides reliable and accurate solutions in all loading conditions for thin and thick shell problems. Reduced integration can be used in the symmetric quadrilateral elements to reduce the computational time. Meshing was separately applied on each single components because of the difference of geometry and size on different components. The view of mesh on roof, stiffener column, and side wall are presented in Figures 5.15 to 5.17.
Figure 5.15 Mesh on Roof

Figure 5.16 Mesh on Stiffener

Figure 5.17 Mesh on Side Wall
For the side wall, the meshing size was chosen to be 0.05 m (50 mm) along the circumferential direction. The element shape is quadric lateral, with the limitation of non-uniform corrugation, the mesh technique is “sweep”. The rest meshing properties of each part is listed in Table 5.3.

### Table 5.3 Mesh Property of Instance

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Meshing Size (mm)</th>
<th>Element type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffener Column</td>
<td>50</td>
<td>S4R</td>
</tr>
<tr>
<td>Roof</td>
<td>50</td>
<td>S4R</td>
</tr>
</tbody>
</table>

The last step in meshing is mesh verification which is used to check the analytical ability and the accuracy based on all the meshed element geometry properties (angle and size). It shows the number of elements, analytical errors (inability), and analysis warnings (inaccuracy) of every part instance. The following Table 5.4 lists these information of each part.

### Table 5.4 Parameters of Mesh Verification

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Element Number</th>
<th>Analysis errors</th>
<th>Analysis Warnings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side wall</td>
<td>685334</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Roof</td>
<td>157380</td>
<td>0 (0%)</td>
<td>4 (0.00350143%)</td>
</tr>
<tr>
<td>Stiffener Column</td>
<td>2353</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

The roof is conical in shape and hence, the size of element decreases rapidly near the top of the roof. Thus, the analysis warning only exists at the top of the roof as shown in Figure 5.18, and the percentage is very low.

![Figure 5.18 Analysis Warnings of Roof Meshing](image)
5.9 MESH CONVERENCE STUDY

Meshing nodes were distributed along the edges of a region to specify the target mesh density in that area of the instance. The mesh of the silo model part was automatically generated by ABAQUS CAE preprocessor using local seed by specifying global average element size. Different approximate global sizes for the element were chosen and tested and the length of element chosen are 50 mm, 100 mm, 150 mm, and 200 mm were used for mesh study. However, the other dimension (width) varied from six mm to 50 mm depending on the geometry. The comparison between results of different mesh sizes is presented in Figure 5.19. The processing (computational) time of FEM in each mesh size is presented in Table 5.5. The configuration of the computer is 64-bit Windows 7 operating system running on Intel® Core™ i7-3770 CPU @ 3.40GHz 3.40 GHz with 16 GB installed memory (RAM).

<table>
<thead>
<tr>
<th>Mesh Size (mm)</th>
<th>50 mm</th>
<th>100 mm</th>
<th>150 mm</th>
<th>200 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational Time (minutes)</td>
<td>68 mins</td>
<td>30 mins</td>
<td>13 mins</td>
<td>11 mins</td>
</tr>
</tbody>
</table>

From Table 5.5, it can be found that the FEM computational time decreases as the mesh size increases. It is because the number of elements decreases with increasing mesh sizes in FEM. As can be observed in Figure 5.19, the lateral displacement increases slightly as the element size is reduced. However, the difference between each mesh size is very small and negligible. Thus, these mesh sizes are all acceptable to use in the meshing process and the 50 mm size elements were finally chosen.
In Figure 5.19, the negative values in lateral displacement below the height of 0.5 m was caused by the effect of moment from the connection between the side wall and the bin floor.

5.10 FE MODEL DEVELOPMENT AND VALIDATION

In reality, stiffener columns were mounted to the side wall by using one vertical row of bolts (see Figure 3.7). However, in the finite element model, stiffener column was tied to the wall with the whole surface of the channel web. Hence, in FE model, a large area of the stiffener would be tied to the wall if entire web of stiffener is tied to the wall (Figure 5.20a). The tie constraint makes all translational and rotational motion and degrees of freedom equal for a pair of surfaces. This would introduce a higher stiffness to the side wall in FE
model. Hence, a thin vertical strip area of the stiffener column web surface was separated with the method of partition on geometry and only this narrow strip area was tied to the wall to avoid artificially higher stiffness (Figure 5.20b). According to the bolt diameter, the width of the strip area was chosen as one mm. Thus, the connection between the side wall and the stiffener column in the finite element model was developed by the partition of the strip area on the web surface. The comparison between previous and developed stiffener is shown in Figure 5.20.

![Figure 5.20 Previous and Developed Stiffener with Partition on Geometry](image)

(a) Full web area is tied  (b) only 1-mm wide trip area is tied

In the FE model, the side wall was consisted of a single corrugated steel sheets. In the field silo, the overlapping areas formed along four edges of every side wall sheet was modeled by doubling the area in the FE model. With consideration of the mechanics characteristic on the side wall sheet, the hoop overlapping area of each steel sheet takes significant influence on the lateral strain and displacement of the side wall. Thus, 16 overlapping rings, (between 17 layers of side wall rings) were modelled in the finite element model by doubling the thickness in the overlapping area. Each overlapping ring’s thickness was defined as the same amount of local steel sheet. According to the corrugation geometry of side wall sheet, the width of each overlapping ring is 50.8 mm (2 inches). The full-scale view of overlapping rings is shown in Figure 5.21.
Thickness adjustment was applied to the finite element model. From the material tensile test, it was found that the thickness of two coupons is 90 percent of the nominal value of the thickness. Thus, all the thickness in the FE model was reduced by ten percent.

The vertical bolt connection between two adjacent horizontal wall sheets of the bottom ring was close to the location of bottom most three LVDTs (see LVDTs 1, 2, and 3 in Figure 3.9). The vertical edge of the sheet was restrained by bolts and as a result additional constraint created from the bolted connection which reduced the displacements that were recorded by these three LVDTs. This edge effect was modelled in FE model by increasing the thickness of the entire bottom ring by 30%. The location of magnetic bases of the bottom three LVDTs are shown in Figure 5.22.
In this FE model, both nonlinear material and nonlinear geometry analytic techniques were used to model the structural behavior of the silo. It allows silo structure to go under a large deformation by introducing the geometric nonlinearity. It also provides the material nonlinearity to analyze the material behavior by defining the material properties and hardening rules. Full Newton’s method was used (which is a default solution technique in ABAQUS) in this FE model to solve the nonlinear equilibrium equations. The time history of the simulation consists of five steps, and each step consists of nonlinear analyses so that the solution of nonlinear path can be traced, the structural equilibrium is reached at the end of each increment. The detail explanations of the Newton's method are presented in ABAQUS user’s manual (SIMULIA, 2011).

5.11 COMPARISON OF FEM AND EXPERIMENTAL RESULTS

The comparison between results obtained from the finite element model and field test at five different levels of filling (35%, 53%, 65%, 83%, and 100%) are presented in Figures 5.23 to 5.34.
Figure 5.23 Comparison of Lateral Displacement at 35% Filled Condition

Figure 5.24 Comparison of Lateral Displacement at 53% Filled Condition
Figure 5.25 Comparison of Lateral Displacement at 65% Filled Condition

Figure 5.26 Comparison of Lateral Displacement at 83% Filled Condition
Figure 5.27 Comparison of Lateral Displacement at 100% Filled Condition

From the comparison between FEM and test result of lateral displacement under different percentage of filling as shown in Figures 5.23 to 5.27, the difference between test data and FE analysis varies in different heights and percentages of filling. This happens because of the dynamic loading effect. The silo bin was filled continuously during the test period with few cycles of unloading in between. Hence, the silo wall experienced dynamic coefficient of friction (\( \mu_d \)) would be more applicable in the FE model development. However, only static frictional coefficient (\( \mu_s \)) was used in this study. Thus, the difference mainly caused due to difference between the dynamic and static load. The difference at the two LVDTs above 2.5 meter height are relatively higher than the difference in data obtained from other LVDTs located below 2.5 m height. This is caused by the reduced rigidity on the area above second rigid anchor.

The comparison of maximum lateral displacement between FE model and field test at five levels of filled (percentage of filling) is shown in Figure 5.28.
Figure 5.28 Comparison of Maximum Lateral Displacement at Five Filled Levels

Figure 5.28 compares the maximum lateral displacement at five different levels of filling. It can be found from this figure that the maximum lateral displacement in FE model is smaller than the test data. This may be caused by the sliding effect from the gaps in between the bolts and the holes which connect two adjacent wall sheets in the same ring. The difference of maximum lateral displacement between FE model and test data is shown in Figure 5.29.

Figure 5.29 Difference of Maximum Lateral Displacement at Five Filled Levels
From Figure 5.29, it can be found that the difference of maximum lateral displacement between the FE model and test data varies in different filled conditions and the magnitude of these differences never exceed 0.22 mm. The fluctuation of these differences may be caused by natural factors like wind force, temperature change, and moisture change.

Comparison of hoop and vertical strains at two heights (0.5 m and 1.47 m) with five filled conditions are shown in Figures 5.30 to 5.33.

From Figure 5.30, it can be found that the difference in vertical strain at 500 mm height between test and finite element model (FEM) decreases as percentage of filling increases. However, the maximum of difference is smaller than 20 με. The relatively larger differences between test and FEM exists until the bin was 80% filled. This is caused by the complex constraint condition from the connection between the bin floor and the side wall. The FE model is not able to simulate the exact bolt connection between the bin floor and the side wall. The comparison of vertical (longitudinal) strain between FE model and field test at height of 1.47 m is shown in Figure 5.31.
The maximum and minimum differences between FE model and test occur at 65% and 83% filled conditions, respectively. The magnitude of the maximum difference on vertical strains is 40 με. It can be found that the vertical strain in field test becomes larger than the vertical strain in FE model at around 85% filled condition.
Figures 5.32 and 5.33 show comparison for hoop strains at 0.5 m and 1.47 m height, respectively. From these two figures, it can be found that the difference between FEM and test result are larger at the height of 0.5 meter. It is because of the complex boundary condition of the connection between the side wall and the inner bottom floor. In general, it is very difficult to simulate the same strain behavior, thus, the numerical model is mainly validated by the lateral displacement.

The lateral pressures on the side wall at 0.825 m height which were calculated from the Janssen’s equation and applied to the FE model are compared with the test data obtain in the field to validate the Janssen’s equation as shown in Figure 5.34.
From Figure 5.34, it is found that the lateral pressures calculated from Janssen’s equation correlate well with the lateral pressures obtained in the test. The small fluctuation in the test data is caused by the discharging in the test. Hence, this indicates that the static load equation presented by Janssen (1895) is valid.

5.12 SUMMARY

This chapter presented the numerical study on silo structure under static grain load. The finite element model developed by ABAQUS (SIMULIA, 2011) is able to simulate complicated structure behavior under static grain load, dead load, and live load caused by wind and snow. The FE model successfully simulated the structural behavior of the test specimen well. This model is the first one of its kind and this modeling technique can be used to develop FE models for other silo structures with a great confidence.
CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 GENERAL

This chapter summarizes the findings of the study and lists conclusions and the recommendations for future study.

6.2 SUMMARY

The major objective of this study was to undertake full-scale field tests for understanding the complex structural behavior of silo subject to grain loading by measuring the lateral displacements, strains, and lateral pressure on the side wall of a large silo in the field. A finite element model (FEM) was developed and validated using a general purpose commercially available finite element code, ABAQUS/Standard version 6.8 (SIMULIA, 2011) using the actual dimensions.

6.3 CONCLUSIONS

A series of conclusion are made based on this study as follows.

1. The maximum lateral displacement of the wall occurs at the height of 1.47 m from the top of the concrete foundation.
2. Janssen’ equation was found to be able to accurately predict the horizontal pressure load on the side wall.
3. The magnitude of hoop (circumferential) strain of the side wall increases as the percentage of filling increases. Hoop strains always remains positive which implies that the side wall is under tension in hoop (circumferential) direction.
4. The vertical (longitudinal) strains of the side wall become negative when the silo is fully filled. This indicates that the side wall is under compression in vertical
(longitudinal) direction.

5. All strains of the side wall are much less than the yield strain even when the silo is completely filled. This indicates that this silo structure experiences elastic deformation only when subjected to grain load.

6. The finite element model developed in this study was validated with the test data.

6.4 RECOMMENDATIONS

This study offered a lot of important enhancements toward the objectives of the project. However, more knowledge on the behaviour and structural assessment of silo structures is needed. Hence, following recommendations are made.

1. Failure mode analysis under side discharging condition, strong wind, and earthquake need to be carried out.

2. Parametric studies of different dimensions and load combinations can also be conducted for optimization of structural dimensions and various structural elements of various silos.
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APPENDIX A: STRAINS ON AND AROUND THE ENTRANCE DOOR

The test silo started being filled at the time of 0 day, it was 50% filled at time of 2.4 days, and it was fully filled at the time of 5 days as shown in Figures A.1 to A.4.

Figure A.1 Strains on the Entrance Door

Figure A.2 Strains on the Channel Beam on Door Frame
Figure A.3 Strains on the Side Wall below the Entrance Door

Figure A.4 Strains on the Side Wall above the Entrance Door
APPENDIX B: STRESS-STRAIN BEHAVIOR OF COUPON SPECIMEN 2

Figure B.1 Stress-Strain Behavior of Specimen 2

Figure B.2 Yield Stress at 0.2 % Offset Strain of Specimen 2
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