University of Southern Queensland

Faculty of Health, Engineering & Sciences

Behaviour & Design of Corrugations in Thin-Walled Silos

A dissertation submitted by

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Abstract

Thin-walled silos commonly store bulk materials such as grain, cement, and chemicals. The flow loads and corrugations in such silos are essential for their design and structural integrity. Flow loads refer to the forces and pressures exerted on the walls of a silo due to the flow of material stored inside. These loads can vary depending on the characteristics of the material (e.g., its density, cohesion, friction), the flow pattern (see Figure 1), and the discharge rate. Corrugations are the vertically oriented ribs or waves often found on the walls of thin-walled silos. These corrugations serve several purposes: structural support, increased wall strength, reduced friction, and aeration. This project aims to investigate the current design of thin-walled silos, develop models that identify stresses of silo walls, and explore potential changes to these designs to reduce and remove undesirable stresses.

The methodology of this project was done by using Strand7. It leverages finite element analysis to assess silo structural behaviour by simulating complex structures. Buckling and collapse load causes will be scrutinised in Strand7, and the stresses causing these failures will be identified and potentially removed. A 2.5m diameter, 6.7m high silo has been developed and shown the stresses that act in the various upper and lower bound flow loads. There have been several different stresses found, including buckling and collapse. This has been found to act locally around the lower section of the silo, most noticeably where the corrugation and the hopper overlap. Revised models are required to see if the potential stresses causing failures in the silos are removable. If they are, possible structural changes can be looked at to see if these stresses can be managed better in these silos.

The conclusions from this project are that thin-walled silos will always have some variety of stresses that will occur at varying stages of their use. Differing bulk solids produce different stresses that can be mitigated by additional structural elements but cannot be removed entirely from the design.

Certification of Dissertation

I certify that this dissertation's ideas, designs, experimental work, results, analyses, and conclusions are my own effort, except where otherwise indicated and acknowledged.

I certify that the work is original and has not been previously submitted for assessment in any other course or institution except where specifically stated.

Riley Doherty

[redacted]

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Nomenclature

A	Internal Cross-Sectional Area of Silo	m^2
a	Acceleration of Upper Mass During Pulse Motion	m/s^2
A_c	Cross Sectional Area of the Flowing Channel	m^2
A_{ch}	Area of Top of Internal Chute (When Full)	m^2
a_K	Lateral Pressure Ratio Factor	–
A_o	External Cross-Sectional Area of Silo	m2
A_{str}	Plan projected area of structural element	m2
A_w	Wall Cross Section Area per Metre	m2
a_ϕ	Angle of Internal Friction Factor	–
a_μ	Wall Friction Coefficient Factor	–
c_{vf}	Vertical Pressure Multiplier	–
D	Internal Silo Cross Section Diameter	m
d_c	Internal Silo Cross Section Diameter	m
d_e	Distance from Near Side Eccentricity Axis	m
H	Total Effective Height of Stored Bulk Solid	m
h	Height above Shock plane to bottom of surcharge	m
h_b	Total Effective Height of Stored Bulk Solid	m
h_c	Height of Vertical Walled Segment	m
H_{cr}	Critical Height	m
h_D	Height Above Discharge Outlet	m
h_l	Height of the Filling Cone or Wedge - Long Side	m
P_f	Flow Load	kPa

ϕ_{iu}	Effective Angle of Internal Friction – Upper	–
ϕ_{il}	Effective Angle of Internal Friction – Lower	–
ϕ_{im}	Effective Angle of Internal Friction – Mean	–
ϕ_{wu}	Wall Friction Angle – Upper	–
ϕ_{wl}	Wall Friction Angle – Lower	–
ϕ_{wm}	Wall Friction Angle – Mean	–
ϕ_r	The angle of Repose	–
Υ_u	Unit Weight of Grain – Upper	kN/m^3
Υ_l	Unit Weight of Grain – Lower	kN/m^3
Υ_m	Unit Weight of Grain – Mean	kN/m^3

Chapter 1

Introduction

1.1 Background

Bulk solids are essential to many sectors, from mining to agriculture. While the nature of the handling tasks and scale of operation vary from one industry to another and, on the international scene, from one country to another according to the industrial and economic base, the relative costs of storing, handling, and transporting bulk materials are, in most cases, very significant. Therefore, handling systems must be designed and operated for maximum efficiency and reliability (Roberts A 2023).

There are three types of storage for raw grain in the agriculture industry. There is brick ware storage, thin-walled steel silo storage and concrete silo storage. As the agriculture sector has developed and various other aspects in manufacture, installation and design, thin-walled silos have become the silo type of choice as cost, design and sizes are more flexible than different storage types.

In thin-walled silos, there are two main types of flow, mass and funnel. The mass flow requires the bulk solid to be in motion at every point in the bin when drawn towards the outlet. There is a bulk solid flow along the walls of the cylinder and the hopper. Mass flow guarantees the complete discharge of the bin contents at predictable flow rates. It is a 'first-in, first-out' flow pattern; when properly designed, a mass-flow bin can re-mix the bulk solid during discharge should the solid become segregated upon filling the bin. The mass flow requires steep, smooth hopper surfaces and no abrupt transitions or in-flowing valleys (Roberts, 2023).

Funnel flow occurs when a hopper has a slope that is too steep and the walls of the hooper are rough. In this scenario, the bulk solid creates a funnel through the centre, creating a “hooper shape” further up the silo. The flow is erratic and gives problems like segregation. The disadvantage of funnel flow is that a large amount of the material is “dead,” whereas it does not move when the outlet is open. The only real advantage to this flow is its protection to the walls. However, this does not outweigh the unsatisfactory ‘first in, last out ‘pattern the bulk solid follows, and in the case of grain silos, costs in the devaluation of the goods stored within the silo (Roberts 2023).

Overall symmetric silo shapes provide the best performance as the asymmetric hoops tend to lead to problems where particle sizes make predicting loads acting on the wall tough (Roberts 2023).

See the different flow patterns below.

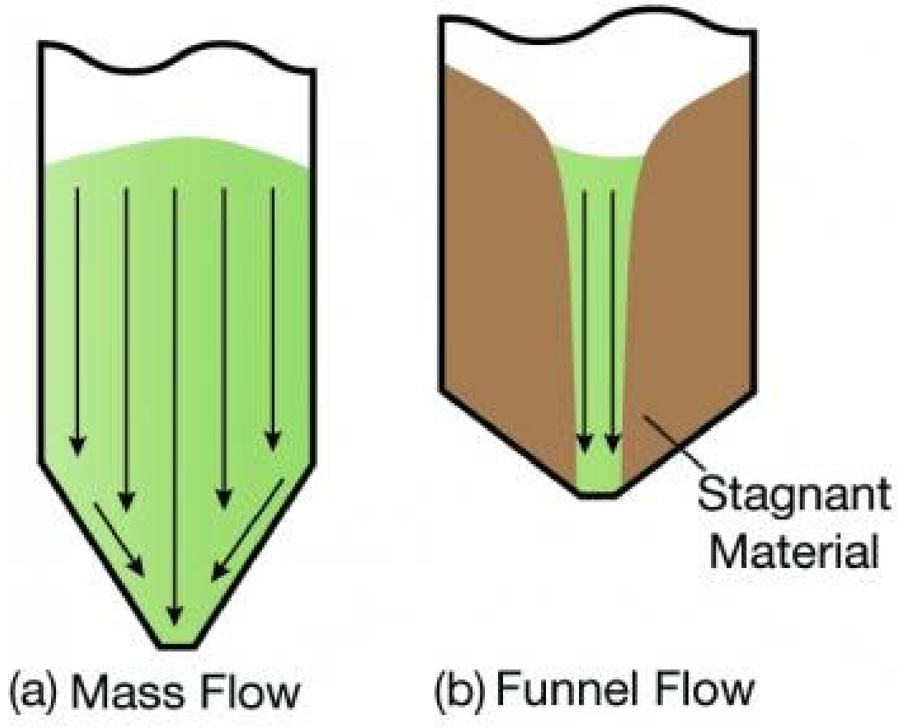


Figure 1: Mass and funnel flow visual.

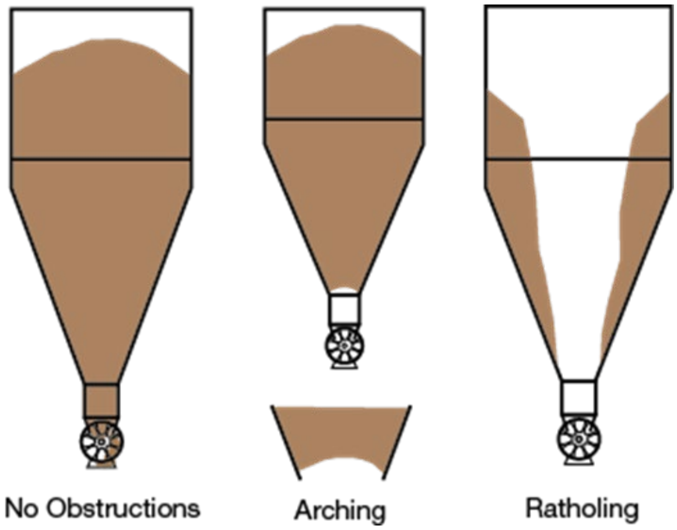


Figure 2: Different types of problems that case funnel flow.

1.2 Project Aims and Objectives

This project aims to investigate the current design of thin-walled grain silos, develop models that identify stresses of silo walls and explore potential changes to these designs to reduce and remove undesirable stresses. These unwelcome stresses can be subjective to what the use of the silo is. However, in grain soils, the recommended flow mass flow creates forces within the silo that can affect the walls positively and negatively as the grain moves from top to bottom. This research aims to draw off knowledge and previous case studies to continue to grow an understanding of how grain flow can impact thin-walled silos.

Design calculations will be conducted to determine the reactions from various grain types to complete the analysis of the effects of mass and funnel flow. They will be followed by finite element modelling using Strand7 to show and calculate desirable and undesirable stresses that can be potentially managed using different designs or removed through design. Different wall designs will be tested to determine if certain corrugations or thicknesses can reduce the reactions.

The objectives for the project are as follows:

1. Complete initial research into the current silo design and the stresses that must be overcome for a successful strategy.

2. Establish characteristics of bulk grain and determine upper and lower bounds of surface and bulk characteristics using information learnt from the TUNRA Bulk Solids Workshop.
3. Research current industry silo designs and models to establish a base model for initial analyses.
4. Analyse Strand7 models of current silos and determine the structural responses over the mechanical characteristics of the bulk solids.
5. Explore the number of stresses, select the critical aspects of bending stress cycle range, collapse load and corrugation shape, and refine the design using more in-depth corrugation and thicknesses.
6. Further development of Strand7 models to refine the stresses and analysis causes and solutions to reduce undesirable areas of stress to determine the best possible design types to remove and utilise stresses acting on the silo walls.
7. Conclude changes in the current silo design that could benefit the industry.

Appendix A – Project Specification shows the endorsed project specification.

1.3 Project Significance

In thin-walled, many stresses can act due to the storage and handling of bulk solids. This project's significance is to analyse and evaluate the stresses and determine if certain wall corrugations help reduce, remove, or potentially worsen these stresses and what will cause failure when overstressed.

Some of the primary stresses that impact thin-walled silos are as follows:

1. Axial Stress

Axial stresses are mainly caused due to the weight of the stored bulk solid pressing down onto the bottom of the silo. The stress distribution is up the vertical axis and increases with the height of the silo, with the worst axial stress being found at the bottom of the silo and around the hooper.

2. Hoop Stress

Hoop stress is caused by the radial pressures exerted by stored bulk solids on the walls of the silo. The stresses act tangentially along the wall surface and are at its highest towards the bottom of the silo.

3. Bending Stress

Occurring in the walls of the silo due to the weight of the stored bulk solids, bending stresses also are affected by external loads. The priorities are usually worse around the hooper and roof of the silos but also act near supports and the internal support bands within the silo wall. These stresses can fail the silo structurally if the wall and other supports are insufficient.

4. Shear Stress

These stresses occur in the walls of the silo as the bulk solids exert lateral forces or when different forces are acting along the border. Sliding or shearing of the wall materials can occur, and excessive amounts of stress can cause failure of the silo.

5. Buckling Stress

Due to buckling loads, tall and slender silos are likelier to fail. The instability of the silo walls under compressive loads from the bulk solids causes the buckling stresses. High levels of buckling stresses can cause poorly designed silos to deform the walls or, in severe cases, collapse the silo.

6. Dynamic Stress

Vibrations, impact loads during bulk solid discharge and filling, and wind loads cause dynamic stress. The most likely failure is fatigue in the silo walls, typically over time and prolonged loads.

The major stresses that will be analysed are bending stress, cycle fatigue effects, and collapse load, which can cause the wall corrugation to collapse or fail in many ways. From the six listed stresses, axial, bending, shear, and buckling will most likely be the most analysed, and the types of corrugations will provide potential problems and solutions to these stresses.

The main aim of this project is to understand how these stresses are impacted by and resolved in the design and analysis of thin-walled grain silos. The design of silo wall corrugation will also be elevated and analysed to see what stresses are the defining stresses, if certain corrugations can reduce or even remove these pressures, and if new designs can work.

1.4 Overview of Dissertation

This dissertation is as follows:

Chapter 1 introduces the research project topic, provides background to the project's development, highlights the significance, and defines the aim and objectives.

Chapter 2 contains the literature review outlining the history of silo technology and advancements and gaps in this knowledge. The methodology for the project and the relevant standards for silos and bulk solids is also provided.

Chapter 3 highlights the history of bulk solid knowledge and how the design loads for the project will be conducted. This identifies the load cases in the upper and lower bound scenarios and explains how these will be used in the modelling stage.

Chapter 4 briefly discusses the modelling set-up for the project and explains the process for the models used.

Chapter 5 provides the results for various load cases and explains the analysis of the silo models. This chapter will also explore other types of wall corrugation and bulk solids.

Chapter 6 concludes the dissertations with a summary of the main findings and suggests further work in silo and bulk solid storage.

Chapter 2

Literature Review

2.1 History of Silos

Grain silos have been used for centuries and have been used to store and protect many types of grains from the elements. “Silo” comes from the Greek word “siros,” which translates to “food storage pit.” Ancient ruins and texts show that the Greeks were using silos as far back as the 8th century BC and a site of Tel Tsaf shows evidence of silos in the 5th century BC. In Asia, a silo pit was the favoured way of storing grain; throughout Turkey, Persia and Malta, large pits were used to preserve grain on massive scales.

Around the 19th century, ground silos were developed. 1873 Fred Hatch invented and built the first upright wooden silo in Spring Grove, Illinois, USA. They were initially made of wood and stone; modern techniques required concrete or steel to hold larger quantities and be much more significant.

Silos are vital to agriculture as they allow grain storage for animal feed or temporary holding without spoilage. Silos hold various bulk solids, including grain, cement, and coal. A bulk solid is a solid that is a loose and dry commodity. It consists of many particles and granules of different sizes (and can also have different compositions and densities) grouped to form a bulk.

The first above-ground silo in Australia was built in 1918 in a small country New South Wales town called Peak Hill. This silo was made of concrete, and the Peak Hill silos are currently operating. However, in modern agriculture, Australian farmers have moved to thin-walled steel silos for various reasons, including cost, manufacturing and size compared to their concrete counterparts. However, country towns in Australia with sizeable regional grain farms have large concrete tower silos to collect grain from the surrounding region and store the grain until it can be transported to be processed.

2.2 History of Silo Research

Mass Flow

Mass flow in thin-walled grain silos is the movement of the bulk solid during the emptying of the silo. Mass flow in bulk solid storage is a uniform flow that empties the silo in a first-in-last-out pattern. The principle is that it is a constant motion when the material is released rather than different layers or channels. This flow pattern avoids the formation of stagnant zones and blockages. The thin walls help with the flow as the low friction coefficient helps to create the motion.

The benefits are that the grain within the silo is never in storage for a long time. The grain keeps its value and can be sold or feed for animals when required. For silo design benefits, mass flow helps reduce the structural elements of the bin by leaving large forces in a singular position of the silo for prolonged periods, and that discharge is much more controllable when emptying. The benefits of mass flow and the want to create it can require aids to discharge. Mainly, the incline of the hooper is correct for the bulk solid to be able to slide, but also mechanical systems can be used to achieve this pattern. These aids help promote mass flow by reducing wall friction on the bulk materials.

Design considerations for mass flow consist of having the correct cone angle and dimensions of the outlet to avoid blockages. These factors ensure efficient flow and avoid problems such as bridging and ratholing (Roberts 2023).

Funnel Flow

Funnel flow is another typical flow pattern in thin-wall, bulk solid storage silos. Also referred to as ratholing, this flow pattern occurs when material moves in a non-uniform manner and a central column form that has a faster flow than the bulk solids near the walls. The cause of funnel flow happens during filling as the bulk in the centre region has increased pressure due to the pressure from the new material. When the silo empties, the centre column has a higher discharge rate and leaves the silo first in a first-in, first-out flow pattern. This creates a funnel of “dead material” that stagnates at the bottom of the silo and can only be removed by forcing it out from inside or outside the silo (Roberts 2023).

The non-uniform flow leads to inefficient discharge, segregation, and structural problems. The problems with the bulk solid being stored in a silo with funnel flow occur in material quality and consistency. Spoilage, causing degradation, can result from exposure to moisture and air due to the stagnant material sitting there for unknown amounts of time. In certain bulk solids like cement, this may not be as serve as it can be in grain silos, as the value of the grain is determined by its quality. Segregated material can also occur from the stagnant material and can add stress to the bottom of the silo and the hooper, along with the machinery and other structures the solid must pass through.

The structural problems that can arise from the pressure are far more erratic than mass flow. The centre column places higher pressure on the silo walls higher up the silo than in the mass flow, where the pressures occur closer to the hopper at the bottom. This places extra stresses typically avoided in grain silos to be higher and wider in diameter to hold more grain. These pressures can cause structural failures in the walls. If the silo has not been designed for these stresses during filling, unwilling and can be increased in high winds. Overcoming funnel flow is advised for grain silos due to the loss in quality in the dead zones of the silo (Sadowski 2010).

The techniques avoid funnel flow if the silo has not been designed. Installing vibration systems and air pads can help promote the bulk solid to flow uniformly and remove stagnant areas of material. Steeper hooper angles and a wider outlet can make the bulk solid within the silo flow uniformly. The geometry of the silo needs to be directly related to the type of bulk solid within the silo and the angle of repose of the bulk movements. Lastly, a change in discharge rates when filling and emptying can be beneficial to relieve the pressures on the centre region of the silo.

Wall Corrugation

The walls of thin-walled grain silos are usually corrugated steel sheets. These are used to enhance the structural integrity and stability of the silo, and the additional strength and rigidity help it to withstand the large forces exerted both internally, from the store bulk solids and externally, from wind and other forces.

The type of corrugation type that is selected depends on several reasons, such as the purpose, the properties of the bulk material and the conditions of the site the silo will be placed. Several types of corrugation are used for thin-walled silos, and they all have different advantages and applications. Manufacturers and engineers need to factor in the differences in silos and what the appropriate corrugation type is required for a certain project. The correct corrugation can result in optimal performance of the silo and can improve the lifespan of the structure if used for the designed purpose.

There are three main corrugation types that all have various strengths. The trapezoidal shape corrugation is a popular choice when designed for thin-walled silos. The design is a series of trapezoidal shape ridges that run around the diameter of the silo and can be of various dimensions. The ridges help to distribute the stresses on the side walls throughout the wall and help to reduce the bending and buckling of the silo and have a well-known strength and efficiency in silo walls.

Annular corrugation is another type that results in enhanced structural support around the circumference of the silo. The design of the annular corrugation is circular or ring-shaped ridges, which help to resist the radial pressures exerted by the bulk solids. To help combat funnelling or bridging, annular corrugation can be used. Another type of silo used is a convex or concave corrugation. Curved ridges on the silo wall offer like the trapezoidal shaped corrugations but are not as widely used. There are also many variations of these three types of corrugation, but all the same principles apply. The corrugation usually is around 800-900mm sheet and is screwed together. There is also a support band in most silos where the sheets are screwed together to give the screws more tolerance to tearing or ripping out of the sheets.

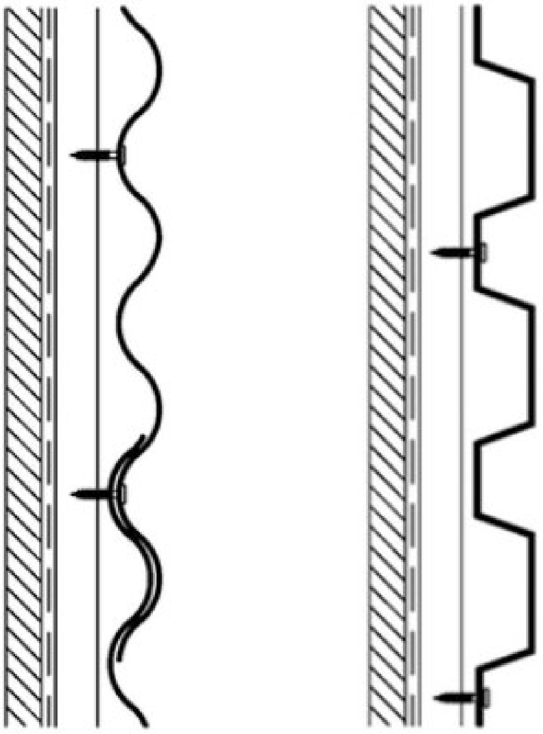


Figure 3: A typical convex/concave and trapezoidal corrugated sheet is above.

2.3 Brief Bulk Solids Research

Grain movement refers to the flow and behaviour of the grains (or bulk) stored in a silo structure. The movements of bulk solids can be very uniform or non-uniform, as already mentioned. However, some certain scenarios and implications impact the flow, and this is from the bulk itself.

Bulk solid has essential properties that must be carefully analysed to help flow through the silo. The major property is the angle of repose and the maximum angle at which a pile of granular material remains stable while flowing. Large outdoor storage systems (under tarps, etc.) use the angle of repose to understand how high the storage pile can be and how the solid can be removed later.

The angle of repose is impacted by many aspects of the bulk solid. Particle size and shape greatly influence the angle of repose, as smaller particles have lower repose angles than large bulk solids. This is because the particles have more surfaces to bind together more efficiently. This is the same principle for irregularly shaped particles and rough surfaces as interlocking to other particles is easier, increasing the angle of repose. Grains such as corn and wheat have an angle of repose ranging from 28 degrees to high 30s (wheat is 28 degrees), whereas clay has an angle of repose around 45 degrees. This can also be due to the density of the particles, as heavier particles enhance the ability of the material to interlock better.

Other aspects, such as cohesion and moisture content, help increase the angle of repose as wet or fine powders typically stick together better than dry and larger particles. Also, the material of the walls inside the silo needs to have friction that can help the material form a base, but that can also create problems with funnel flow where it is either not designed for or required. Overall, the angle of repose requires the correct mix of the above factors to help the bulk solids have the design of hopper, chutes, and silo walls to make handling and storing the material as easier as possible. This will also massively reduce the chances of arching, bridging or dead zones appearing within the silo, which can exert excess stress not previously designed.

Understanding grain movement within the silo and how such aspects as the angle of repose help to design a silo for the required pressures correctly. Getting efficient and correct flow patterns is key to having a safe and profitable silo. Filling techniques, friction and discharge rates are all aspects that must be designed and controlled carefully to prevent damage to the stricture and the bulk solids it holds.

Filling a silo with bulk solids is where initial pressures occur, and this filling can be the initial cause of problems with flow in the silo. As the grain is filled from the top, a conical pile is created at the centre of the silo and sits at the angle of repose. After the silo has been filled, the settlement of the bulk solid causes voids to be filled, and the bulk density is increased. This can cause compaction and flow problems that make it difficult for the grain to flow out of the chute. One of these problems is bridging, which creates an arch over the hopper as the material compacts and becomes cohesive. These blockages can only be removed by completely emptying the silo and using vibrations and other techniques. Moisture and temperature can also affect the chances of bridging and stagnant zones.

2.4 Relevant Silo Standards

In Australia, thin-walled silos are governed by specific standards and guidelines to ensure their safe design, construction, and operation. The primary standard that addresses the requirements for thin-walled silos is AS 3774-2016 "Steel Structures" - Part 6: "Cold-formed steel structures."

AS 3774-2016 provides guidelines for designing and constructing cold-formed steel structures, including thin-walled silos. This standard covers various aspects, including material selection, structural design, fabrication, erection, and maintenance. It aims to ensure the structural integrity and safety of thin-walled silos throughout their service life.

Some key provisions and requirements outlined in AS 3774-2016 for thin-walled silos include:

Design Loads: The standard specifies the design loads, including dead loads, live loads, and environmental loads, that must be considered during the design process. These loads are determined based on factors such as the material stored, location, and intended use of the silo.

Material Selection: AS 3774-2016 provides guidelines for selecting materials for thin-walled silos. It outlines the properties and characteristics of steel materials, including minimum yield strength, ductility, and corrosion resistance.

Structural Design: The standard provides design criteria and methodologies for calculating the structural capacity of thin-walled silos. It covers stability, strength, buckling, and deformation considerations. Designers must follow specific equations and procedures to ensure the structural adequacy and stability of the silos.

Fabrication and Construction: AS 3774-2016 includes provisions for fabrication and construction practices. It outlines requirements for welding, fastening, and connection details to ensure the integrity of the silo structure during fabrication and erection.

Maintenance and Inspection: The standard emphasises the importance of regular maintenance and inspection of thin-walled silos. It provides guidelines for conducting assessments, identifying potential issues, and carrying out necessary repairs or maintenance activities to ensure the ongoing safety and performance of the silos.

It is essential for designers, engineers, and builders involved in thin-walled silo projects in Australia to comply with AS 3774-2016. Adhering to this standard helps ensure the structural integrity and safety of the silos, minimising the risk of failures and accidents.

It is worth noting that standards may be periodically revised or updated to incorporate new research findings, technological advancements, and industry practices. Therefore, it is crucial to refer to the latest standard version and consult with relevant authorities or professional bodies to ensure compliance with the most up-to-date requirements for thin-walled silos in Australia.

2.5 Gap in Silo Research

Thin wall silos are crucial in storing bulk materials across various industries, including agriculture, mining, and construction. These structures offer advantages such as cost-effectiveness, easy assembly, and efficient space utilisation. However, despite their widespread use, there are significant gaps in research about thin wall silos. This article aims to explore and highlight these gaps, emphasising the need for further investigation and providing insights into potential areas of study. By addressing these gaps, researchers and engineers can enhance the design, construction, and performance of thin wall silos, improving safety, increasing efficiency, and better utilisation of resources.

One of the primary gaps in thin wall silo research lies in structural analysis and design. Although numerous studies have focused on conventional silos, limited attention has been given to the behaviour and performance of thin wall silos under different loading conditions. Further investigation is required to understand the structural response, failure modes, and load distribution mechanisms specific to thin wall silos. Researchers can develop accurate and reliable design guidelines, load models, and failure criteria for these structures by conducting advanced numerical simulations, experimental studies, and field measurements.

The material properties of the stored bulk materials greatly influence the behaviour of thin wall silos. However, comprehensive research is lacking in investigating the interaction between the stored material and the silo structure. Understanding the flow characteristics, consolidation behaviour, and pressure distribution of different materials within thin wall silos is crucial for designing efficient discharge systems and preventing undesirable phenomena such as arching, ratholing, and segregation. Further research is needed to explore the properties of a wide range of materials, including powders, granular materials, and cohesive solids, and their effects on the structural integrity and overall performance of thin wall silos.

Thin wall silos are subjected to various environmental factors such as temperature variations, moisture ingress, and chemical exposure. However, the influence of these environmental effects on the durability and long-term performance of thin wall silos remains inadequately explored. Investigating the effects of temperature differentials, cyclic loading, corrosion, and material degradation is crucial to ensure the structural integrity and serviceability of these silos. Furthermore, research focusing on developing protective coatings, moisture control measures, and corrosion-resistant materials can significantly extend the lifespan of thin wall silos and reduce maintenance costs.

Seismic events pose significant challenges to the safety and stability of thin wall silos. Although research on the seismic behaviour of conventional silos exists, limited attention has been given to the specific characteristics and vulnerability of thin wall silos during earthquakes. In-depth studies are required to investigate the dynamic response, failure mechanisms, and retrofitting strategies for these structures. Advanced modelling techniques, shake table tests, and field investigations can provide valuable insights into the behaviour of thin wall silos under seismic loads, leading to the development of robust design guidelines and retrofitting solutions to enhance their earthquake resistance.

Thin wall silos are essential for bulk material storage, yet several significant research gaps hinder their optimal design, performance, and durability. The identified gaps in structural analysis and design, material properties and behaviour, environmental effects and durability, and seismic performance and retrofitting emphasise further investigation. Bridging these gaps through advanced numerical simulations, experimental studies, and field measurements will pave the way for improved design guidelines, enhanced safety measures, and cost-effective solutions for thin wall silos. Addressing these research gaps will not only improve the understanding of the complex behaviour of these structures but also contribute to more efficient and sustainable storage solutions across various industries.

A study by Adam J. Sadowski and Michael Rotter discusses thin-walled silos, and the following is the conclusion of the study. The flow channel size significantly impacts the behaviour of a slender, thin-walled metal silo during eccentric pipe flow discharge. The predictions derived from finite element (FE) analysis differ based on whether the analysis is geometrically linear or nonlinear. While small flow channels have a mild effect on the silo's behaviour under realistic modelling conditions, medium and large flow channels adversely affect it. Geometric nonlinearity causes the silo wall to spread more circumferentially, allowing it to bear a significant portion of the compressive stresses generated during abnormal discharge. This reduces peak compression and enhances the silo's resistance to buckling. Eccentric pipe flow forms eigenmode-affine imperfections, which stiffen the cylinder against circumferential bending and improve its buckling strength. However, these imperfection forms are unsuitable for this load condition design. Similar behaviour was observed in previous studies regarding axisymmetric weld depression. Based on the findings, it can be concluded that this structure is not significantly affected by imperfections during eccentric pipe flow, or undiscovered exotic imperfection forms may lead to significant sensitivity and a negative relationship (Sadowski, Rotter 2012).

2.6 Strand7 Modelling

Strand 7 will be the modelling software used for the project. The software will be provided by Osborn Consulting Engineers (see Appendix C – Resources). The models and drawings so certain-sized silos will also be provided by Osborn Consulting to have correct and modern silo dimensions. The use of Strand 7 and other software is the leading advancement in the design of silos and many other industries.

The analysis of silos is most done using finite element systems like Strand 7. The software can evaluate the structural behaviour of the silo. Finite element analysis (FEA) is based on a numerical method and uses simulation on complex structures modelled in the software. The response to the various scenarios is processed by the FEA system, calculates stress distribution and deformation, and can show the failure methods and causes when used correctly (Golshan 2021).

In this project, the stresses, deformation, and failure modes will be used to identify certain weaknesses and areas that can be improved on its current and potentially new corrugation designs. The causes and results of buckling a collapse load will be the main areas looked at using the Strand7 software. Using the results with various techniques and bulk grains, an optimised design and usage can be evaluated and show if corrugation types, thickness, and internal supports can aid structural performance or negatively make the silo less safe (Golshan 2021).

The process that will be used in the analysis during the project will be quite simple and will be as follows:

1. Modelling: The modelling will begin in SolidWorks software and see a small portion of the silo (around 15 degrees) drawn in 3d. In SolidWorks, the shape, and dimensions of the hooper and the different wall types will be drawn and exported to Strand 7. In Strand 7, the shape will be rotated and copied to complete, and the full silo and the height will be determined by how many 800 mm-900 mm wall sections are placed.
2. Analysis: the analysis setup and solution will be the main area of the project. The model analysis will show the stresses from various static and dynamic loads and will be found from load cases such as filling, emptying, and/or a variety of live loads, including wind and collision loads. The analysis will be done to show how the silo will react in different situations and with varying materials and corrugations to determine what case the worst and best loads. The solution will offer the silo structure and its worst deformation and where certain stresses are heightened due to the various load cases. This will help show what can be improved in the silo design and evaluate what can and cannot be done with the limitations of the silo geometry. Potential failures and the overall performance of the silo structure will be analysed, and the model will then be redefined to help determine the best-case stresses.

Chapter 3

Design Loads Due to Bulk Solids

3.1 Introduction

TUNRA have done highly detailed analysis and studies into all aspects of bulk solids handling. This includes the loads affecting the silo bin walls during filling, storage and emptying. The following is the summary of the studies presented during the TUNRA Bulk Solid Workshop.

This study employs design guidance calculations outlined in the Australian Standard, AS3774:1996 - Loads on Bulk Solids Containers, and the European Standard, EN.1991.4.2006, Eurocode 1 - Actions on Structures - Part 4: Silos and Tanks. Additionally, various technical papers are reviewed and interpreted to comprehend potential silo quaking loads in the case study. These calculations are then conducted to determine the anticipated dynamic loads impacting the internal structure during the silo's unloading process through the bottom outlets. Notable papers include works by Roberts, A.W., such as "Basic Principles of Bulk Solids Storage, Flow and Handling" (1998), "Flow Dynamics or 'Quaking' in Gravity Discharge from Bins" (2002), and others, which collectively contribute to understanding silo behaviour.

Before the primary calculations for internal structural pressures, preliminary estimates are carried out to comprehend the silo loads originating from normal operations. These calculations align with AS3774:1996, Section 6 - Determination of Normal Service Loads, and EN.1991.4.2006, Section 5 - Loads on the Vertical Walls of Silos.
Section 6.10 of AS3774:1996 provides calculations for specific scenarios related to internal structural elements within the stored solid. These scenarios encompass vertical, horizontal,

and frictional tractions on interior structural features. The calculations illustrate that the pressures experienced by the silo walls are transferred to internal structures, sometimes with an amplification factor. Since EN.1991.4.2006 lacks a distinct method for calculating pressure on internal structures, the approach from the Australian Standard is adopted.
In the case study, a worst-case scenario assumes eccentric discharge as a potential contributor to structural failure. This form of release, which is not symmetric through the silo's centre axis, generates additional pressure changes on the walls. Calculations in AS3774:1996, Section 6.5, and EN.1991.4.2006, Section 5.2.4, analyse the impact of eccentric discharge. A similar methodology from AS3774:1996 is extended to the results from the European Standard, with eccentric discharge pressures applied to internal structures.
The technical papers by Roberts, A.W. and collaborators provide insights into the magnitude and frequency of dynamic pulses resulting from silo quaking in different scenarios.
All calculations in the report assume the silo is filled with wheat. Although there are minor variations in bulk material properties among different standards and technical papers, efforts are made to ensure each set of calculations aligns with the relevant technical resource. This provides meaningful comparisons can be drawn between results. Significant disparities in material properties are noted and adjusted for consistency in the analyses.

AS 3774-1996 is an Australian Standard titled "Loads on Bulk Solids Containers." It provides guidelines and recommendations for determining the loads on bulk solids containers, such as silos, bins, and hoppers, due to the weight of the stored bulk materials, including the loads imposed by the material itself and the environmental conditions. The standard applies to the design and construction of bulk solids containers, considering the properties of the stored material, the environmental conditions, and other relevant factors.

It defines various loads and load combinations that should be considered in the design, including the dead load (weight of the container and its contents), live load (additional loads due to factors like vibration or dynamic forces), and environmental loads (wind, snow, seismic, etc.), AS 3774-1996 guides determining the properties of bulk materials, including their density, flow characteristics, and angle of repose. These properties are crucial for calculating loads accurately. The standard outlines the design considerations for bulk solids containers, such as selecting appropriate materials, designing structural elements, and using safety factors. It specifies how different loads should be combined to determine the maximum loads the container may experience. This helps ensure that the container is designed to withstand worst-case scenarios. It emphasises documenting the design process, including load calculations and material properties, to facilitate compliance verification and future maintenance.

It is important to note that standards like AS 3774-1996 are crucial for ensuring the safety and reliability of bulk solids containers, especially in industries where storing granular or powdered materials is common, such as agriculture, mining, and manufacturing. Compliance with such standards helps prevent accidents, structural failures, and material losses. However, standards may be updated over time, so checking for the latest revisions and any specific requirements or modifications that may apply to your situation is essential.

3.2 Calculation of Loads

The subsequent computations adhere to the guidelines specified in the Australian Standard, AS3774:1996 – Loads on Bulk Solids Containers. Since the flow characteristics for wheat are not explicitly addressed within these standards, specific attributes used in the ensuing calculations are estimated, drawing insights from AS3774, EN.1991.4 and prior industry expertise. The particulars of these wheat attributes, instrumental in computing the loads, can be found in Section 3.4.1.1 and Section 3.4.1.2, respectively.

This section is dedicated to completing the subsequent calculations, which serve as crucial inputs for the finite element analysis of both the silo and its internal structure:

1. Normal wall pressures during discharge (Section 3.4.1.6)
2. Frictional traction on vertical walls during discharge (Section 3.4.1.7)
3. Vertical pressures in stored solid during discharge (Section 3.4.1.8)
4. Normal wall pressures during eccentric discharge (Section 3.4.1.9)
5. Vertical loads on internal structures during discharge (Section 3.4.1.10)
6. Horizontal loads on internal structures during discharge (Section 3.4.1.10)
7. Frictional traction loads on internal structures during discharge (Section 3.4.1.10)
8. Horizontal loads on internal structures during eccentric discharge (Section 3.4.1.10)

The remaining sections of this segment, encompassing various tables of calculations and pertinent information, play a pivotal role in determining the computations above. The above sections and the following data will be entered into used to calculate the loads on the silo in upper and lower-bound cases through a spreadsheet that has been designed by Osborn Consulting Engineers. Table 1 refers to the variables used to create the initial and flow loads for the silo. Table 2 covers the dimensions of the base silo that will be analysed. The silo will be 5.1m high (between hooper and cone, wall segments) and will have a diameter of 2.5m. This silo would replicate an average silo being used on an average farm across Australia. There are many more silo sizes, which may be included later in the research. The figure below this shows where these details are found in a silo. Table 3 consists of the wall corrugation roughness that will be incorporated into the calculations of the design loads that will be analysed. This roughness calculations can be found in Section 2 of AS3774:1996.

Table 1 - Characteristics Values of Wheat (AS3774:1996, Table 3.1)

Unit Weight of Grain – Upper:	*ϒu*	=	9	kN/m3
Unit Weight of Grain – Lower:	*ϒl*	=	7.5	kN/m3
Unit Weight of Grain – Mean:	*ϒm*	=	8.25	kN/m3
Effective Angle of Internal Friction – Upper:	*ϕiu*	=	32.0	°
Effective Angle of Internal Friction – Lower:	*ϕil*	=	26.0	°
Effective Angle of Internal Friction – Mean:	*ϕim*	=	29.0	°
Wall Friction Angle – Upper:	*ϕwu*	=	30.0	°

Wall Friction Angle – Lower:	ϕwl	=	18.0	°
Wall Friction Angle – Mean:	ϕwm	=	24.0	°
The angle of Repose:	ϕr	=	23/34	°
Vertical Pressure Multiplier:	*cvf*	=	1.4	

Table 2 - Geometric Parameters of Silo - Australian Standards (AS3774:1996, Section 2)

Height of Vertical Walled Segment	hc	5.1	m
Internal Silo Cross Section Diameter	dc	2.5	m
Hopper Half Angle	alpha	30	degrees
Outlet Diameter		1	m
Roof Angle	beta	30	degrees
Leg Length	hl	3.6	m
Height of Roof Above Toe	hr	0.721688	m
No. of Sheets	no. Sheet	6	
No. of Legs	no. Colum	10	
Clause 2.1.2 (A1 < 1 < A2 < 3 < A3)	hb/dc	2.630361	A2
Clause 2.2.1	beta<phir	ok	
Height of Filling Cone Peak	hs	0.530594	m
Height of Reference Surface	ho	0.176865	m
Effective Surface	hb	6.575903	m

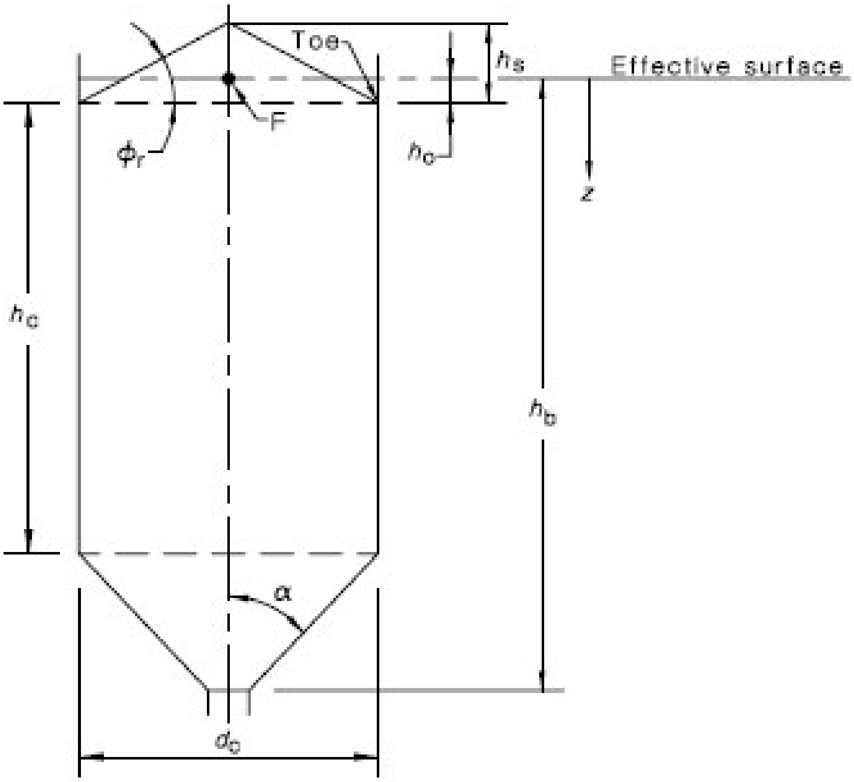


FIGURE 2.6 CHARACTERISTIC GEOMETRIC PARAMETERS

Figure 4 – This figure refers to Table 3. The figure shows what the letters mean in terms of where they are found in a silo.

Table 3 - Wall Roughness of Silo - Australian Standards (AS3774:1996, Section 2)

		Lower	Upper	
Angle of Wall Friction	Phiw	15	25	D4
Angle of Hopper Wall	Phiw_h	15	25	D4
Depth of Smooth Wall	x2	0.36	m	
Depth of Corrugated Wall Sheet	y1	0.035	m	
	u2	0.0886076		
	u3	0.9113924		
	mui	0	0	
	muw	0.2679492	0.466308	
	mueff	14	23.02497	

		Lower	Upper	
Angle of Wall Friction in Calc	Phiw	13.7	23.0	degrees
Angle of Hopper Wall in Calc	Phii	0	0	degrees
	Phiw_h	15	25	degrees

Below are various tables from AS3774-1996 related to the above table.

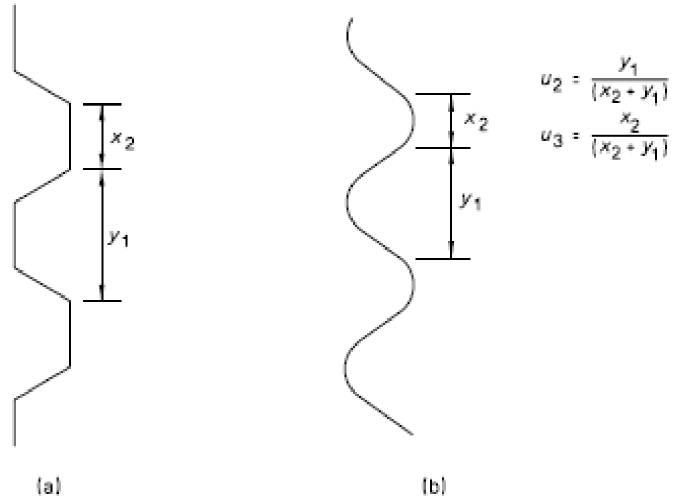


FIGURE B1 DIMENSIONS OF PROFILE SHEETING

Figure 5: From AS3774-1996, showing the requirements for dimensions of sheeting.

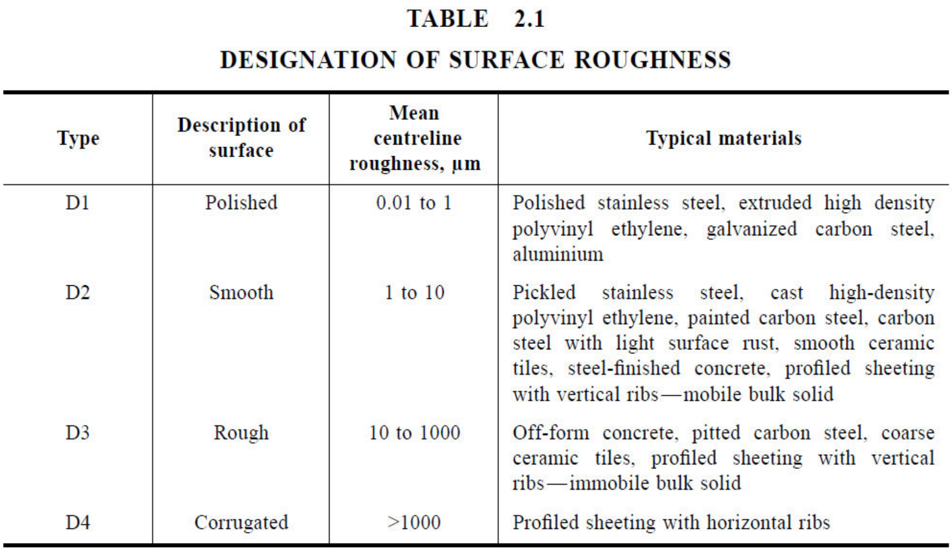


TABLE 2.1
DESIGNATION OF SURFACE ROUGHNESS

Type	Description of surface	Mean centreline roughness, µm	Typical materials
D1	Polished	0.01 to 1	Polished stainless steel, extruded high density polyvinyl ethylene, galvanized carbon steel, aluminium
D2	Smooth	1 to 10	Pickled stainless steel, cast high-density polyvinyl ethylene, painted carbon steel, carbon steel with light surface rust, smooth ceramic tiles, steel-finished concrete, profiled sheeting with vertical ribs—mobile bulk solid
D3	Rough	10 to 1000	Off-form concrete, pitted carbon steel, coarse ceramic tiles, profiled sheeting with vertical ribs—immobile bulk solid
D4	Corrugated	>1000	Profiled sheeting with horizontal ribs

Figure 6: From AS3774-1996, showing Table 2.1 of the surface roughness.

Table 4: Showing required inputs into an Excel spreadhseet for the project. See this spreadsheet in Appendix H.

C1 Description: Axisymmetric path where the centre of gravity of the flowing material roughly coincides with the vertical container axis, e.g., circular container with concentric discharge opening.			
Wall Material of Silo:	=	Horizontal corrugations – non profiled sheet roughness D2 - galvanised sheet)	(Clause 2.1.5, AS3774:1996)
Description of Wall Surface:	=	Smooth	(Table 2.1, AS3774:1996)
Mean Centreline Roughness:	=	1 to 10 µm	(Table 2.1, AS3774:1996)
Flexibility Description:	=	Rigid (Type E1)	(Clause 2.1.6, AS3774:1996)

<table>
<tr><td>Continuity of Walls Type:</td><td>=</td><td>F1</td><td colspan="2">(Clause 2.1.7, AS3774:1996)</td></tr>
<tr><td colspan="5">F1 Description: Two-way continuous walls, e.g. fully welded steel containers and reinforced or prestressed concrete containers with a minimum of 0.35% vertical reinforcement.</td></tr>
<tr><td>Cross Section Type:</td><td>=</td><td>Round (Type G1)</td><td colspan="2">(Table 2.2, AS3774:1996)</td></tr>
<tr><td>Characteristic Dimension:</td><td>rc</td><td>=</td><td>2.74</td><td>(Table 2.2, AS3774:1996)</td></tr>
<tr><td>Discharge Outlet Type:</td><td>=</td><td>H1/H3</td><td colspan="2">(Clause 2.1.9, AS3774:1996)</td></tr>
<tr><td colspan="5">H1 Description: Centrally located circular or square discharge outlet and designed for uniform flow across the entire outlet area. H3 Description: Eccentrically placed circular or square discharge opening, or a series of such openings around circumference. (Leads to Eccentric Flow and Non-Uniform Loads on the Container).</td></tr>
<tr><td>Flow Promotion Method:</td><td>=</td><td>Gravity (Type J1)</td><td colspan="2">(Clause 2.1.10, AS3774:1996)</td></tr>
</table>

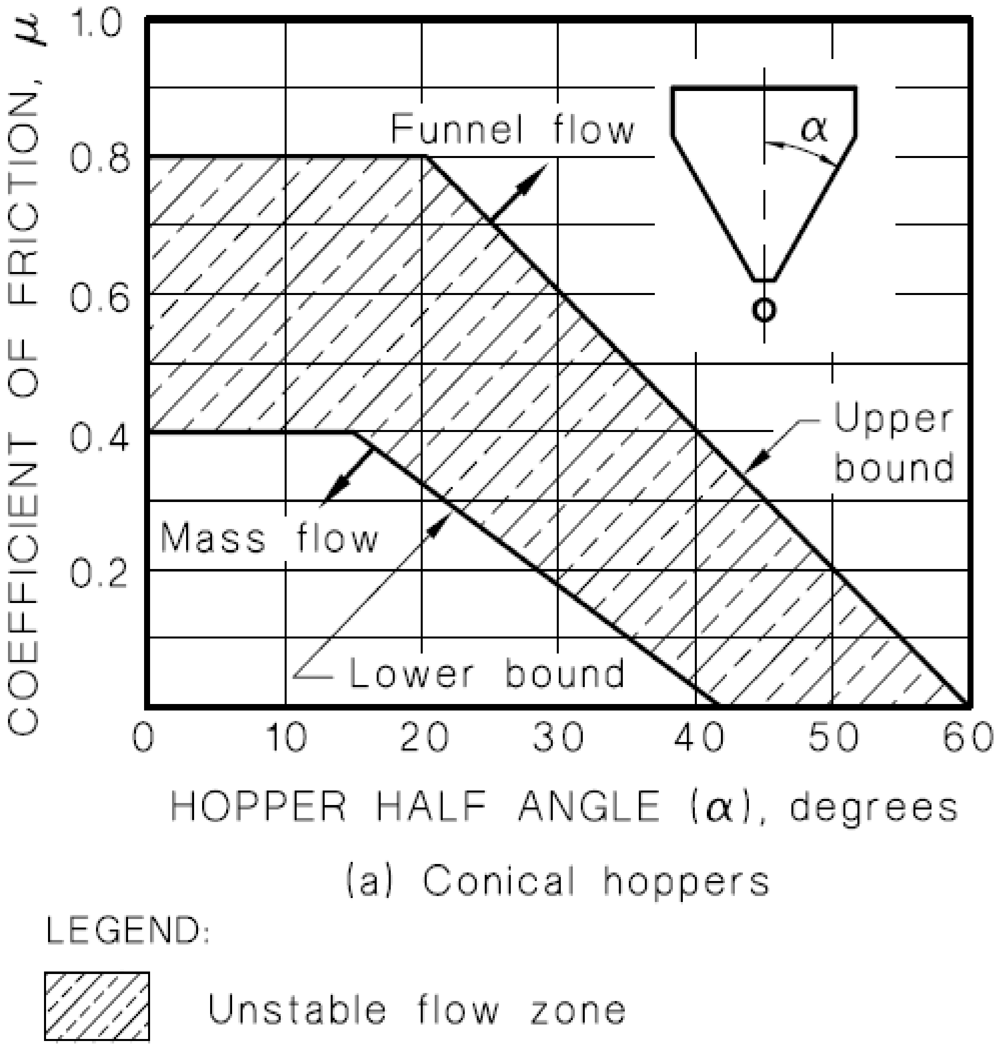


Figure 7: Showing the relation of coefficient of friction and flow patterns.

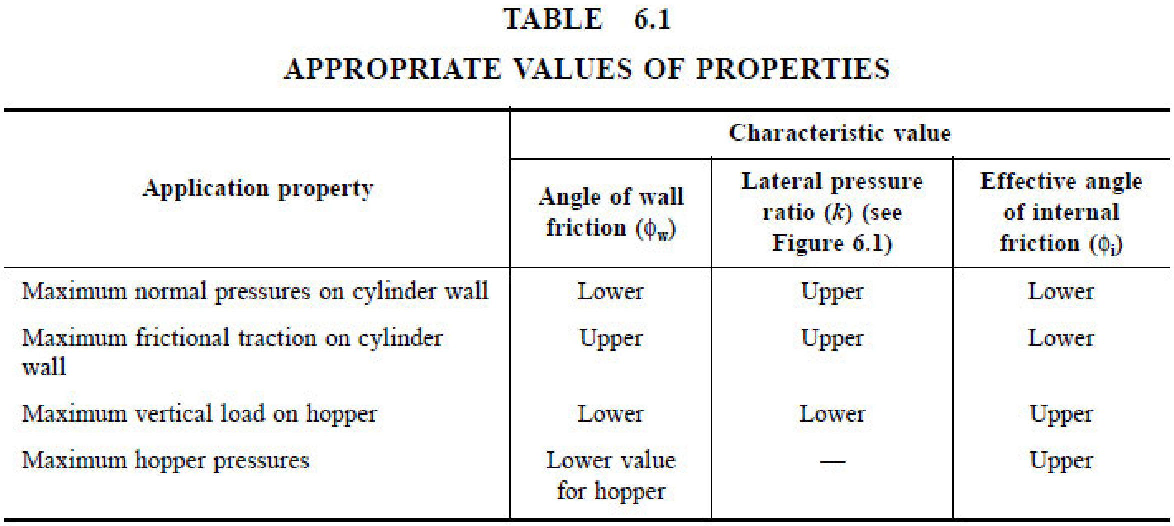


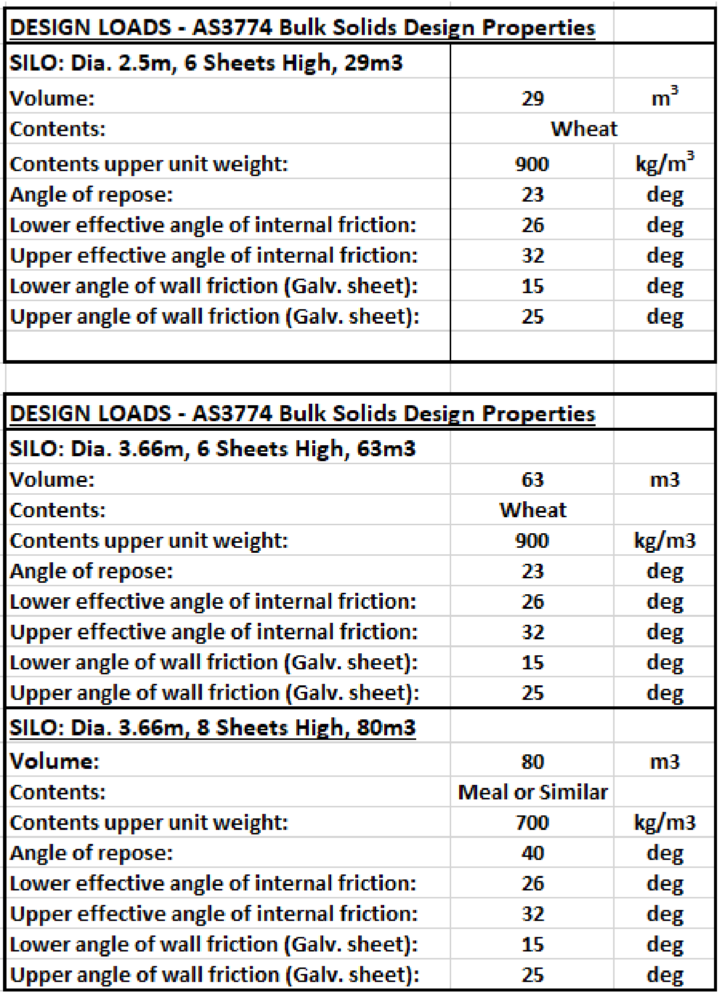
TABLE 6.1

APPROPRIATE VALUES OF PROPERTIES

Application property	**Characteristic value**		
	Angle of wall friction (ϕ_w)	**Lateral pressure ratio (k) (see Figure 6.1)**	**Effective angle of internal friction (ϕ_i)**
Maximum normal pressures on cylinder wall	Lower	Upper	Lower
Maximum frictional traction on cylinder wall	Upper	Upper	Lower
Maximum vertical load on hopper	Lower	Lower	Upper
Maximum hopper pressures	Lower value for hopper	—	Upper

Figure 8: Table 6.1 of AS3774-1996 showing the values of properties for application.

Table 5 – Design Properties Tables



DESIGN LOADS - AS3774 Bulk Solids Design Properties		
SILO: Dia. 2.5m, 6 Sheets High, 29m3		
Volume:	29	m^3
Contents:	Wheat	
Contents upper unit weight:	900	kg/m^3
Angle of repose:	23	deg
Lower effective angle of internal friction:	26	deg
Upper effective angle of internal friction:	32	deg
Lower angle of wall friction (Galv. sheet):	15	deg
Upper angle of wall friction (Galv. sheet):	25	deg

DESIGN LOADS - AS3774 Bulk Solids Design Properties		
SILO: Dia. 3.66m, 6 Sheets High, 63m3		
Volume:	63	m3
Contents:	Wheat	
Contents upper unit weight:	900	kg/m3
Angle of repose:	23	deg
Lower effective angle of internal friction:	26	deg
Upper effective angle of internal friction:	32	deg
Lower angle of wall friction (Galv. sheet):	15	deg
Upper angle of wall friction (Galv. sheet):	25	deg
SILO: Dia. 3.66m, 8 Sheets High, 80m3		
Volume:	80	m3
Contents:	Meal or Similar	
Contents upper unit weight:	700	kg/m3
Angle of repose:	40	deg
Lower effective angle of internal friction:	26	deg
Upper effective angle of internal friction:	32	deg
Lower angle of wall friction (Galv. sheet):	15	deg
Upper angle of wall friction (Galv. sheet):	25	deg

3.3 Load Cases

Out of the four possible load cases, three of these cases have been highlighted as the worst cases from the silo design. Using clause 6.2 of the AS3774-1996, the lower-lower, upper-lower, and lower-upper cases have been selected as the worst three cases.

Section 6 guides the design of hoppers used for storing bulk solids. Hoppers are containers with sloping walls that facilitate the flow of bulk solids, such as grains, powders, and granular materials. The standard outlines various types of hoppers, including conical hoppers, wedge hoppers, and pyramidal hoppers. Each class has different design considerations and characteristics, and the definitive guides selecting the appropriate type for a given application.

Section 6 discusses the flow patterns of bulk solids within hoppers. It covers concepts such as mass flow and funnel flow, which are essential for designing hoppers that ensure reliable and efficient discharge of materials. The standard recommends designing hoppers, including the angle of repose (the angle at which the material naturally settles) and the angle of internal friction (the angle at which the material starts to slide). These angles are crucial for determining the hopper's geometry.

Section 6 discusses the design of hopper outlets, including the size and shape of openings. It emphasises the importance of ensuring that the outlet size and geometry promote reliable material flow without blockages or rat-holing (material flow channelling). Section 6 addresses the structure of hopper design, including calculating stresses and loads that hoppers may experience due to the weight of the stored material and other forces. Proper structural design is crucial to ensure the safety and integrity of the hopper. The standard also touches on the design of supporting structures for hoppers, including the need for adequate foundations and helps to bear the weight of the hopper and its contents.

Overall, Section 6 of AS 3774-1996 provides essential guidance for the design of hoppers used in storing and handling bulk solids, focusing on ensuring efficient material flow and structural integrity. Engineers and professionals involved in bulk solids handling can refer to this section to help design hoppers that meet industry standards and requirements.

The following tables (Tables 6, 7 and 8) and graphs (Figures 9, 10 and 11) are the design loads for the models. The tables show the initial and flow forces for the three cases as well as regular and friction forces in kPa.

Case	LL			
	INITIAL FORCES		FLOW FORCES	
	Normal	Friction	Normal	Friction
z (m)	kPa	kPa	kPa	kPa
0.00	0.00	0.00	0.00	0.00
0.48	1.75	0.50	2.90	0.60
0.96	3.35	0.96	5.54	1.15
1.44	4.80	1.38	7.94	1.66
1.92	6.12	1.76	10.12	2.11
2.40	7.32	2.11	12.12	2.53
2.88	8.42	2.42	13.93	2.90
3.36	9.42	2.71	15.58	3.25
3.84	10.33	2.97	17.08	3.56
4.32	11.16	3.21	18.45	3.85
4.80	11.91	3.42	19.70	4.11
5.28	12.59	3.62	20.83	4.34
5.28	20.24	5.42	32.60	8.74
5.44	21.24	5.69	31.17	8.35
5.60	22.23	5.96	29.64	7.94
5.76	23.23	6.22	27.99	7.50
5.93	24.23	6.49	26.23	7.03
6.09	25.23	6.76	24.34	6.52
6.25	26.23	7.03	22.30	5.98
6.41	27.22	7.29	20.11	5.39
6.58	28.22	7.56	17.75	4.76

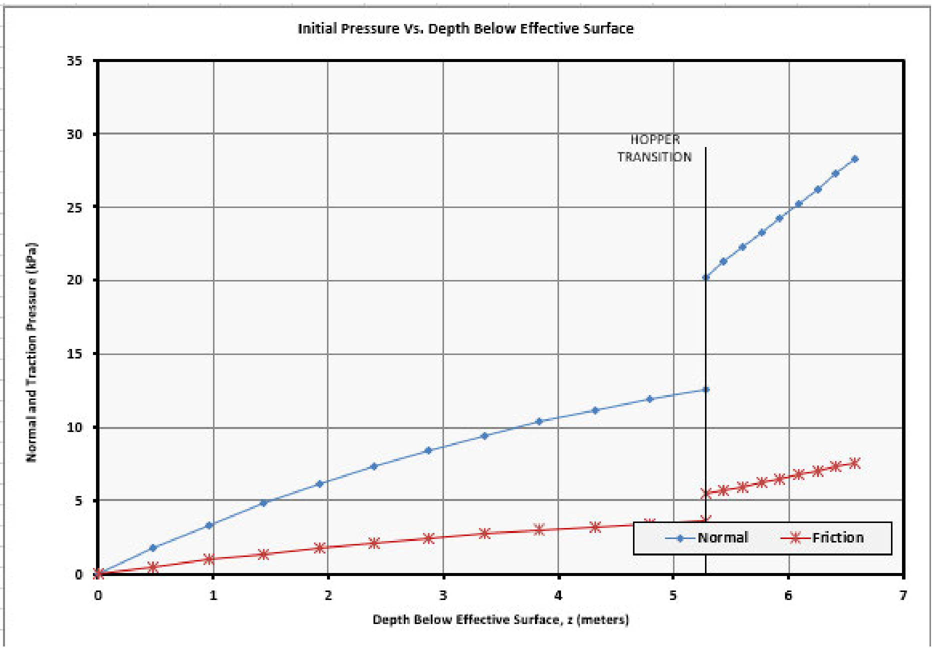
Table 6 – Lower/Lower Bound Load Table (2.5m Dia. Wheat – 6 Sheets)

Case	LU			
	INITIAL FORCES		FLOW FORCES	
	Normal	Friction	Normal	Friction
z (m)	kPa	kPa	kPa	kPa
0.00	0.00	0.00	0.00	0.00
0.48	1.45	0.42	2.41	0.50
0.96	2.80	0.80	4.63	0.97
1.44	4.05	1.16	6.69	1.40
1.92	5.20	1.49	8.60	1.79
2.40	6.27	1.80	10.37	2.16
2.88	7.26	2.09	12.00	2.50
3.36	8.17	2.35	13.52	2.82
3.84	9.02	2.59	14.92	3.11
4.32	9.80	2.82	16.21	3.38
4.80	10.53	3.03	17.41	3.63
5.28	11.20	3.22	18.53	3.86
5.28	17.70	8.25	25.52	11.90
5.44	18.51	8.63	24.95	11.63
5.60	19.32	9.01	24.28	11.32
5.76	20.13	9.39	23.49	10.95
5.93	20.94	9.76	22.59	10.53
6.09	21.75	10.14	21.54	10.05
6.25	22.55	10.52	20.34	9.49
6.41	23.36	10.89	18.96	8.84
6.58	24.17	11.27	17.37	8.10

Table 7 – Lower/Upper Bound Load Table (2.5m Dia. Wheat – 6 Sheets)

	INITIAL FORCES		FLOW FORCES	
	Normal	Friction	Normal	Friction
z (m)	kPa	kPa	kPa	kPa
0.00	0.00	0.00	0.00	0.00
0.48	2.33	1.12	3.85	1.34
0.96	4.19	2.01	6.93	2.42
1.44	5.69	2.73	9.41	3.28
1.92	6.88	3.31	11.39	3.97
2.40	7.84	3.77	12.97	4.52
2.88	8.61	4.14	14.24	4.96
3.36	9.23	4.43	15.26	5.32
3.84	9.72	4.67	16.08	5.60
4.32	10.12	4.86	16.73	5.83
4.80	10.43	5.01	17.26	6.01
5.28	10.69	5.13	17.68	6.16
5.28	12.14	3.25	19.57	5.24
5.44	13.14	3.52	19.32	5.18
5.60	14.14	3.79	18.95	5.08
5.76	15.14	4.06	18.45	4.94
5.93	16.14	4.32	17.80	4.77
6.09	17.14	4.59	17.00	4.55
6.25	18.13	4.86	16.02	4.29
6.41	19.13	5.13	14.86	3.98
6.58	20.13	5.39	13.49	3.62

Table 8 – Upper/Lower Bound Load Table (2.5m Dia. Wheat – 6 Sheets)



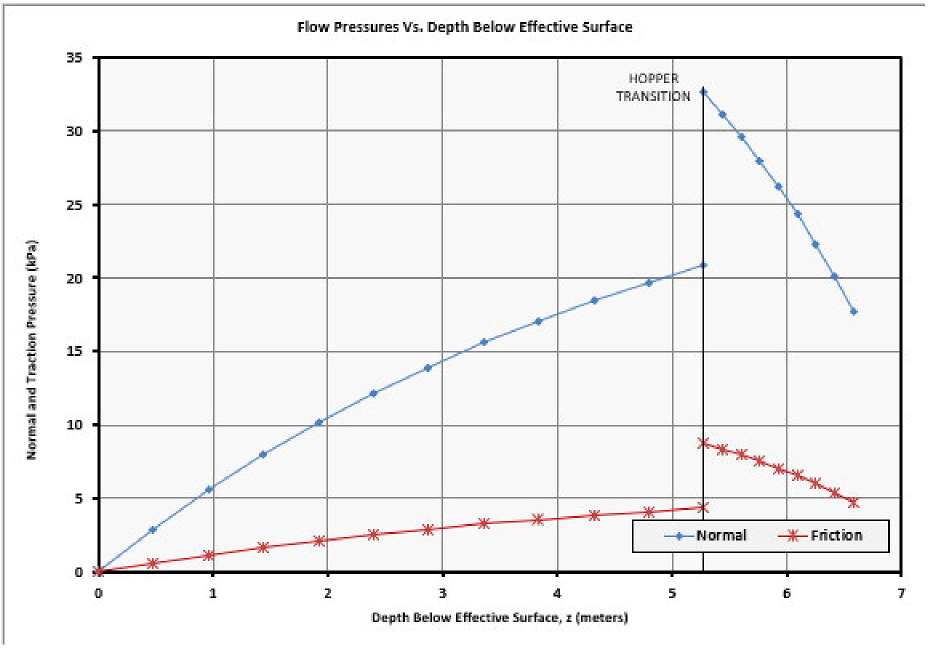
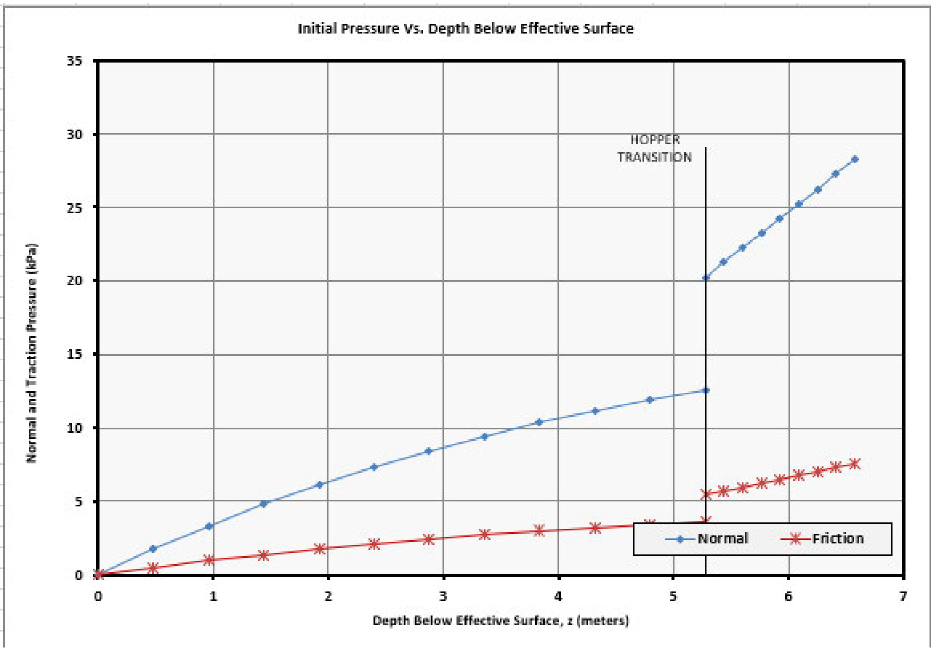


Figure 9 – Lower/Lower Bound Load Graphs (2.5m Dia. Wheat – 6 Sheets)



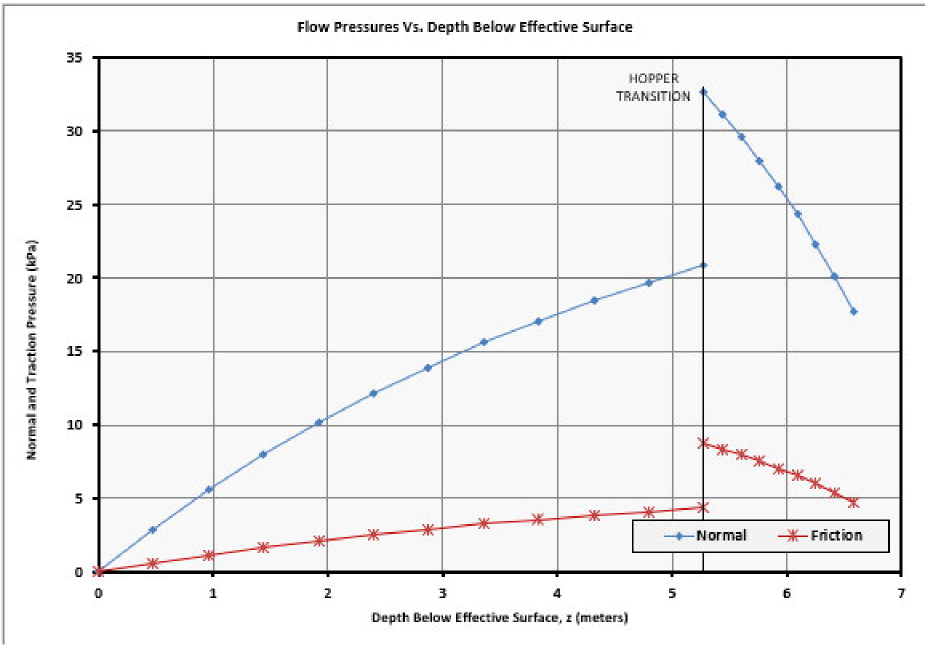
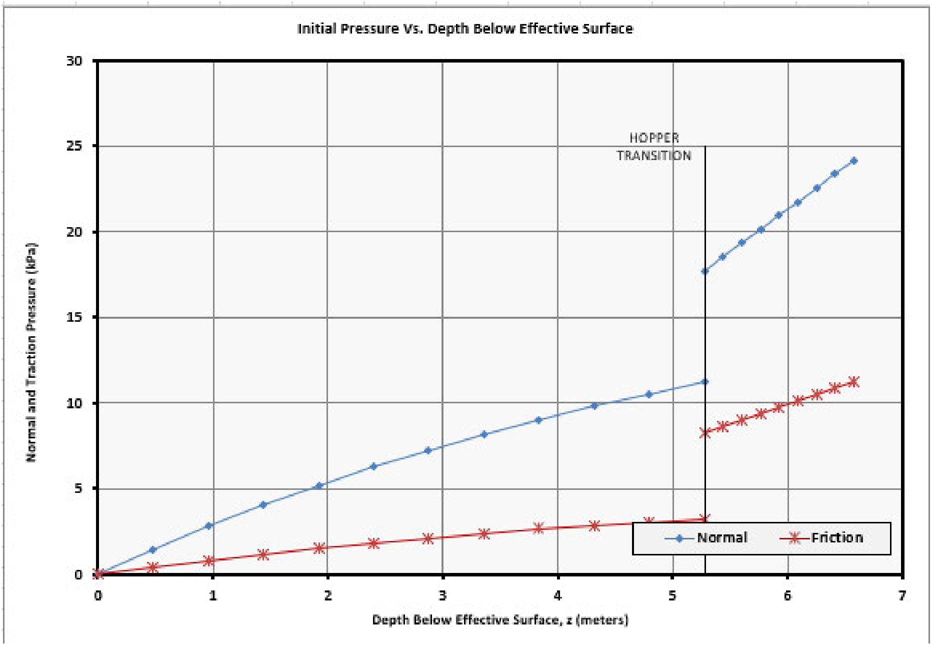


Figure 10 – Lower/Upper Bound Load Graphs (2.5m Dia. Wheat – 6 Sheets)



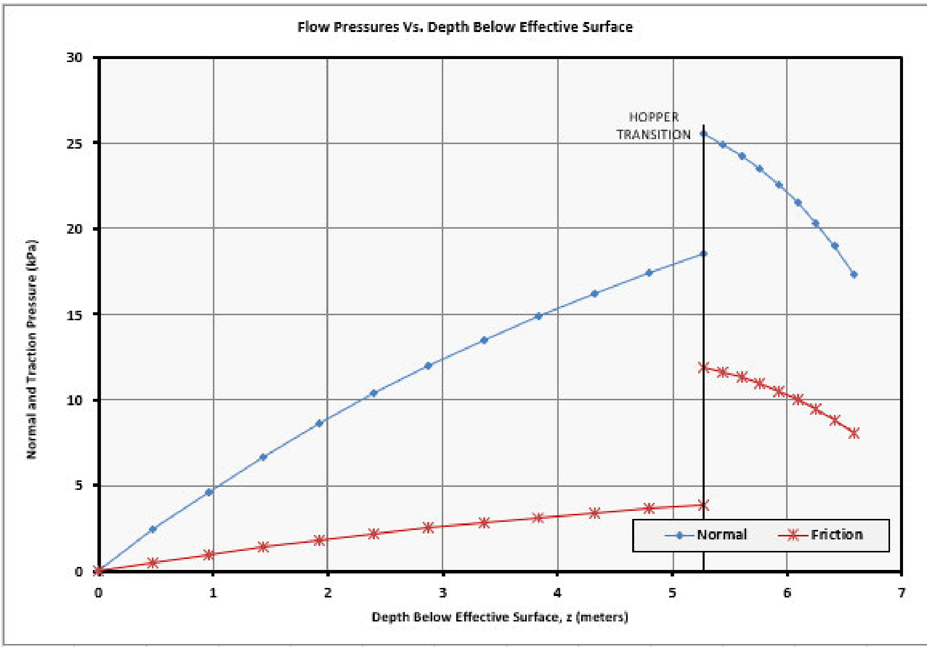


Figure 11 – Upper/Lower Bound Load Graphs (2.5m Dia. Wheat – 6 Sheets)

These tables are graphs that have been produced by a spreadsheet made by Osborn Consulting Engineers and include many details that have been helpful in the design of the loads acting on the silo. This spreadsheet can be found in Appendix H. These spreadsheets (one for the three different silos and grains) were designed to use the AS3774-1996 Australian Standard to create loads, calculations on columns and sheeting and find bolt requirements. For this pro, only the loads were used as the scope is only focusing on the wall sheeting. Future research would analyse the entire silo and see how the different thicknesses and corrugation styles interact with the columns and hopper.

Chapter 4

Modelling

4.1 SolidWorks Design

SolidWorks is a widely used computer-aided design (CAD) and computer-aided engineering (CAE) software application. It is primarily utilised for designing and modelling 3D objects and mechanical systems. SolidWorks is a powerful software suite that offers both CAD and CAE capabilities. CAD is used for creating 3D models and 2D drawings, while CAE helps simulate and analyse the behaviour of these models under various conditions.

SolidWorks enables users to create detailed 3D models of objects and assemblies. This is valuable for designing products, machinery, and structures. Parametric modelling allows designers to define and modify features with parameters. This makes it easy to make changes and updates while maintaining design intent.

SolidWorks automatically generates 2D drawings and documentation from 3D models, streamlining the design-to-production process. SolidWorks is a comprehensive CAD and CAE software solution used for 3D modelling, simulation, and documentation across various industries. Its parametric design capabilities, collaboration tools, and integration options make it a valuable tool for engineers and designers.

SolidWorks was not used for the finite element modelling due to personal preference for Strand7 for the analysis and SolidWorks for the initial modelling. SolidWorks and Strand7 work well together and are easily exported and imported into one another through certain file types.

The below figures show the initial design of the silo in SolidWorks. The idea of using SolidWorks to model a 15-degree slice of the silo and import the section into Strand7 is to make the meshing and geometry of the Strand7 model more straightforward and more accessible for the model to solve. Doing this makes the model solve quicker, and more in-depth analysis can be undertaken to. Adding legs and other structural components of the silo is also much easier as the 15-degree sections are mirrored and connected in identical sections as the mesh is the same. The working of the initial model is seen in the following figures.

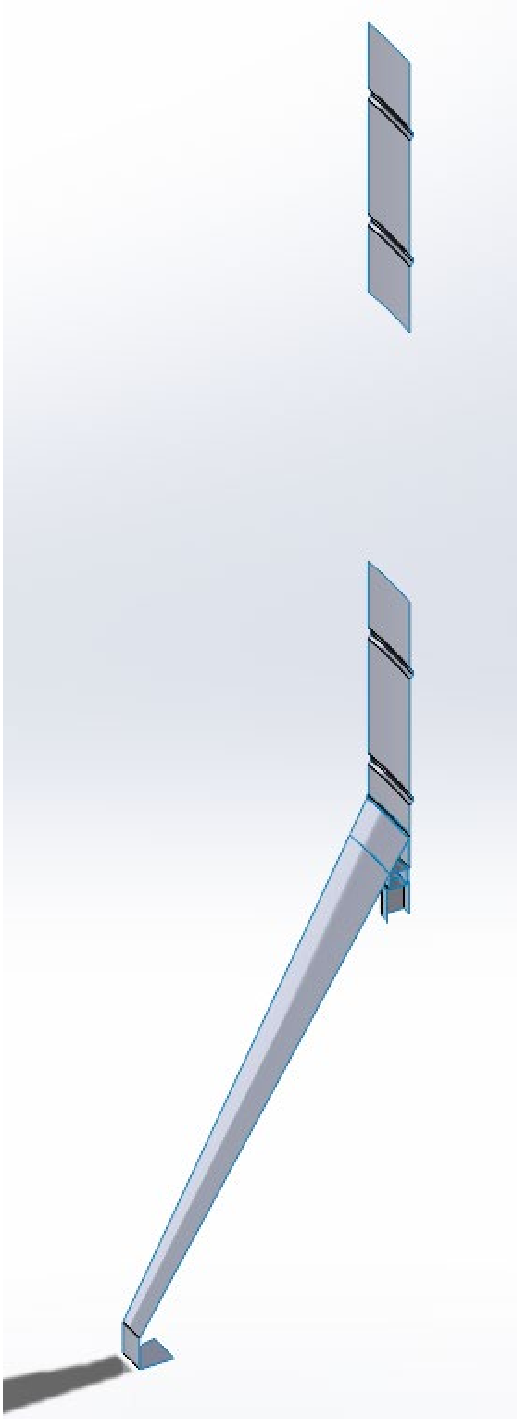


Figure 12: SolidWorks model for the 2.5m diameter silo.

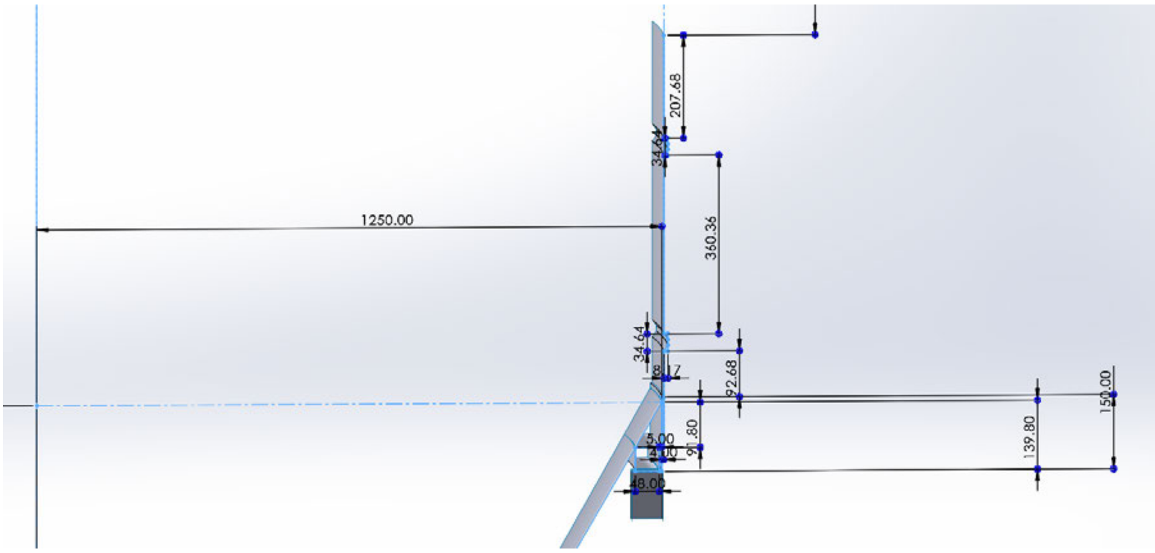


Figure 13: SolidWorks model for the 2.5m diameter silo.

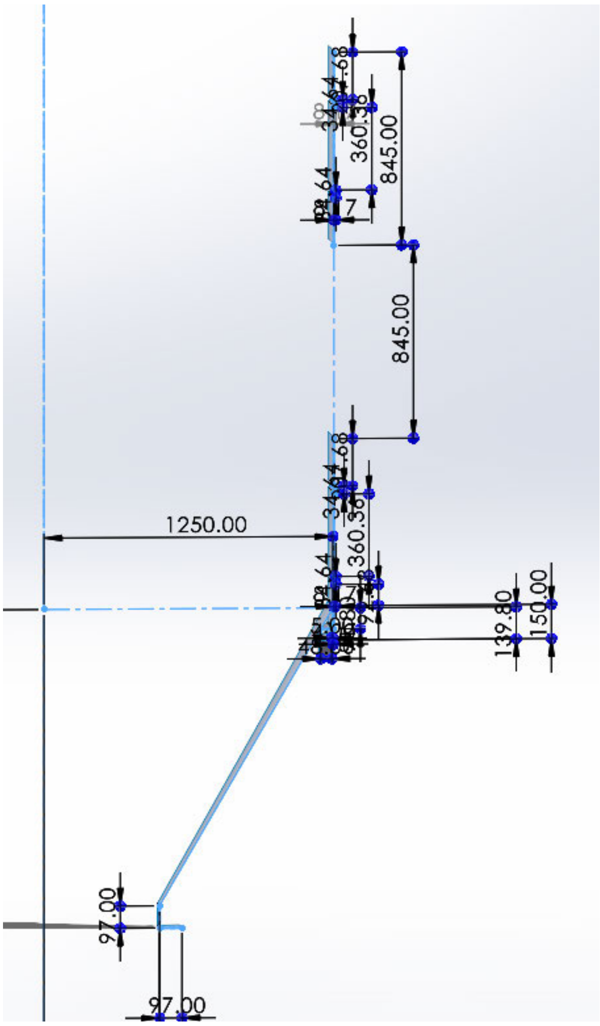


Figure 14: SolidWorks model for the 2.5m diameter silo.

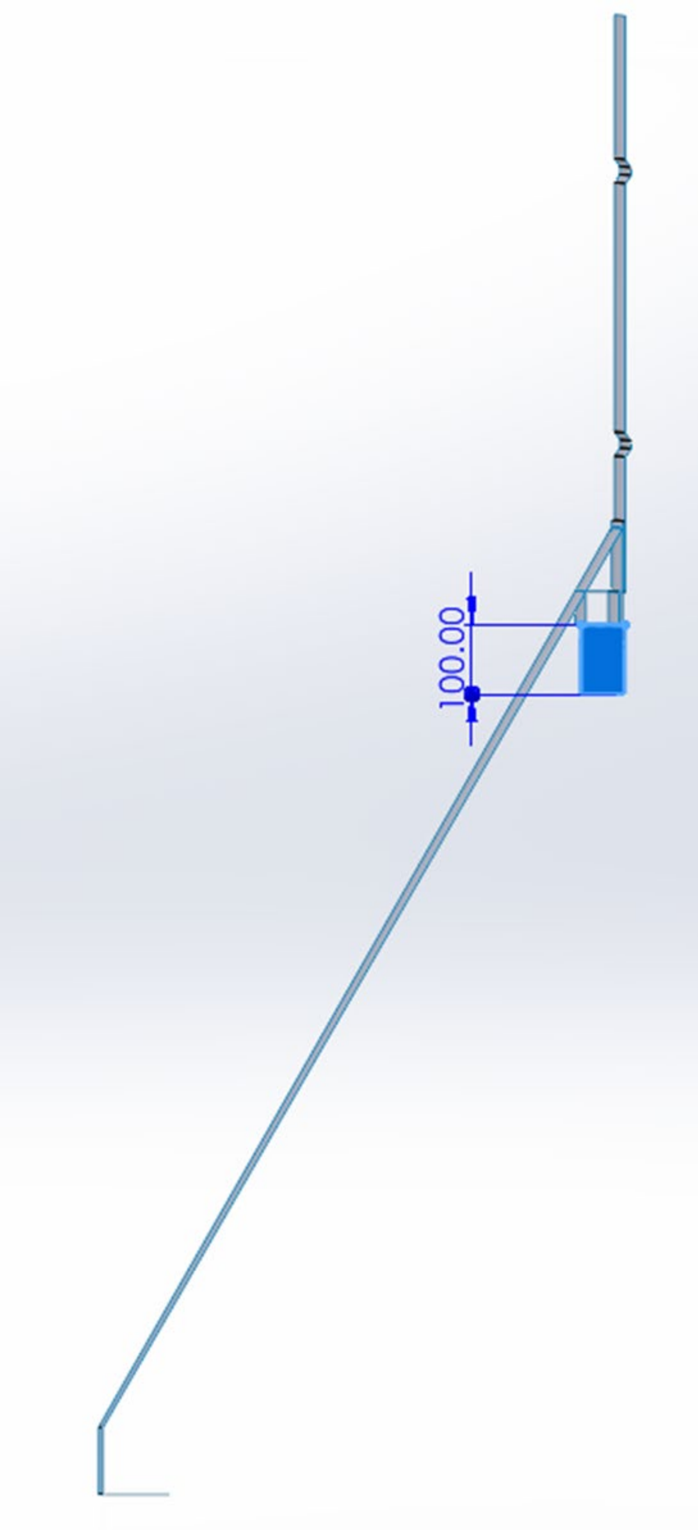


Figure 15: SolidWorks model for the 2.5m diameter silo.

4.2 Strand 7 Modelling

The Strand7 modelling was completed using the software from Osborn Consulting Engineers. The modelling was very simple after exporting the SolidWorks section. The model was constructed by firstly meshing and revolving the shape into a 30-degree section before creating the entire silo. The different groups of the model include the wall sections, hopper, roof, a 200mm by 16mm plate around the bottom of the silo wall and a 100 SHS leg section that is 150mm deep to replicate the top of the legs. The rest of the support and bracing were just drawn as beams in Strand7 and connected using the various restraints available in Strand7. The model is calibrated or cleaned by the software. This involves a straightforward process of ensuring all nodes, plates and beams are connected and that there are no problems with the design.

The following are several figures showing the model of the silo in Strand7 after being imported from SolidWorks. The initial models are industry standard dimensions of either 2.5m or 3.6m diameter silos ranging from 5-8 sheets high. These are confirmed as the standard dimensions and wall thickness (1.5mm) used around the Darling Downs by Denny's Silos (Satake) Allora.

Modified dimensions will be done by changing the thicknesses and the shape of the wall corrugations by making them either bigger or smaller. The hope is that these modifications can either show improvement or worsening stresses compared to the initial models to determine the best possible design of the wall corrugations.

The following four figures (Figures 16, 17, 18, 19) show the basic modelling of the 2.5m diameter silo with five sheets of wall corrugation. Figure 16 shows a front-on view of the silo showing the basic layout of the silo. Figure 17 is a similar view of the silo but in an isocentre view showing smaller details of the model, including the hooper detail. Figure 18 is a bottom view of the silo showing the legs and the initial forces acting on the walls and hooper. Figure 19 is a similar view as Figure 18 but a top view showing the top beam and, again, the Initial forces acting on the wall sheets.

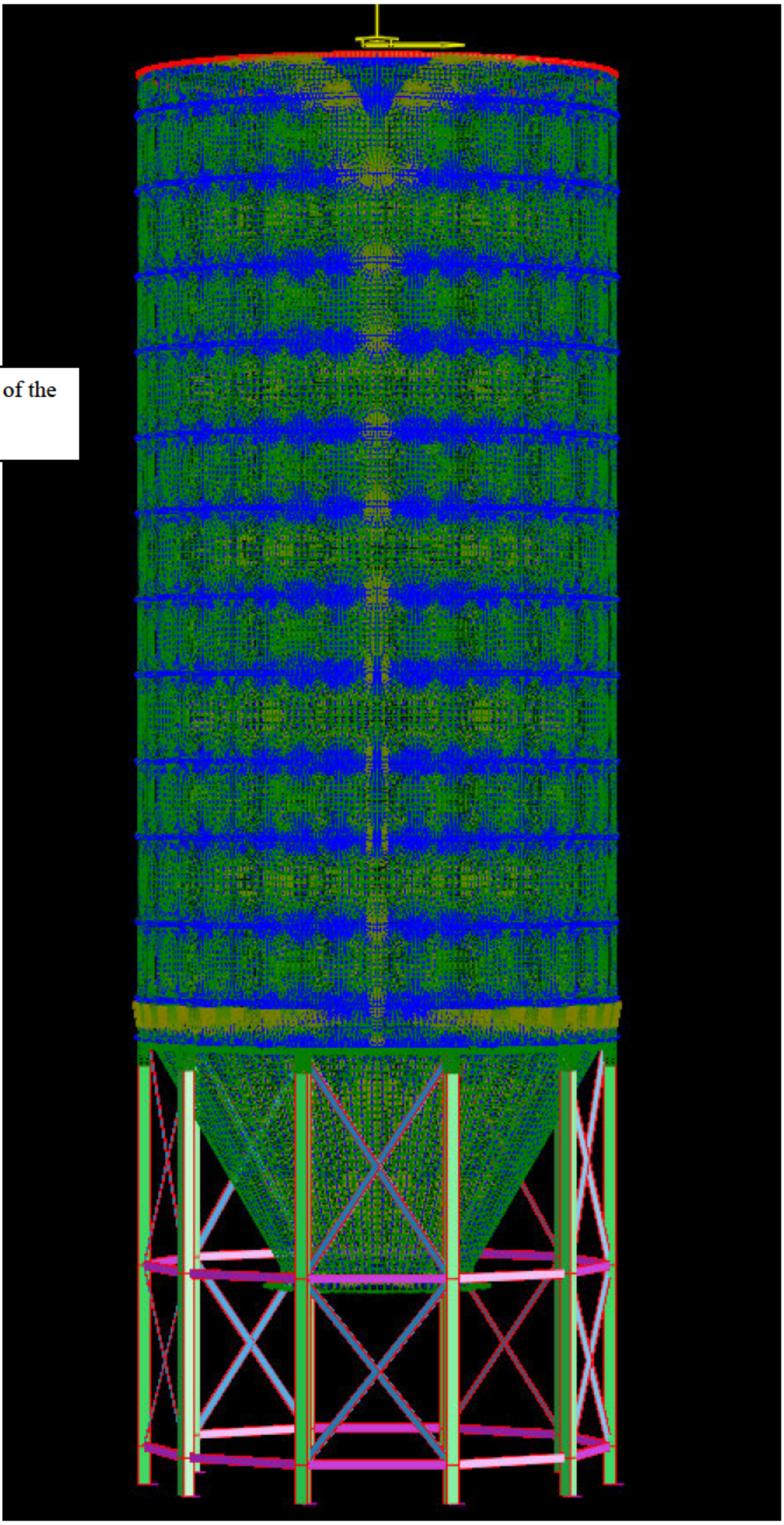


Figure 16: Left is a front on view of the 2.5m diameter silo.

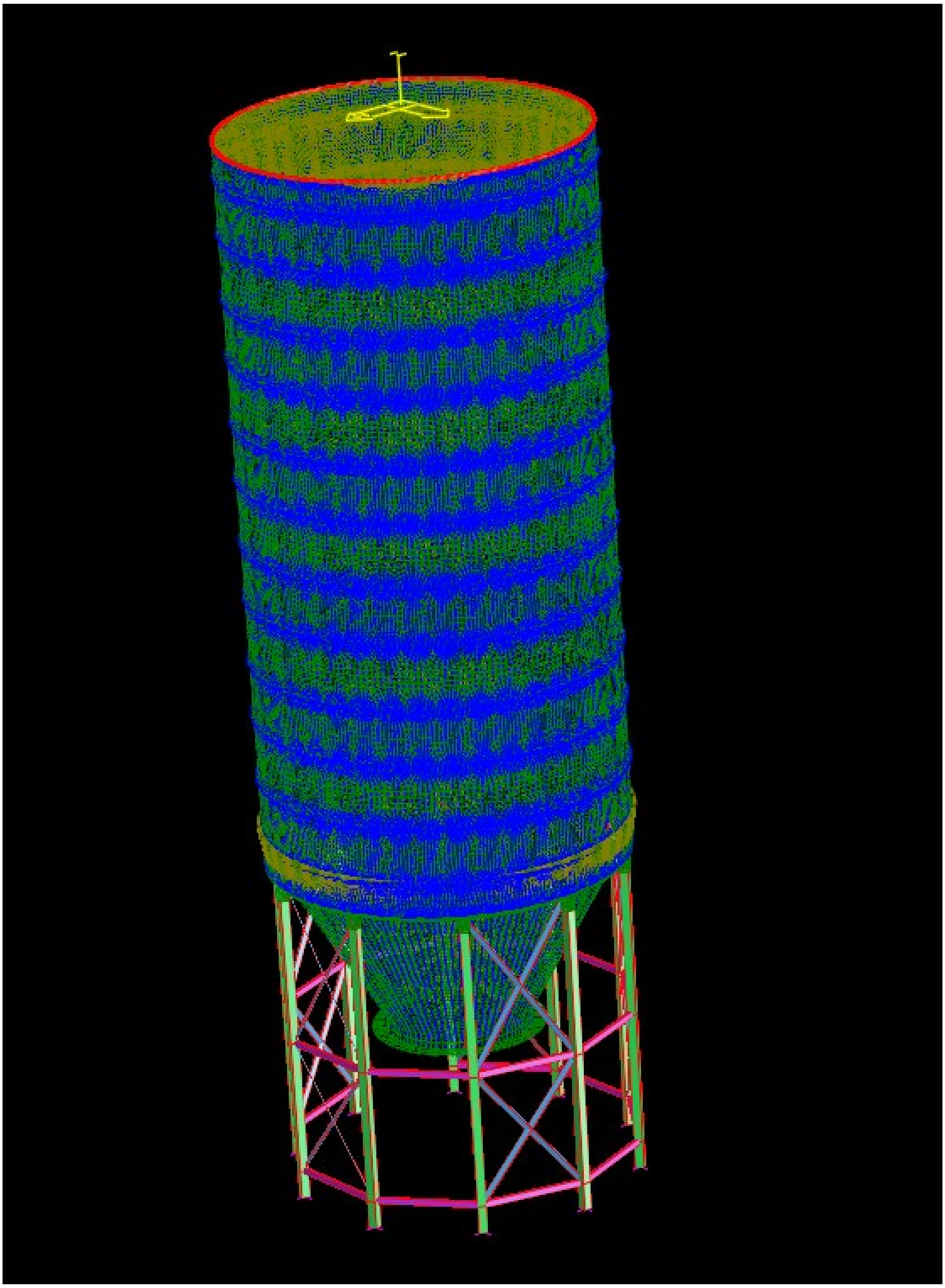


Figure 17: An isometric view of the 2.5m diameter silo is above.

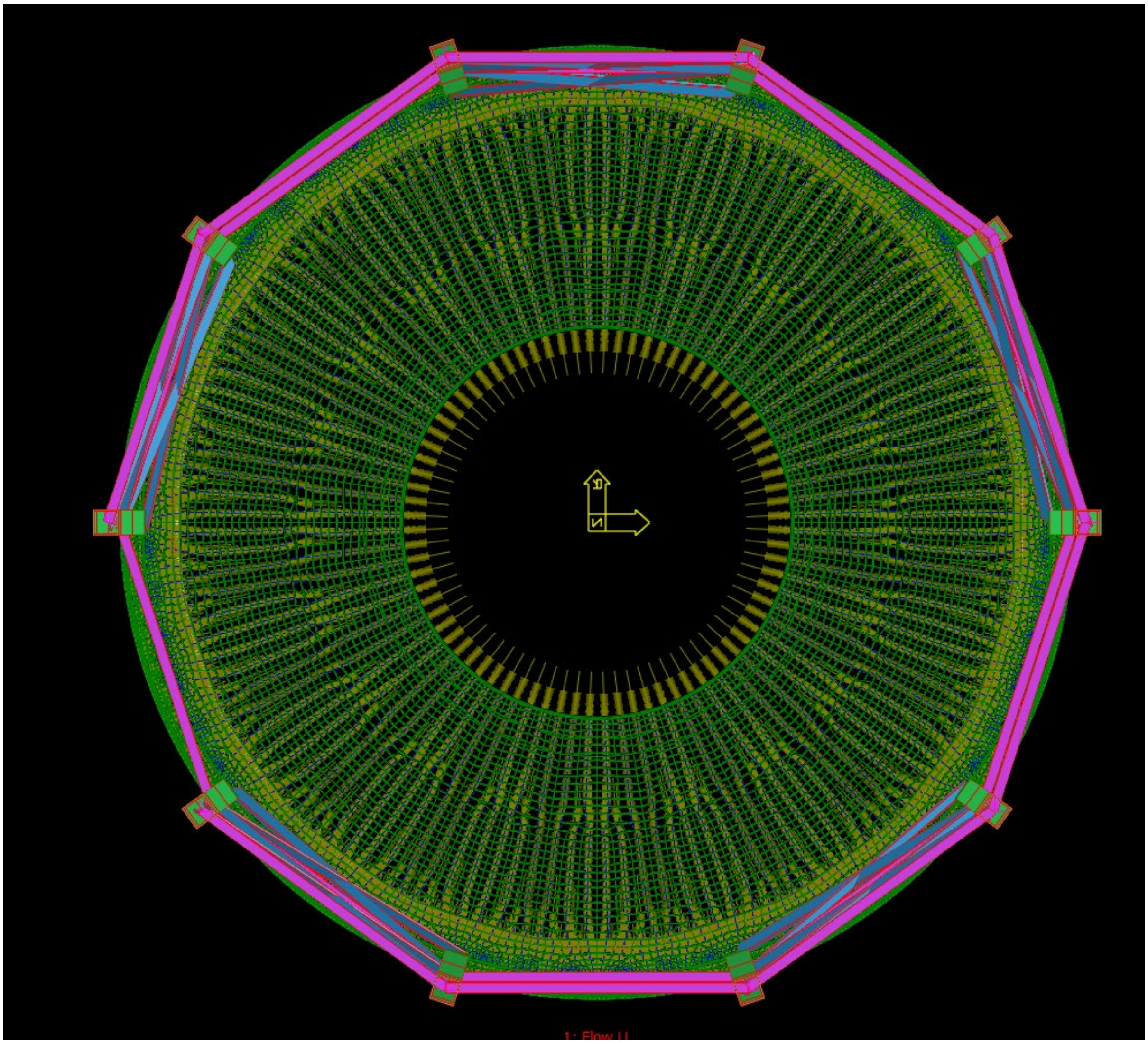


Figure 18: The bottom view of the 2.5m diameter silo is above.

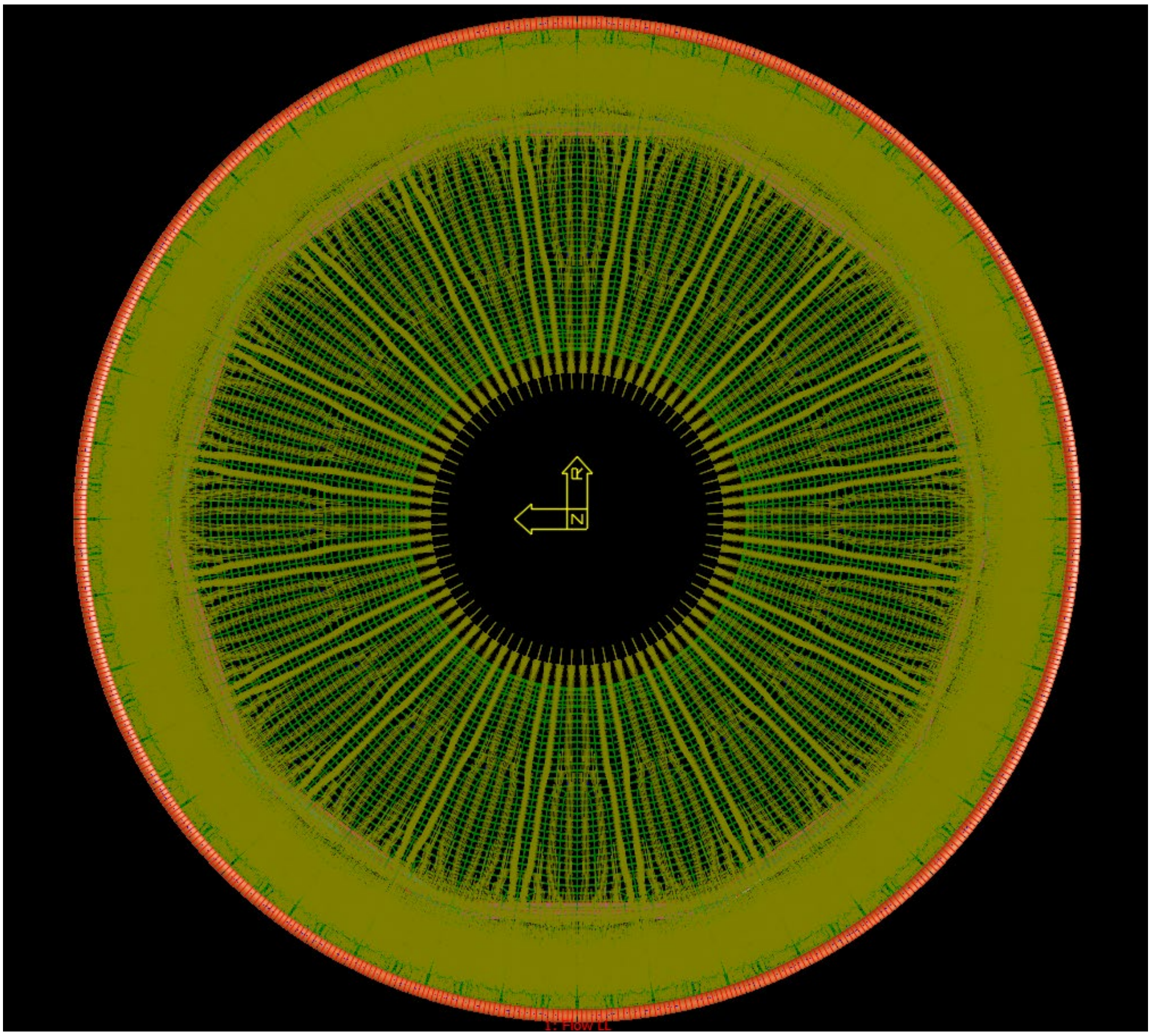


Figure 19: Above is the top view of the 2.5m diameter silo.

Chapter 5

Results

5.1 Initial Results

Initial results were completed on three-sized silos with wheat and meal as the grain. The three sizes were 2.5m diameter by six sheets high, 3.6m diameter by six sheets and 3.6m diameter by eight sheets high. Wheat was used in the first two cases, and the meal was done in the taller silo. These initial models were completed with 1.5mm thick wall section, as that is the industry norm.

The initial results showed that the most impacted sections were the ribs or grooves on the wall section. These sections are only stick about 30mm out and are roughly 50mm long (trapezoids). The ribs or grooves in the corrugation of a thin-walled silo serve several essential purposes in the design and functionality of the silo. The primary function of these ribs or grooves is to enhance the structural integrity of the thin-walled silo. By adding corrugation, the walls of the silo become more rigid and better able to withstand external forces such as wind, snow, and the weight of the material stored inside. This helps prevent buckling or collapsing of the silo walls.

The corrugations distribute the stress and load more evenly across the surface of the silo wall. This means that the silo can support more weight without deformation or failure. The increased strength is significant when storing heavy or dense materials. Corrugations allow thinner walls to be used without sacrificing structural integrity. Thinner walls mean less material is required for construction, which can reduce the overall cost of building the silo.

The grooves or ridges created by corrugation can also help improve the flow of the material stored inside the silo. When materials like grains or powders tend to stick or become compacted, the corrugated walls can promote better flow by reducing friction and moving the material downward. Depending on the design and material used, the corrugated walls can provide some degree of thermal insulation. This can help maintain the temperature of the stored materials, which is essential for certain types of storage, such as in agricultural silos where temperature control is necessary to prevent spoilage. Corrugations also allow for some expansion and contraction of the silo walls due to temperature changes without causing damage. This flexibility is essential in regions with significant temperature variations.

The table below (Table 9) shows the initial forces acting around the ribs. The figures after this will help visualise the differences between the ribs, drawing more stress and force to them than the straight sections of wall corrugation. The ribs are the warmer colours (red, orange, yellow), and the flat sections are mostly blue (Figures 20, 21, 22). The lower half of the silo attracts much higher stresses as the loads are higher at the base and around the hopper. The bottom two to three sheets of corrugation attract the forces in the table below.

	LL		LU		UL	
	Stress (Mpa)	Force (kN/m)	Stress (Mpa)	Force (kN/m)	Stress (Mpa)	Force (kN/m)
2.5 Dia Wheat - 6 Sheets	259.92	95.84	236.96	85.05	380.40	132.60
3.6 Dia Wheat - 6 Sheets	396.25	124.17	374.75	124.69	512.00	172.12
3.6 Dia Meal - 8 Sheets	273.08	107.01	218.59	86.10	437.14	149.91

Table 9: The initial stress (MPa) and forces (kN/m) acting on the ribs of the wall corrugations.

From the above table, the 1.5mm thick corrugations pass due to the sheeting capacity of 550MPa. Wheat also has larger forces as the properties are more significant than the meal. However, the larger sized silo may be impacted further when thicknesses are reduced, or corrugations are changed.

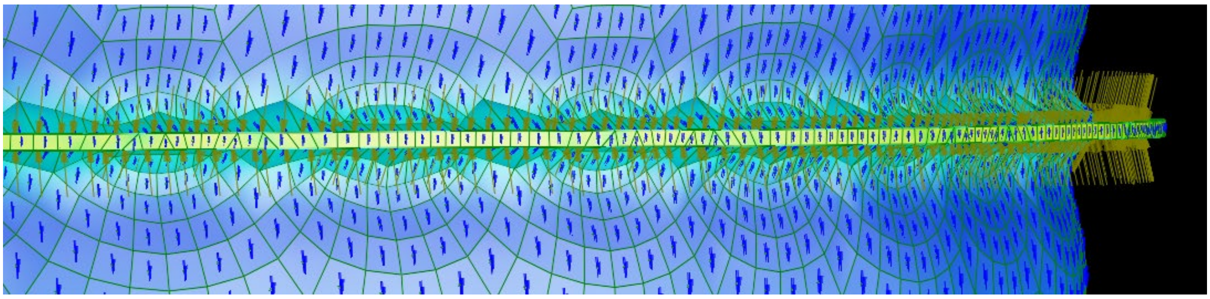


Figure 20: Screenshot of initial models highlighting that the ribs attract higher levels of stress.

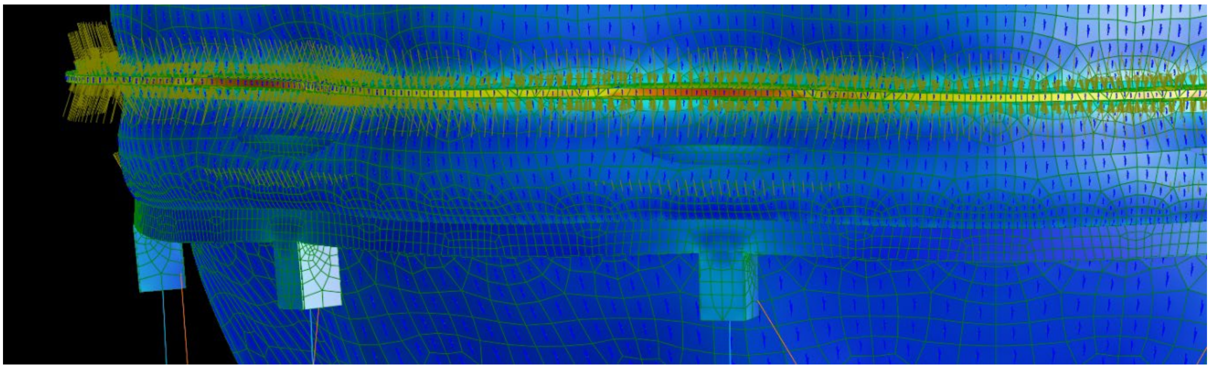


Figure 21: Screenshot of initial models highlighting increased stresses in the ribs of the silo.

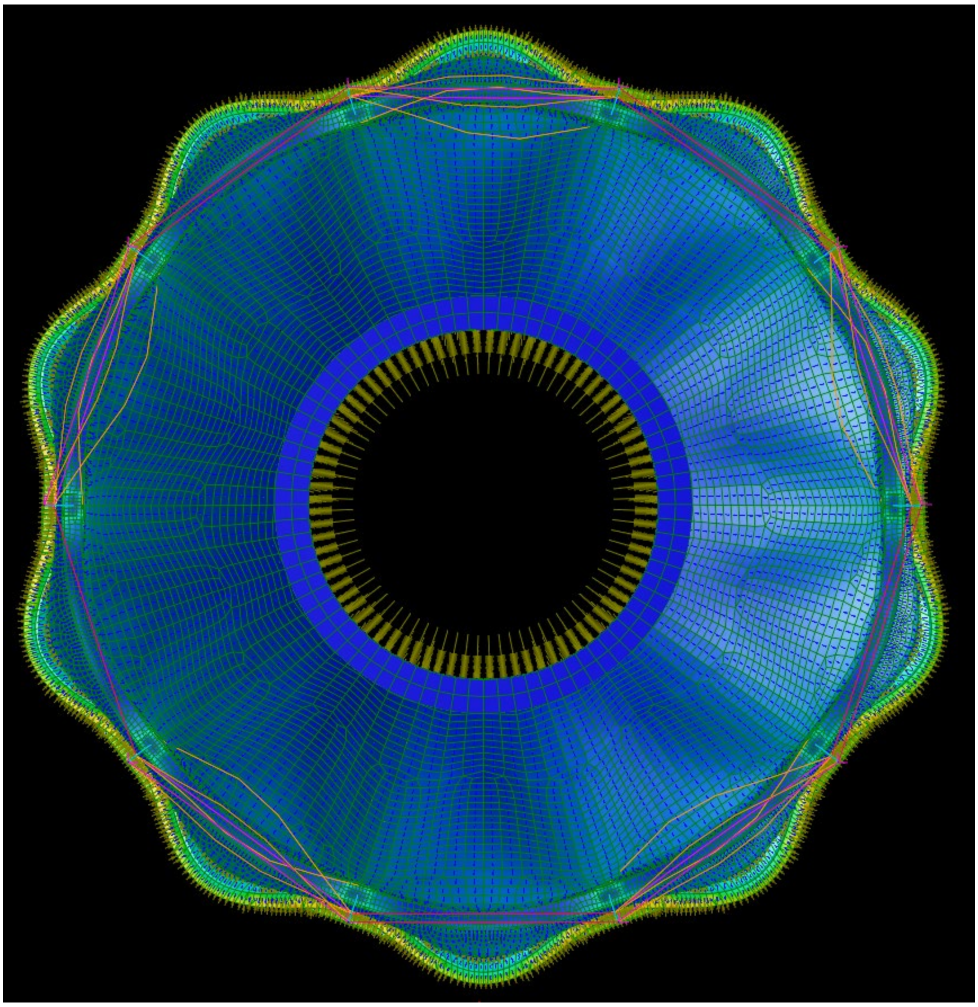


Figure 22: Screenshot of the model highlighting the increased stresses of the ribs at the lower section of the silo.

The outcomes of the initial models were to identify the areas of the corrugations that are impacted the most by the movements of the grain flowing through them. From the models and the table of forces, the ribs are the area that can be modified to reduce these stresses, and the thicknesses of the material can potentially be reduced to save money on the weight of the sheeting and construction. The modified models will include various thinner-sized wall corrugations, ranging between 1.0mm and 1.5mm, to identify if more optimum thicknesses are available.

5.2 Modified Results

5.2.1 Modified Corrugation Thickness

As stated in the section 5.1, The thickness of the corrugation was to first modification to the silos. The 1.0mm to 1.5mm range had two to four values depending on the silo size and bulk solid being stored. The tables below show the results in the rib stresses and forces from the modified models.

	LL		LU		UL	
Wheat 2.5m Dia	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)
1.0mm	459.59	124.91	400.59	109.65	753.73	185.50
1.2mm	339.92	109.31	303.49	96.47	553.15	158.51
1.35mm	292.26	101.74	265.43	90.09	453.62	143.93
1.5mm	259.92	95.84	236.96	85.05	380.40	132.60

Table 10: The results for the 2.5m diameter wheat silo with different wall thickness.

The 2.5m diameter silo (holding wheat) showed increasing stresses and forces, as was expected when decreasing the thickness of the wall. From the results, only the 1.35mm thickness would not fail, however, the 1.2mm thickness failed the upper-lower case by 0.5% of the capacity. With further research, this could be analysed better to determine if 1.2mm could work on smaller-scale silos. As seen in Table 10, the 1.0mm thickness failed by some margin and cannot work.

	LL		LU		UL	
Wheat 3.6m Dia	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)
1.0mm	567.83	152.26	522.57	233.86	920.07	226.70
1.2mm	477.64	138.23	445.38	122.13	692.62	199.23
1.35mm	431.80	130.49	405.61	115.65	580.90	184.19
1.4mm	419.03	128.25	394.56	113.78	551.35	179.89
1.5mm	396.25	124.17	374.75	124.69	512.00	172.12

Table 10: The results for the 3.6m diameter wheat silo with differing thickness.

As seen in Table 10, a 1.4mm thickness was analysed for the 3.6m diameter silo. This was because of the small failure in which the 1.35mm thickness was analysed. The 1.4mm thickness failure by 0.25% and, as stated before, for the 2.5m diameter wheat silo, this could be further analysed to determine if this failure would occur. The table shows that the 1.0mm and 1.2mm thicknesses failed by large margins. However, with more in-depth analysis on the structural elements (outside the scope of this project) and potentially modified models, the 1.35mm and 1.4mm thickness may be sufficient in practice.

	LL		LU		UL	
Meal 3.6m Dia	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)
1.0mm	657.23	188.87	566.92	154.27	955.09	268.18
1.2mm	534.91	168.74	470.64	138.83	728.13	233.69
1.4mm	456.80	154.54	407.85	127.88	602.08	209.46
1.5mm	273.08	107.01	218.59	86.10	437.14	149.91

Table 11: The results for the 3.6m diameter meal silo with differing thickness.

Table 11 shows the results from the modified thicknesses of the meal silo. The meal silo was two sheets taller or 1690mm taller than the wheat silo with the same diameter. The results from the models show similar results to the wheat silo, however, the dimensions of the meal silo maybe the 1.4mm thick wall corrugations to fail by 9.7%. This failure perhaps relieved by adding structural members inside the silo or by different corrugation designs. The structural members would need to be designed outside of this project.

From the tables above and the models, a 1.4mm wall thickness seems sustainable for thin-walled silos of this size. This would require additional analysis of the members themselves and how this would interact with the wall corrugations and the existing structural members (columns, etc.).

The following figures are from the model, showing the deflections on the model at a scale of 5%. This 5% is required to see the deflection as it is quite low no matter the forces, as the cylinder of wall sheeting must stay relatively circular. Strand7 does not show the material failing as such but will continue to hold its shape to a degree, and after a certain point of failure, the model will be unrecognisable and just be a mess of meshed plates. As this is not the case for these models, the 5% scale has been used. From other load cases, these figures can be found in Appendix G.

The deflection found from the Strand7 models was incredibly low. As stated, the deflection was only visible at a 5% scale and was as little as 1mm in some cases. The deflection was not recorded for this analysis as it was not worth the time and analysis to collect the data from the model and display it in this report. The deciding factor of the failure and the review of successful thicknesses and corrugation designs were determined entirely off the stresses and forces found from the Strand7 models.

Figure 23: The deflection of the 1.0mm thick, 3.6m diameter wheat silo at 5% scale for the upper-lower case.

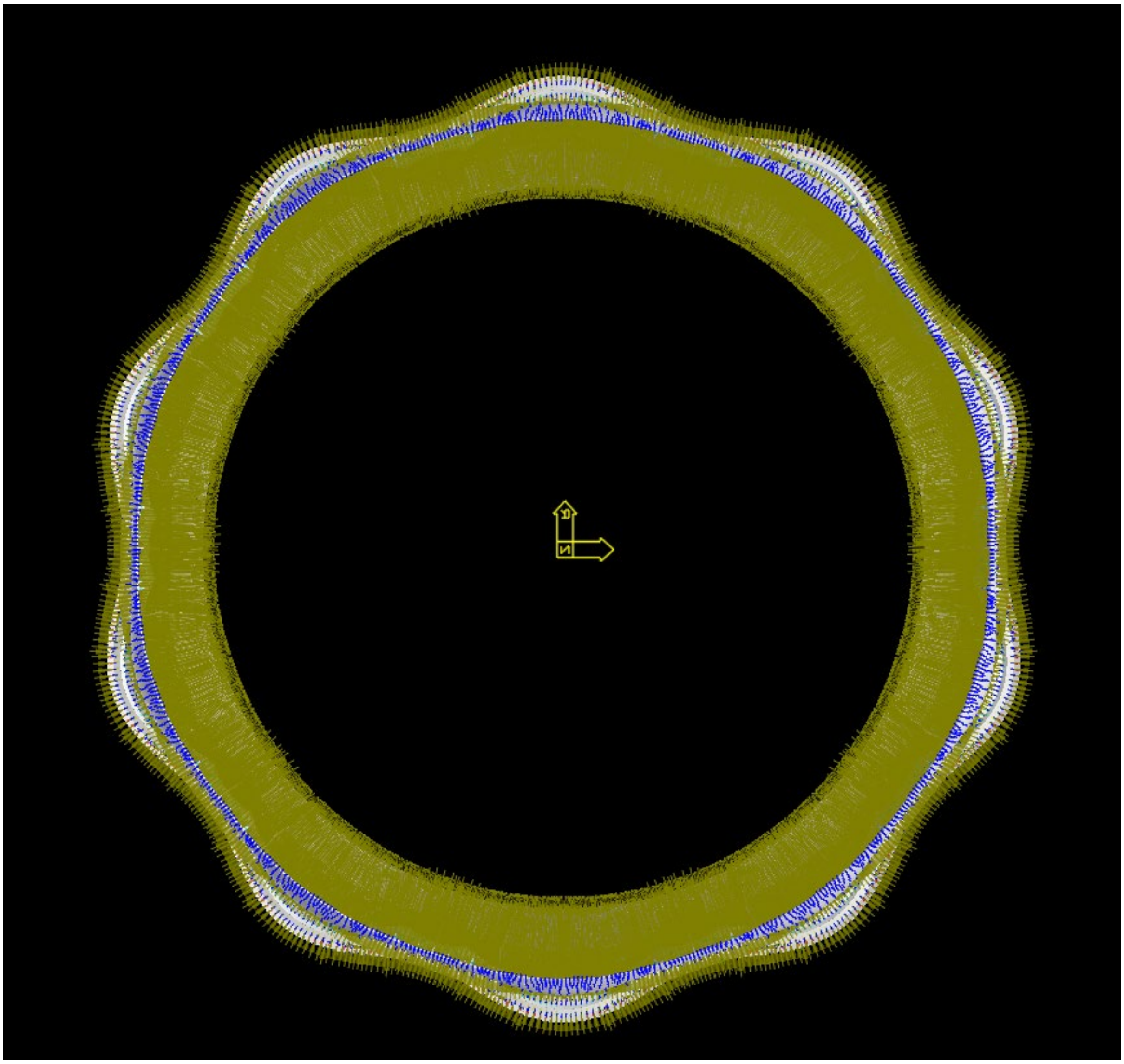


Figure 24: From the bottom view, the deflection of the 1.0mm thick, 3.6m diameter wheat silo at 5% scale for the upper-lower case.

Figure 25: From an isometric view, the deflection of the 1.0mm thick, 3.6m diameter wheat silo at 5% scale for the upper-lower case.

5.2.2 Modified Corrugation Shapes

Two modified corrugation shapes were conducted for the 2.5m diameter wheat silo case. The 2.5m diameter silo was used as it is a simpler size than the 3.6m silo and easily converted to a larger silo. It was also done to conserve time and get simpler results. The thickness will be 1.5mm thick initially, and the thicknesses that failed in the initial corrugation will also be reanalysed to see whether the change of shape would deal with the stresses and forces acting on the walls better or worse.

The two modified corrugation shapes are a flat wall sheets and a larger rib. The flat wall corrugation can be seen in Figures 26, 28 and, 29, and the larger rib in Figures 27, 30, 31, 32 and, 33. The larger rib is the same width out of the silo wall (8mm) and has been increased from 34mm to 150mm to see how the larger rib would work. It is assumed that this would attract larger stresses but exceed the capacity of the sheeting (550MPa). It is not clear how the flat surface of the wall will handle the loads and is expected to fail quite quickly as the ribs do provide a large amount of the structural capacity of the sheeting.

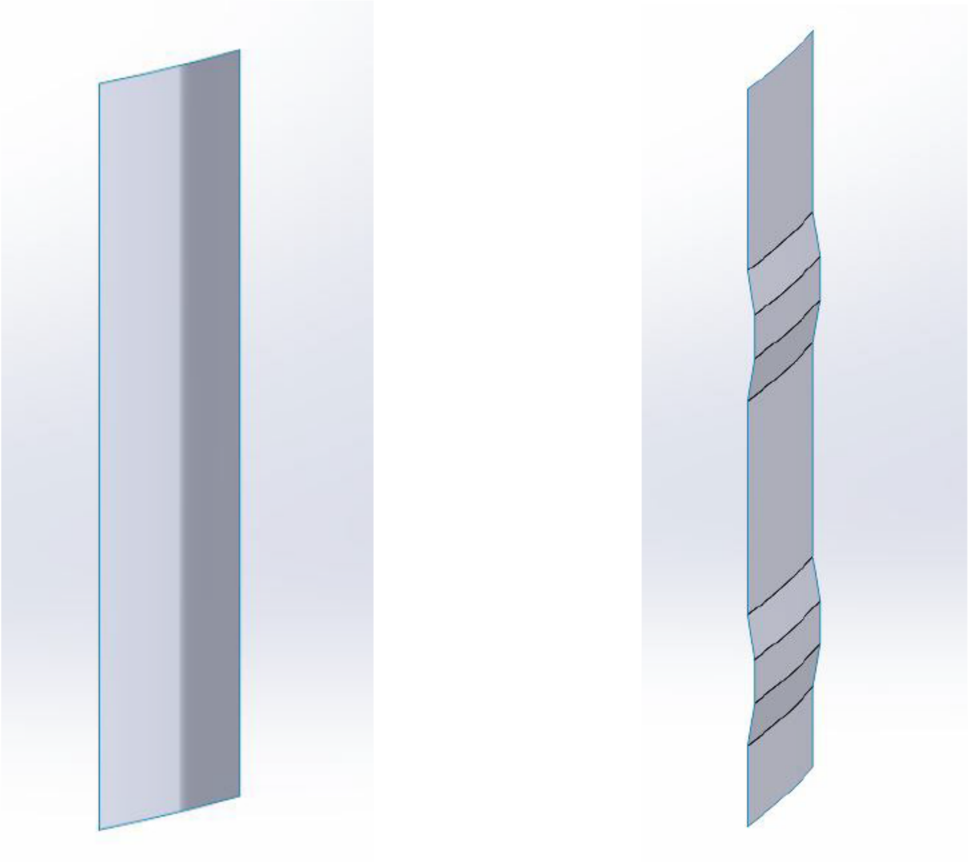
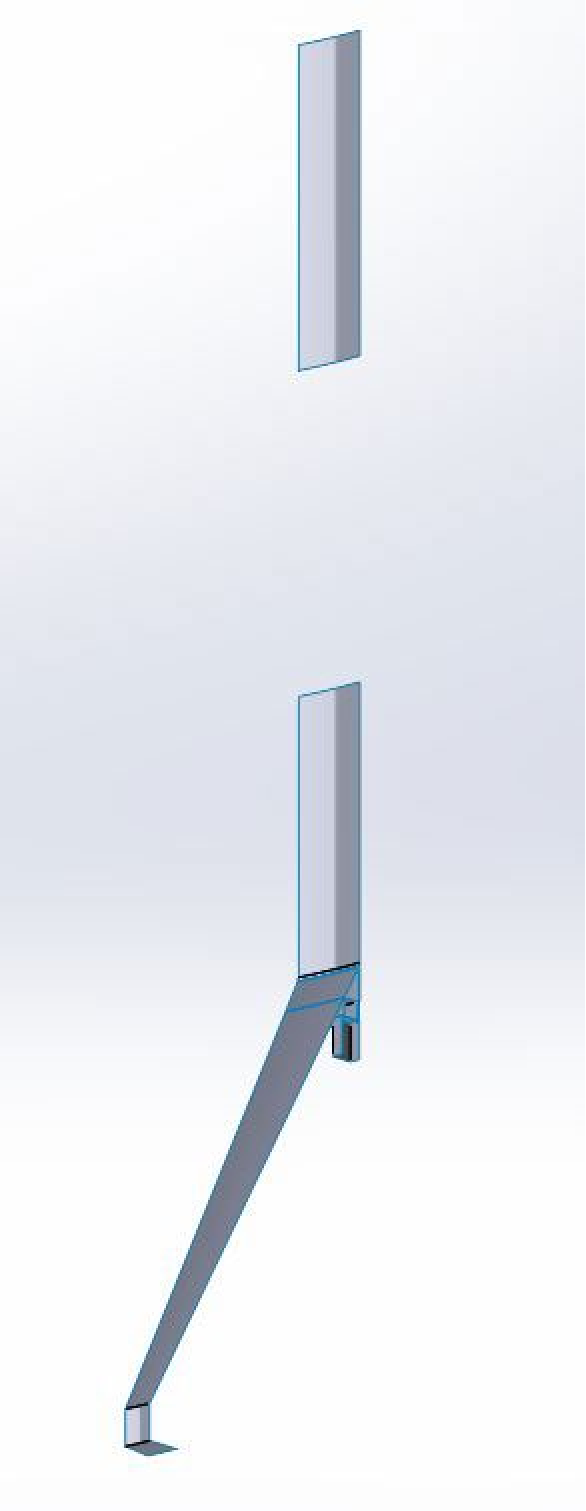


Figure 26 (left): SolidWorks model of the flat corrugation. Figure 27 (right): SolidWorks model of the bigger rib corrugation.



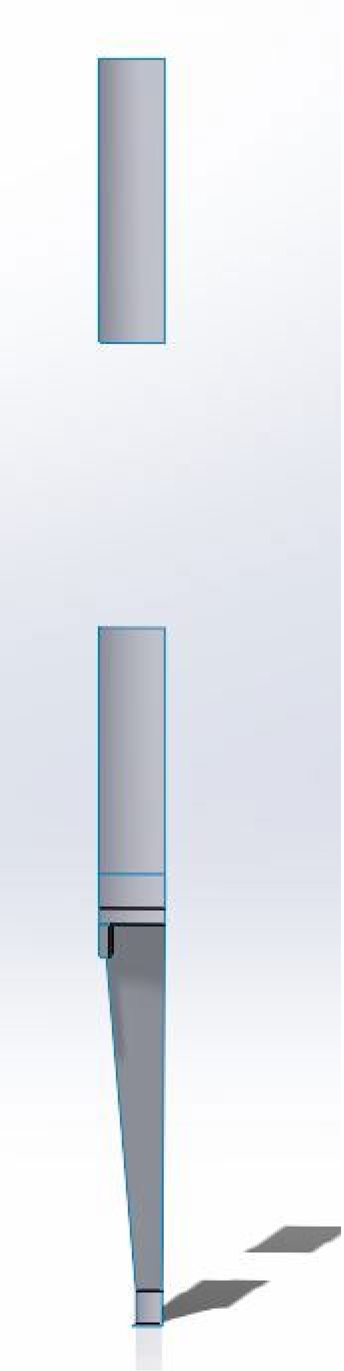
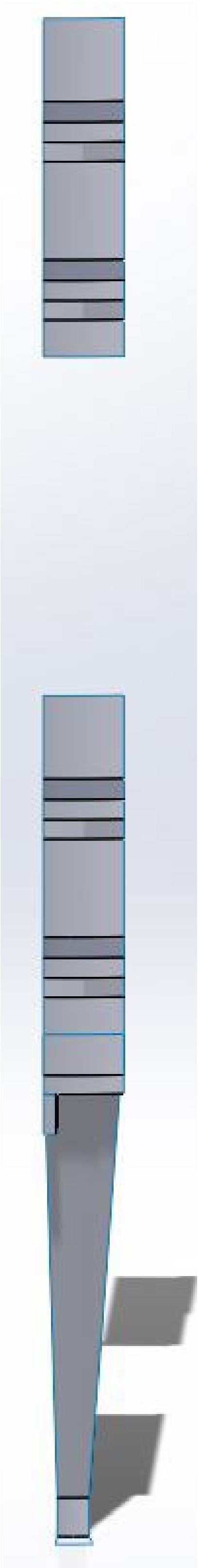


Figure 28 (left): An isometric view of the flat SolidWorks models.

Figure 29 (right): A behind view of the flat corrugation from SolidWorks.



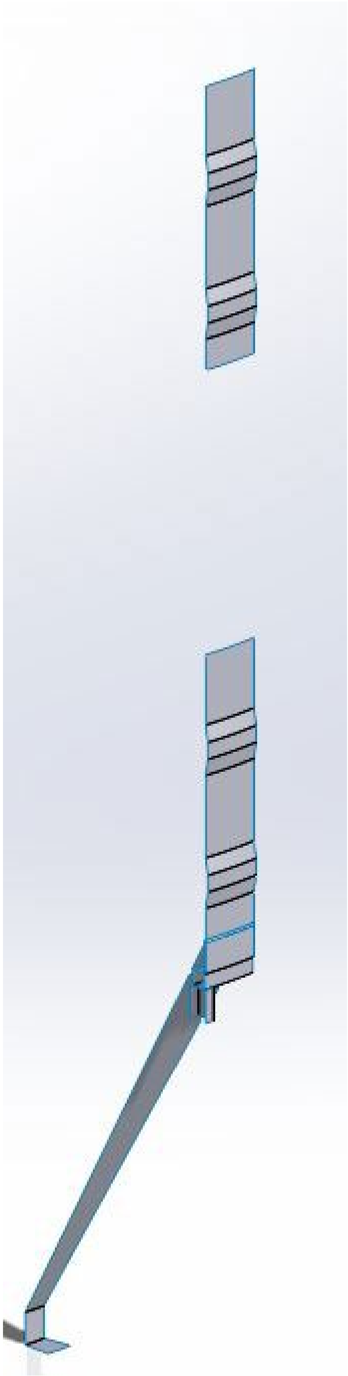


Figure 30 (left): A behind view of the larger ribbed wall corrugation model from SolidWorks.

Figure 31 (right): An isometric view of the larger ribbed wall corrugation from SolidWorks.

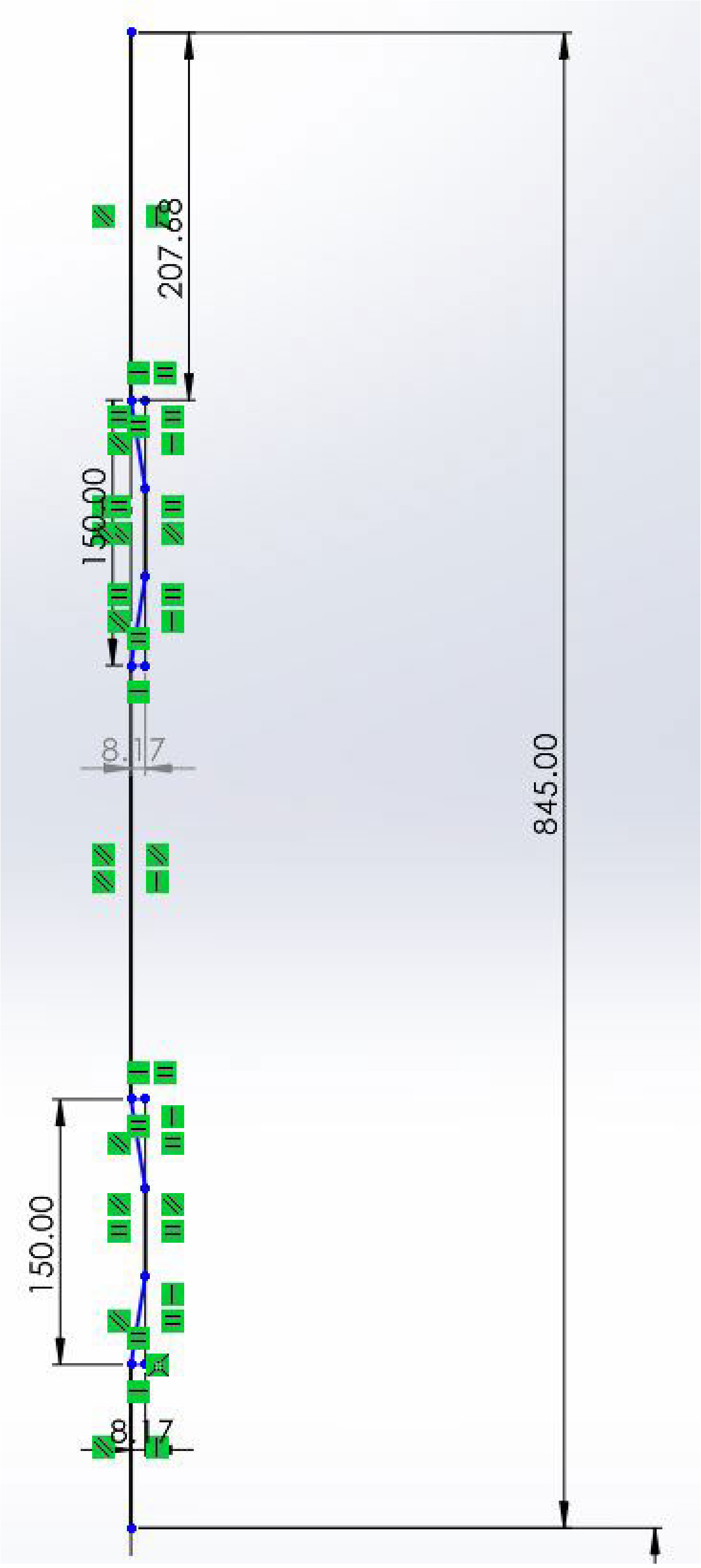


Figure 32: The dimensions one sheet section of the larger ribbed wall corrugation.

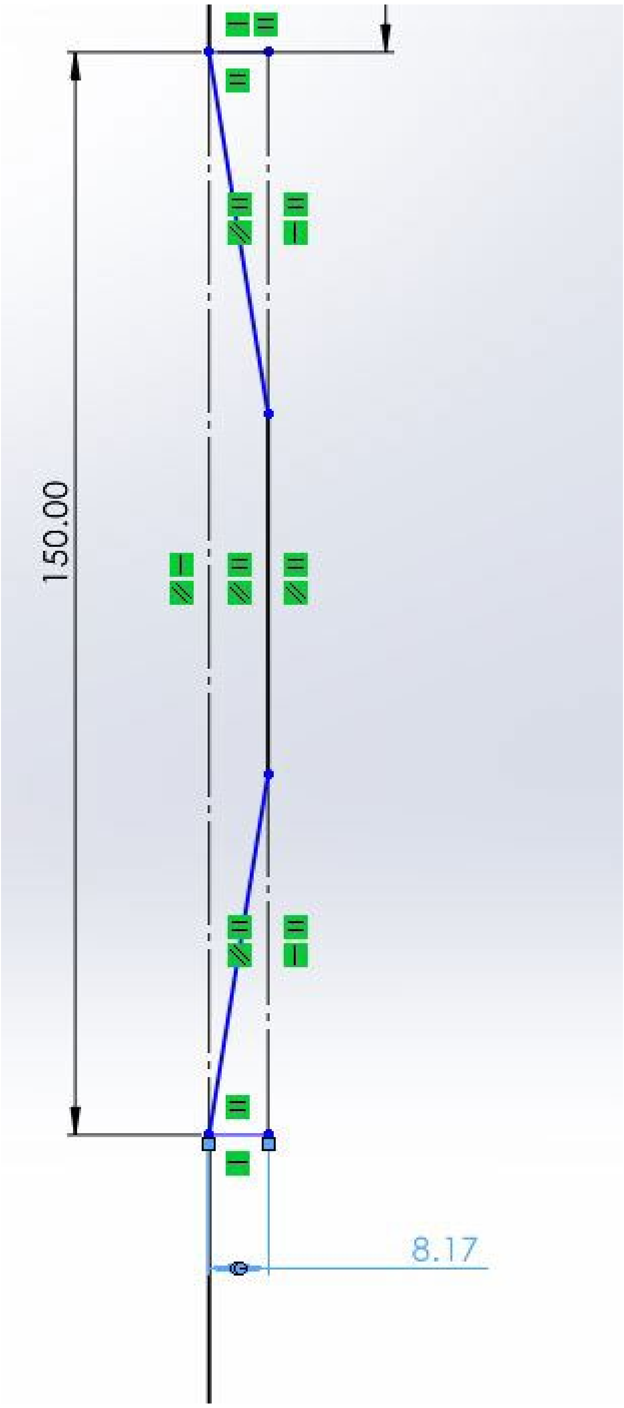


Figure 33: A close of the dimensions of the larger ribbed model.

These modified models were then imported and analysed the same way as the initial models, and thickness changes were completed. Figure 34 and Figure 35 show the two corrugation types in Strand7. Other figures can be found in Appendix F.

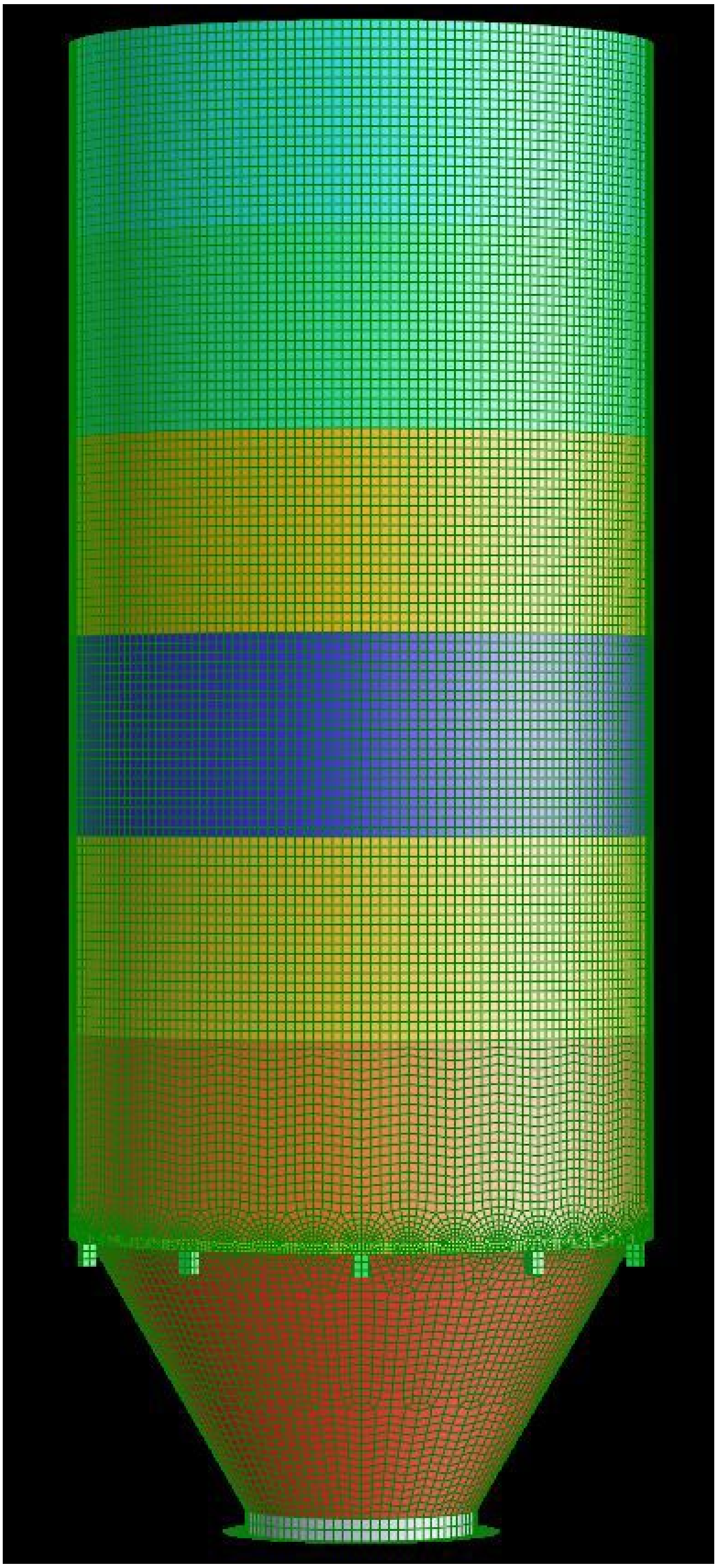


Figure 34: A front view of the flat corrugation from Strand7.

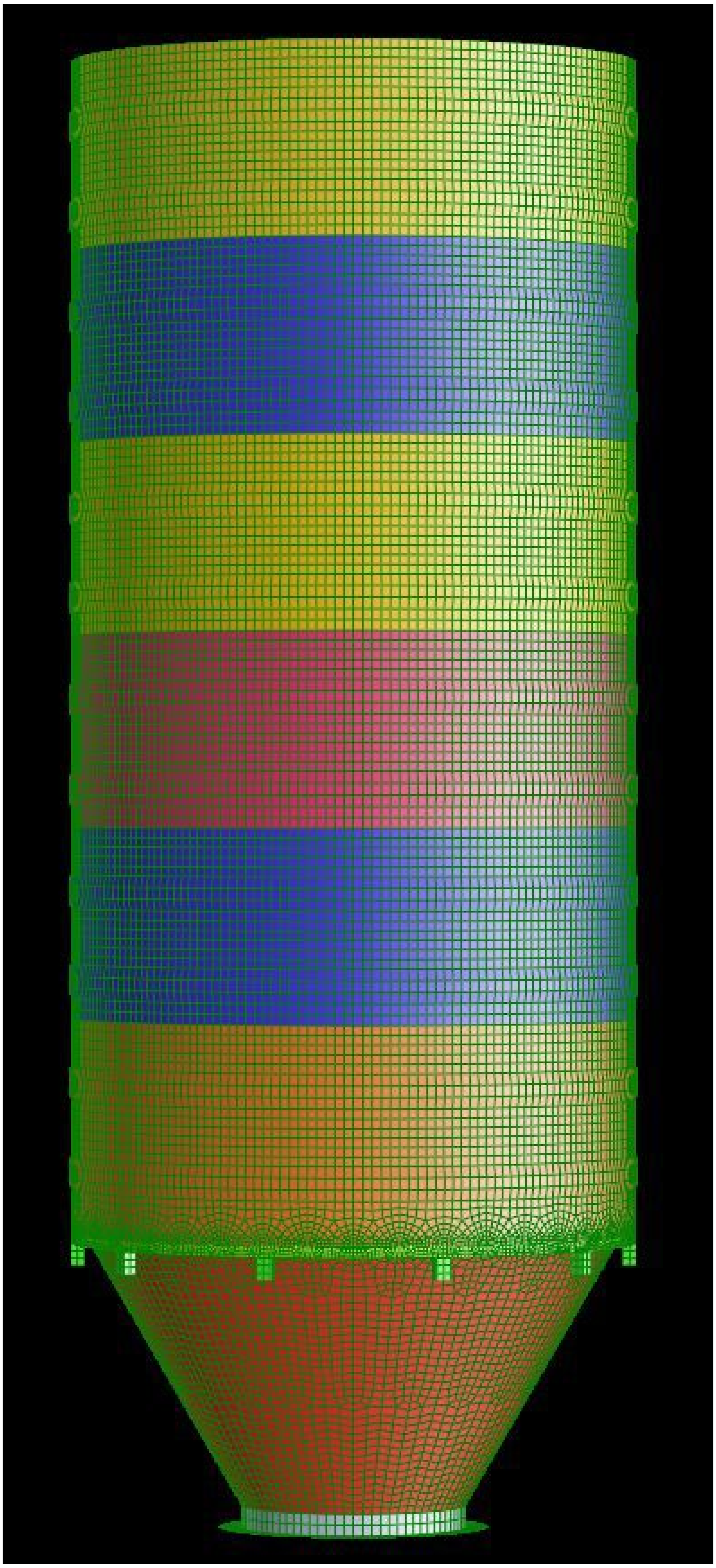


Figure 35: A front view of the larger ribbed corrugation from Strand7.

5.2.3 Modified Corrugation Shapes Results

As mentioned earlier, the modified models were analysed the same as the initial models. The 2.5m diameter wheat silo, six sheets high, is the same as the initial silos; however, the modified wall corrugations as seen earlier. The first analysis was the larger ribbed corrugations. The thickness of the model started at 1.5mm thick and was reduced to 1.2mm as this was the minimum possible passing thickness in the initial models. Table 12 below shows the results for the larger ribbed model.

	LL		LU		UL	
Wheat 2.5m Dia (Larger Ribs)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)
1.2mm	187.5	84.4	175.1	73.9	331.1	119.9
1.5mm	172.0	80.1	153.1	69.4	264.4	110.2

Table 12: The results from the modified larger ribbed wall corrugations.

From the results of the larger ribbed corrugation, it seems that the 150mm long ribs are much stronger than the smaller 35mm ribs. The 1.5mm thick analysis shows that the stresses of the corrugation peak at 264.4MPa, much lower than the initial model (380MPa), and pass the capacity of the wall sheeting. However, the 1.2mm upper-lower case is the highlight of the analysis as the recording of 331.1MPa comfortably passes the capacity of the sheeting and is easily a lower stress than the 553MPa recorder for the initial model. Figure 36 shows the front view of the 1.5mm thick model under the upper-lower load case. The forces are also considerably lower than the results of the initial 2.5m diameter silo. From the results, this corrugation design could be very successful in holding bulk material.

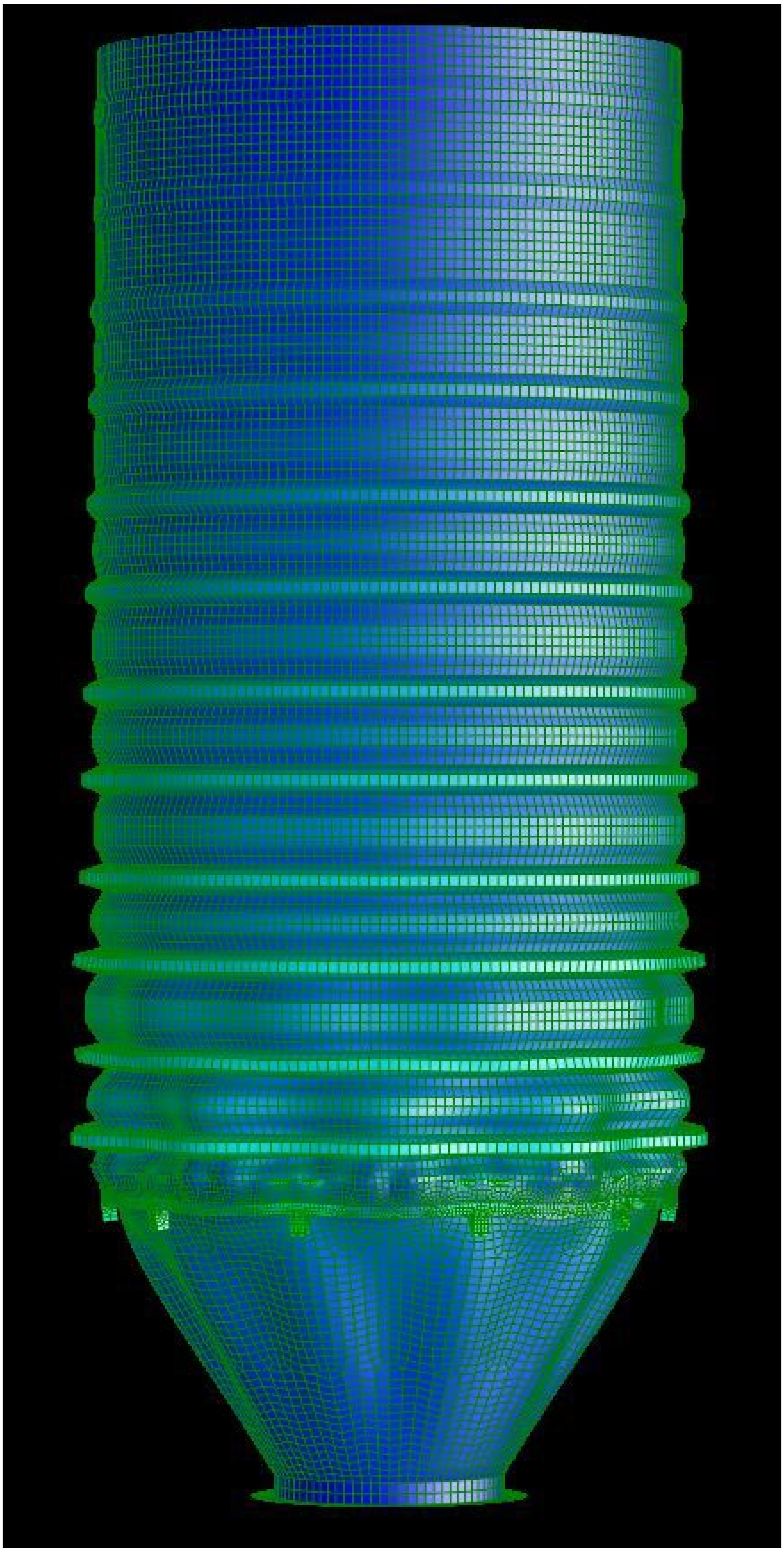


Figure 36: The front view of the results of the 1.5mm larger ribbed corrugation under the upper-lower case.

The second model was of a flat-walled silo with no ribs. This model was designed to show the effects that the ribs have in holding the silos' structure, not to show its strength as a possible corrugation type, as a flat-walled silo requires extra structural elements to replicate the ribs in corrugated sheeting. However, the following table (Table 13) does show the strength of the models.

	LL		LU		UL	
Wheat 2.5m Dia (Flat-Walled)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)	Stress (MPa)	Force (kN/m)
1.5mm	73.3	55.1	73.6	50.3	97.6	70.1

Table 13: The results from the flat-walled silo.

The results cannot be used as a reference to the strength of the silo as the results are incorrect due to the lack of additional structural elements of the silo. The deflections of the wall sheeting were far too great (over 50mm) for the design to be reviewed as the wall sheeting itself. This design would require further research and analysis into the entire silo structure not just the sheeting. Figure 37 will show the deflection of the flat-walled silo that would be reduced and removed with the use of structural elements inside the silo. The remaining figure for the results of the modified models can be found in Appendix G.

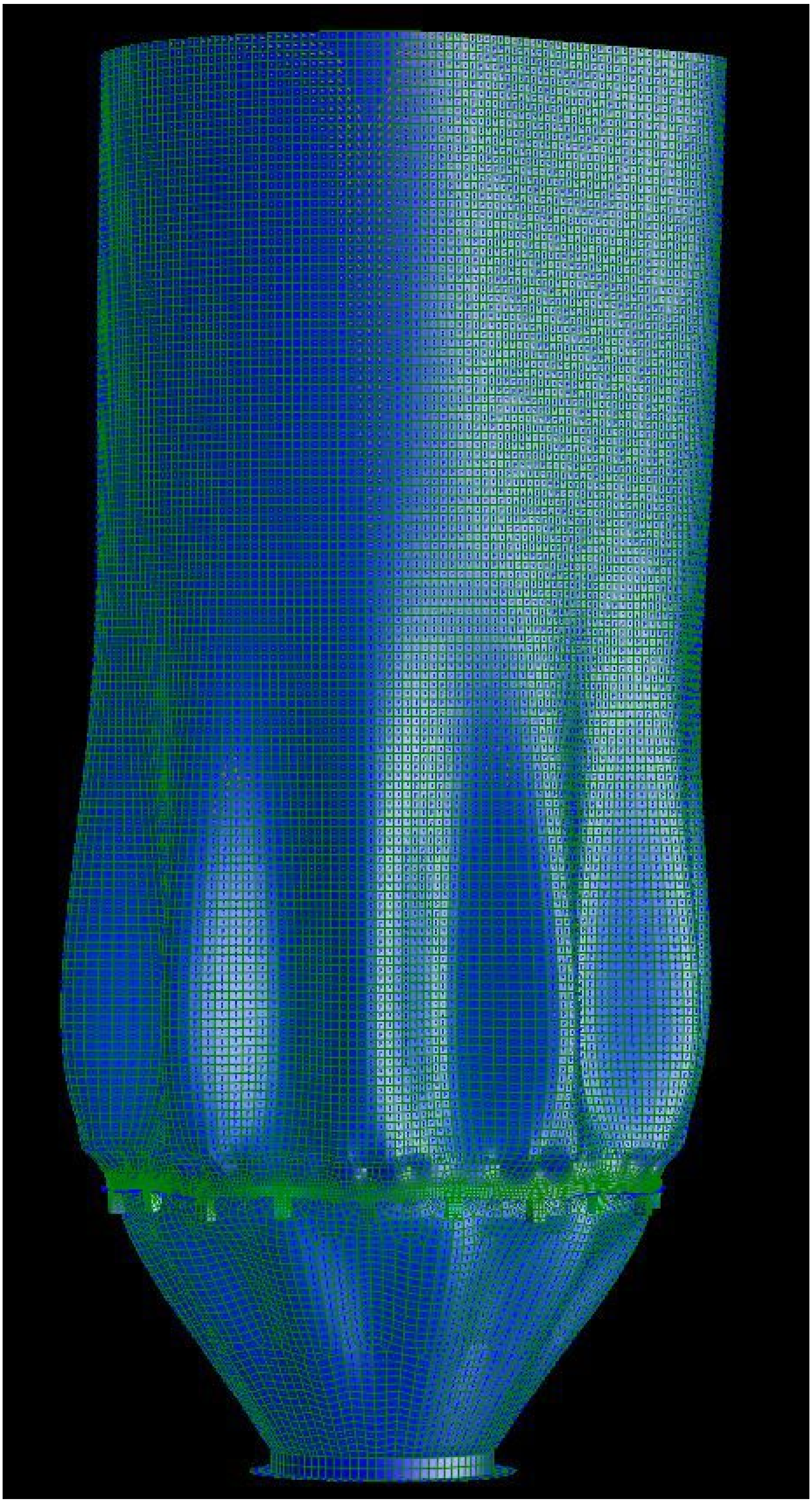


Figure 37: The deflection of the flat-walled silo under the lower-lower case. Front View.

Chapter 6

Conclusion

6.1 Summary of Findings

The stresses acting on the thin-walled silo corrugations using Strand7 were investigated. Solving the analysis for the silo, Strand7 used the three load cases of the various upper and lower bound mechanics from AS3774-1996, in particular section 6. The modification of the wall thickness and shape of the corrugations were investigated after initial design and analysis were completed on an industry standard silo wall corrugation to determine if the current design was the optimum and if reductions in thickness and shape can be made to reduce a variety of expenses while also being structurally capable of handling the flow loads without failure. The following is a summary of key findings of the research;

- The ribs or grooves of the silo wall are the most important area of the sheeting in its structural ability.
- The current industry standard wall corrugation can be reduced to a thickness of 1.2mm, allowing theoretical and physical testing is completed, for small scale silos.
- Flat-walled silos are not a safe silo design structural without the help of structural elements inside the silo to replace the ribs found in corrugated silos.
- A larger (longer) rib can handle the stresses and forces acting on the silo wall better than the current (shorter) ribs under the same loading and size of silo.

Overall, the silo design currently is an optimum design for large scale silos, but the smaller silos, which is more utilised by smaller farm operations, may be more optimum with a larger rib and reduced thicknesses. This would reduce material and in turn, reduce the cost for construction and maintenance.

6.2 Project Outcomes

This project aims to investigate the current design and thin-walled grain silos and develop models that identify stresses of silo walls, and explore potential changes to these designs to reduce and/or remove undesirable stresses. These undesirable stresses can be subjective to what the use of the silo is. The following points achieved this.

1. **Complete initial research into current silo design and the stresses that must be overcome to have a successful design.**

Initial research into current silo standard of AS3774-1996 (Loads on bulk solids containers), gave great insight into the current requirements of silos in Australia and how they need to be designed and loaded in the analysis stage. This, with research from various number of sources and from engineers who have worked in silo design, a greater understanding of the flow loads and how bulk solids interact and move within silos.

2. **Establish characteristics of bulk grain and determine upper and lower bounds of surface and bulk characteristics, by using information learnt from TUNRA Bulk Solids Workshop.**

The TUNRA Bulk Solids Workshop was a massive help for this project and was very knowledgeable for this thesis and my future career. The first three lectures were the most critical information for this project, and they help understand what a silo that holds grain should be doing and how it is possible to achieve the required flow through the design and analysis stage. It was also a significant part of the literature review and had minor influences on the loadings and combinations for the silo analysis.

3. **Research current industry silo design and models to establish a base model for initial analyses.**

From the current standard designs from local silo manufacturers in the Southern Downs were used as the base model as an 'industry standard' design to firstly analysis and see how the silo acts under loading. These models allowed for three different models, either diameter on bulk solid being analysed, and this would later determine what designs would be modified after the initial analysis.

4. **Analyse Strand7 models of current silos and determine the structural responses over the mechanical characteristics of the bulk solids.**

The initial models showed that the ribs of the silo attracted the largest loads and stresses and highlighted that area as the required area for modifications in the later stages of the project. These ribs or grooves are designed to attract larger amounts of stress and loads from the bulk solid, and from the initial models, it was shown that it is modelled correctly and acting as a silo should with the design being used.

5. **Explore the number of stresses, select the critical aspects of bending stress cycle range, collapse load and corrugation shape, and refine the design using more in-depth corrugation and/or thicknesses.**

From the initial models of both 2.5m and 3.6m diameter, the first refinement was decreasing the thickness of the models between 1.0mm to 1.5mm to have a comparison of the stresses and forces acting on the ribs with less material. The Upper-Lower case meant that many of the 3.6m diameter cases failed the 550MPa stresses and had over 200kN/m acting on the ribs. The larger silo designs were improbable to be able to be reduced in thickness. However, the 2.5m diameter silo was able to be reduced to a potential 1.2mm thickness. This resulted in the modified shape of the

6. **Further development of Strand7 models to refine the stresses and analysis causes and solutions to reduce undesirable areas of stress to determine the best possible design types to remove and utilise stresses acting on the silo walls.**

As it is not possible to remove the stresses acting on the silo walls, the design of the silo corrugation was modified to see if a larger rib would impact the silo. These modifications showed that the larger rib was an optimum design for the size and bulk solid of the material, and changes to thickness could also be a possibility, Australian Standards allowing.

7. **Draw conclusions on changes in the current silo design that could benefit the industry.**

The current design was deemed to be optimum for all designs of silos that were analysed. The only changes could be a slight reduction in the thickness; however, this reduction decreases with the increase in the size of the silo. A potentially better design of wall corrugation with a 150mm rib length was analysed, and it has the potential to be a better design for smaller scale silos, but this would require physical testing to determine this.

6.3 Further Research

This research has experimented with the ideas around thin-walled silos and their potential changes in design. There are several further research and investigation that would greatly benefit to enhance the knowledge and ability of the wall corrugation and the silo structure itself. The following research exists:

- Experiment in finite software to explore other aspects of the silo in relation to the changes in the wall corrugation.
- Physical experiments into wall corrugation design to see comparison to the finite software and real-world forces.
- Experiment with finite software in different loading cases and the effects not only on the wall corrugation but all structural aspects of the silo.
- Studies into the plausibility of reduction in thickness or change in design within the industry to see if there is enough need financially and if it can be a sustainable change.

Chapter 7

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Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For:	Riley Doherty
Title:	Behaviour & Design of Corrugations in Thin-Walled Silos
Major:	Civil Engineering
Supervisors:	Karu Karunasena
Enrolment:	ENG4111 – EXT S1, 2023 ENG4112 – EXT S2, 2023
Project Aim:	To investigate the current design and analysis of thin-walled grain silos and develop models that identify stresses of silo walls and explore potential changes to these designs to reduce and remove undesirable stresses

Program: Version 1, 13th March 2023

Example below

1. Initial research into the current silo design and the stresses that must be overcome for a successful strategy.
2. Establish characteristics of bulk grain and determine upper and lower bounds of surface and bulk characteristics.

3. Current Research industry silo design and models.
4. Current and analyse Strand7 models of current silos and determine the structural responses over the mechanical characteristics of the bulk solids.
5. Explore the number of stresses and select the critical aspects of bending stress cycle range, collapse load, and corrugation shape.
6. Further development of Strand7 models to refine the stresses and analysis of causes and solutions to reduce undesirable stress areas.
7. Conclude changes in the current silo design that could benefit the industry.

If time and resources permit:

1. Explore other areas of undesirable stresses and complete steps 5-7 with these additional stresses.

Appendix B – Assessment of Consequential Effects

B.1 – Consequential Effects

Engineers Australia has set out ten aspects presented below and is part of the ongoing sustainability and engineering practice initiative.

1. **Development today should not undermine the development and environmental needs of future generations. (Impact of this project on finite resources and waste production):** This project does have some benefits to resources and waste production as it analyses the ability of grain storage in silos used today. Potential modifications can occur from this analysis. If it does not require new silo designs, it may impact the structure and life span of existing and future silo designs to prevent waste generation due to the removal of existing structures and the waste of lost products inside silos.
2. **Environmental protection shall constitute an integral part of the development process. (Identify the environmental protection dimensions of your project work which will need to be accommodated in your designs.):** In regards to the environmental protection requirements of the project, the design and analysis will consume energy in an office space and equipment and waste from the designer. If the office area were powered using renewable resources, then this would neglect the energy consumption. Physical works are not planned for this project, but the project of the environment will be heavily considered if these works ever come forward.

3. **Engineering [and surveying] people should take into consideration the global environmental impacts of local actions and policies. (Assess the (potential) global impact of your project work or what might flow from it in future years, i.e. not**

just the immediate impacts this year (which are likely to be small).): The flow of the analysis can create a new silo design that can help reduce the losses in the current designs of silos. The best possible storage design can be used to help reduce food waste, and the future effects would reduce pollution in transport and storage due to the lost product and would allow the food supply chain to become a more streamlined process by removing the significant losses associated with storage.

4. **The precautionary approach should be taken – scientific uncertainty should not be used to postpone measures to prevent environmental degradation. (Ordinarily, the general rule of caution may be stated as: 'If in doubt – don't.' and this is obviously sensible. However, with respect to on-going or potential environmental degradation, a proactive approach is expected, i.e. an approach of: 'do nothing because we're not absolutely certain' is not 'best practice'. Does the need for action despite incomplete or uncertain knowledge apply to your project work?);** Environmental precautions can be taken during the analysis and design of the project, as per point 2. Physical works and long-term costs and impact on the environment would vary depending on what studies and works that would occur.

5. **Environmental issues should be handled with the participation of all concerned citizens. (Assess who might be impacted (or who might perceive an impact) and set out a plan for their involvement.):** If physical developments occurred from the results of the analysis in this project, the impacted people within the agriculture industry and, in some cases, the waste of the existing structures that would need to be replaced. The plan for the agriculture industry would be to evaluate the outcomes of replacing the current structures by taking the cost of replacement, design, and the potential losses due to product losses with current silo designs. After this evaluation had been completed, the existing silos would need to be recycled in the appropriate use of the new techniques or other services.

6. **The community has a right of access to, and an understanding of, environmental information. (Structure the appropriate parts of your Project Appreciation – and your dissertation – such that these aspects of your work are easily accessible (i.e. by appropriate headings / sub-headings) and readily understandable by the**

general community.): This section of the consequential effects are not overly applicable to this dissertation. If physical work evolves from this report, the environmental issues and risk mitigation would be accessible from council. This dissertation can be easily read, and information found from the table of contents.

7. **The polluter should bear the cost of pollution, and so environmental costs should be internalised by adding them to the cost of production. (Identify these (potential) costs, even if they will not form part of your project work cost this year.):** The only costs from the project are the use of power and the programs from Osborn Consulting Engineers. The costs would amount to roughly $1000 from the programs of Strand7 and SolidWorks.

8. **The eradication of poverty, the reduction in differences in living standards and the full participation of women, youth and indigenous people are essential to achieve sustainability. (Identify potential impact of your project work on any such groups: if you feel the answer is 'nil' then this needs to be justified. Consider, for example, process automation which results in a saving of labour – does the saving of labour benefit those whose labour is no longer required?):** The listed groups may be positively affected by this project as the improvements in food storage will massively help the storage and distribution of the grains through regions in rural and remote areas such as deserts and other poverty-stricken regions of the world.

9. **People in developed countries bear a special responsibility to assist in the achievement of sustainability. (Examine the scenario in which the outcomes of your project work is utilised in all countries of the world, undeveloped as well as developed. Are the sustainability outcomes the same; or is there a different (perhaps rather more negative?) sustainability outcome for undeveloped communities?):** If this project had the results to impact all areas of the globe, the responsibility of developed nations would be to help develop the analysis to become a real-world physical design that can be utilised to have a sustainable food storage system that reduces the amount of waste product in terms of loses in cost and food.

10. **Warfare is inherently destructive of sustainability, and, in contrast, peace, development and environmental protection are interdependent and indivisible. (How might your project work, and/or its outcomes, contribute to international understanding?):** If the global food supply is shared equally between the developed agricultural nations and an understanding exists that it is everyone's understanding to create and improve supply chain demands, then this analysis may allow for a greater understanding of the reduction of waste and, in turn, create a supply chain that continues to provide grain to countries that require it with less loses they currently experience.

B.2 – Ethical Responsibility

According to the Engineers Australia Code of Ethics, engineers are obligated to utilise their expertise and abilities for the betterment of society and to establish sustainable engineering solutions for the future. Engineers must adhere to the general regulations of Engineers Australia concerning competence, continuous professional development, and the code of ethics (Engineers Australia, 2019). The code of ethics comprises the following principles:

1. Displaying Integrity
2. Practicing with Competence
3. Demonstrating Leadership
4. Advocating for Sustainability Throughout this study, utmost caution has been taken to ensure strict adherence to the Engineers Australia code of ethics.

Appendix C – Risk Assessment

As this project has no real-world design or testing, the risks are only related to the design aspect and, the office space that the analysis will be done in. The risks related are using incorrect standards and assumptions and getting results that are not reflective of the aim of the project. All risks have little to no real-world implications if they occur.

Below is the risk assessment for this project.

Most Likely Consequence

consequence	safety	Environment	equipment
disastrous	Fatality	Release/impact outside the site boundary with long term major damage. Extensive public alarm, media coverage	Complete loss of site / Maximum foreseeable event >$10,000,000
critical	Disabling injury – i.e. amputation and/or permanent loss of bodily function	Release/impact outside the site boundary with temporary damage. Major public alarm, attracting media coverage	Partial loss of site / Major business interruption event >$1,000,000
serious	Non-permanent injury or ill health with the potential of lost time	Release/impact within the site boundary with significant damage and process/business disruption. Serious public alarm	Serious property or equipment damage / Interruption to production capability >$100,000
moderate	Injury requiring medical review	Release/impact within the site boundary with minimal damage and process/business disruption. Moderate public alarm	Property or equipment damage / Interruption to production capability > $1,000
minor	Injury resulting in First Aid	Release/impact contained in immediate vicinity. No public alarm	Insignificant property or equipment damage / Interruption to production capability < $1,000

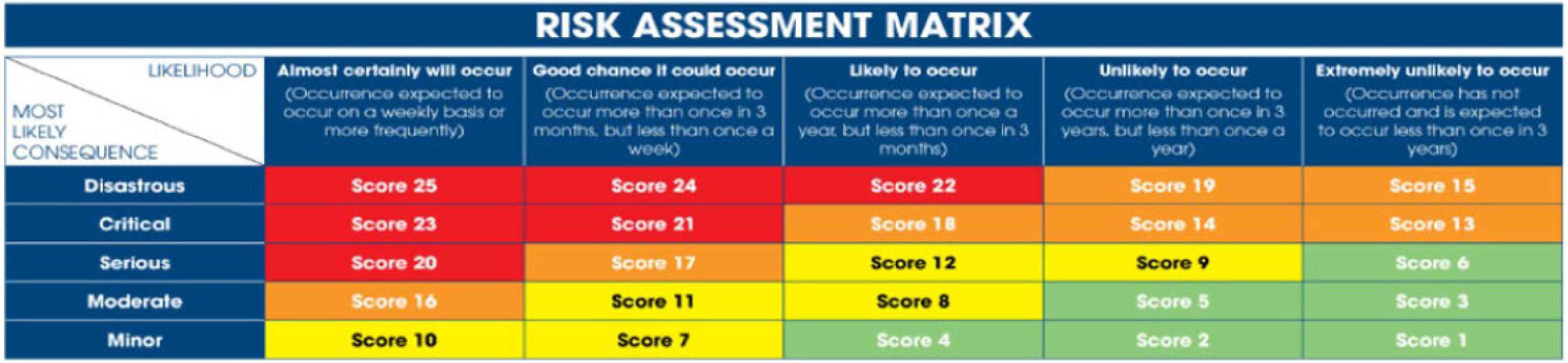
HAZARD DESCRIPTION Completing Design Process	**Actual Hazards**	**Risk Rank (before)**	**Controls**	**Risk Rank (after)**
Office		8		5
	Trip hazards, poor ergonomics, poor hydration, and nutrition,		Ensure clean and organised office space with no cables, or other trip hazards on the floor. Purchase and setup good quality ergonomic office equipment with pre work	

			stretches, frequent standing, sitting, and moving. Ensure plenty of water and healthy nutrition throughout each day	
Design		16		8
	Incorrect methodology for design		Ensure to use of relevant standards, guidelines, and legislative documents. Ensure correct use of software programs. Verify results of software outputs comparing results with design guidance calculations	
Intellectual Property	Lose or use of property incorrectly, resulting in incorrect or plagiarised work	9	Cite all sources and resources used during the project Ensure correct data is used in analysis to reduce risks of plagiarism	3

Appendix X - Risk Assessment **Project / Task No:**	**Project ID:**	**Project Title:**	Behaviour & Design of Corrugations in Thin-Walled Silos	**Initial Date**	20/02/2023

Review Date:	09/07/2023	**Rev No: 1**	1	**Client:**	USQ	**HAZOP Facilitator:**	Riley Doherty

Reviewed Standards or legislation:	**For Design Phase** • • Australian Standard AS 3774:1996 Loads on bulk solids containers • • Roberts, A.W." Basic Principles of Bulk Solids Storage, Flow and Handling". TUNRA Bulk Solids Handing Research Associates, The University of Newcastle. 1998. • • EN1991-4 – Eurocode 1 Actions on Structures, Part 4 Silos and Tanks • • Roberts, A.W. (2014) "Developments in Silo Loadings Research Over the Past 120 Years, Australian Bulk Handling Review, Vol. 19, No. 6, November/December 2014 (pp.24-32) • • Kobylka, Molenda, & Horabik. (2019). Loads on grain silo insert discs, cones, and cylinders: Experiment and DEM analysis. Elsevier, Powder Technology (343), 521–532.



RISK ASSESSMENT MATRIX

MOST LIKELY CONSEQUENCE / LIKELIHOOD	Almost certainly will occur (Occurrence expected to occur on a weekly basis or more frequently)	Good chance it could occur (Occurrence expected to occur more than once in 3 months, but less than once a week)	Likely to occur (Occurrence expected to occur more than once a year, but less than once in 3 months)	Unlikely to occur (Occurrence expected to occur more than once in 3 years, but less than once a year)	Extremely unlikely to occur (Occurrence has not occurred and is expected to occur less than once in 3 years)
Disastrous	Score 25	Score 24	Score 22	Score 19	Score 15
Critical	Score 23	Score 21	Score 18	Score 14	Score 13
Serious	Score 20	Score 17	Score 12	Score 9	Score 6
Moderate	Score 16	Score 11	Score 8	Score 5	Score 3
Minor	Score 10	Score 7	Score 4	Score 2	Score 1

Appendix D – Resources and Timelines

Required Resources:

From Osborn Consulting Engineers

- Use of Strand7 software
- Australian Standards
- Basic Silo Designs/Drawings
- Enrolment in TUNRA bulk solids Course – Completed

From USQ

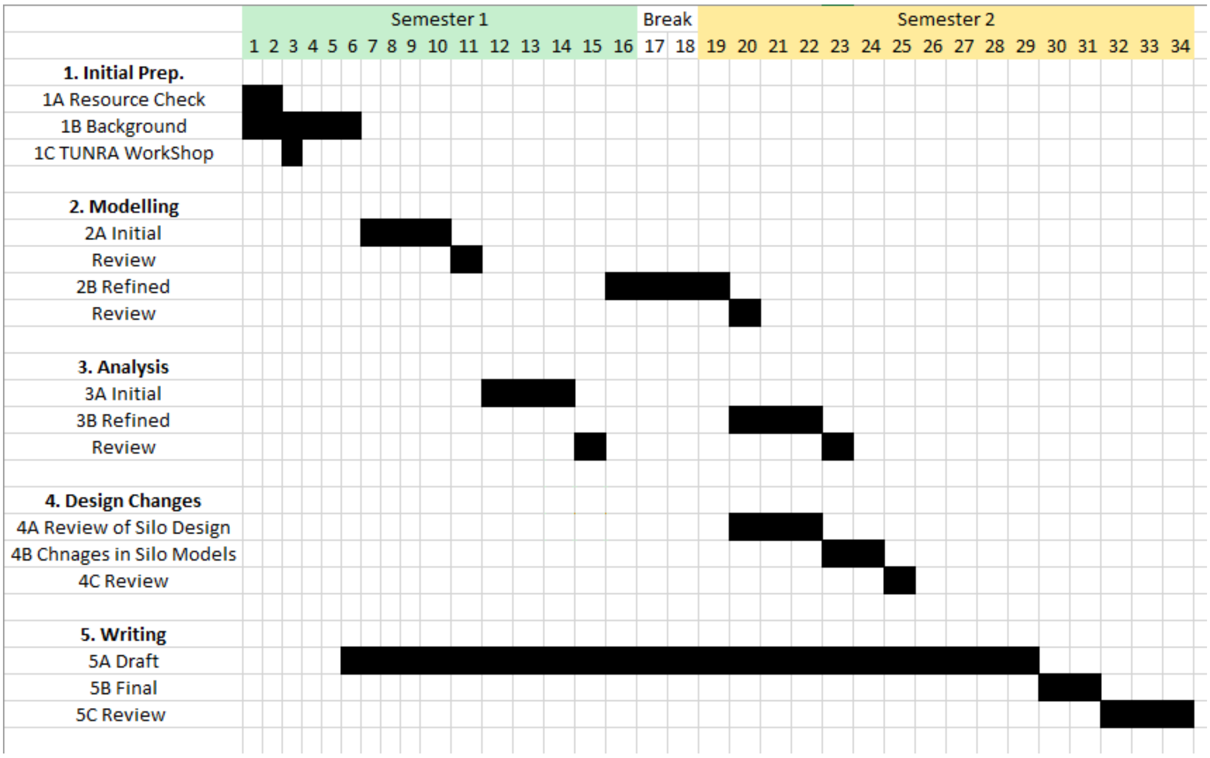
- n/a

No extra physical resources are required other than computers, which can be accessed. If any additional resources are necessary, they will be added, and the needs of that resource will be detailed.

All resources from Osborn Consulting Engineers can be used and sufficiently supplied. If silo drawings cannot be provided, other means will be taken to get detailed drawings.

Contact with supervisor Karu Karunasena will be roughly fortnightly and over email. Additional meetings and phone calls will be set up when required. During certain stages, phone calls and Zoom meetings will be set up to discuss the problems and ideas to help produce the required standard of work for this project.

Below is the timeline for the project.



	Semester 1																Break		Semester 2															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1. Initial Prep.																																		
1A Resource Check	■	■																																
1B Background	■	■	■	■	■	■																												
1C TUNRA WorkShop			■																															
2. Modelling																																		
2A Initial							■	■	■	■																								
Review											■																							
2B Refined																■	■	■	■															
Review																				■														
3. Analysis																																		
3A Initial												■	■	■																				
3B Refined																				■	■	■												
Review															■								■											
4. Design Changes																																		
4A Review of Silo Design																				■	■	■												
4B Chnages in Silo Models																							■	■										
4C Review																									■									
5. Writing																																		
5A Draft						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
5B Final																														■	■			
5C Review																																■	■	■

Appendix E – Load Case Tables and Graphs for Strand 7

E.1 3.6m Diameter Silo – Wheat – 6 Sheets

Table 14 – Lower/Lower Bound Load Table (3.6m Dia. Wheat – 6 Sheets)

Case	LL			
	INITIAL FORCES		FLOW FORCES	
z (m)	Normal kPa	Friction kPa	Normal kPa	Friction kPa
0.00	0.00	0.00	0.00	0.00
0.48	1.77	0.51	2.70	0.61
0.95	3.43	0.99	5.24	1.18
1.43	4.99	1.43	7.61	1.72
1.91	6.45	1.85	9.85	2.22
2.39	7.82	2.25	11.94	2.70
2.86	9.11	2.62	13.90	3.14
3.34	10.31	2.96	15.75	3.56
3.82	11.45	3.29	17.48	3.95
4.30	12.51	3.60	19.10	4.31
4.77	13.51	3.88	20.62	4.66
5.25	14.44	4.15	22.05	4.98
5.25	23.20	6.22	37.39	10.02
5.52	24.84	6.66	36.08	9.67
5.78	26.48	7.09	34.57	9.26
6.05	28.12	7.53	32.82	8.79
6.32	29.75	7.97	30.82	8.26
6.58	31.39	8.41	28.55	7.65
6.85	33.03	8.85	25.97	6.96
7.12	34.66	9.29	23.05	6.18
7.38	36.30	9.73	19.73	5.29

Table 15 – Lower/Upper Bound Load Table (3.6m Dia. Wheat – 6 Sheets)

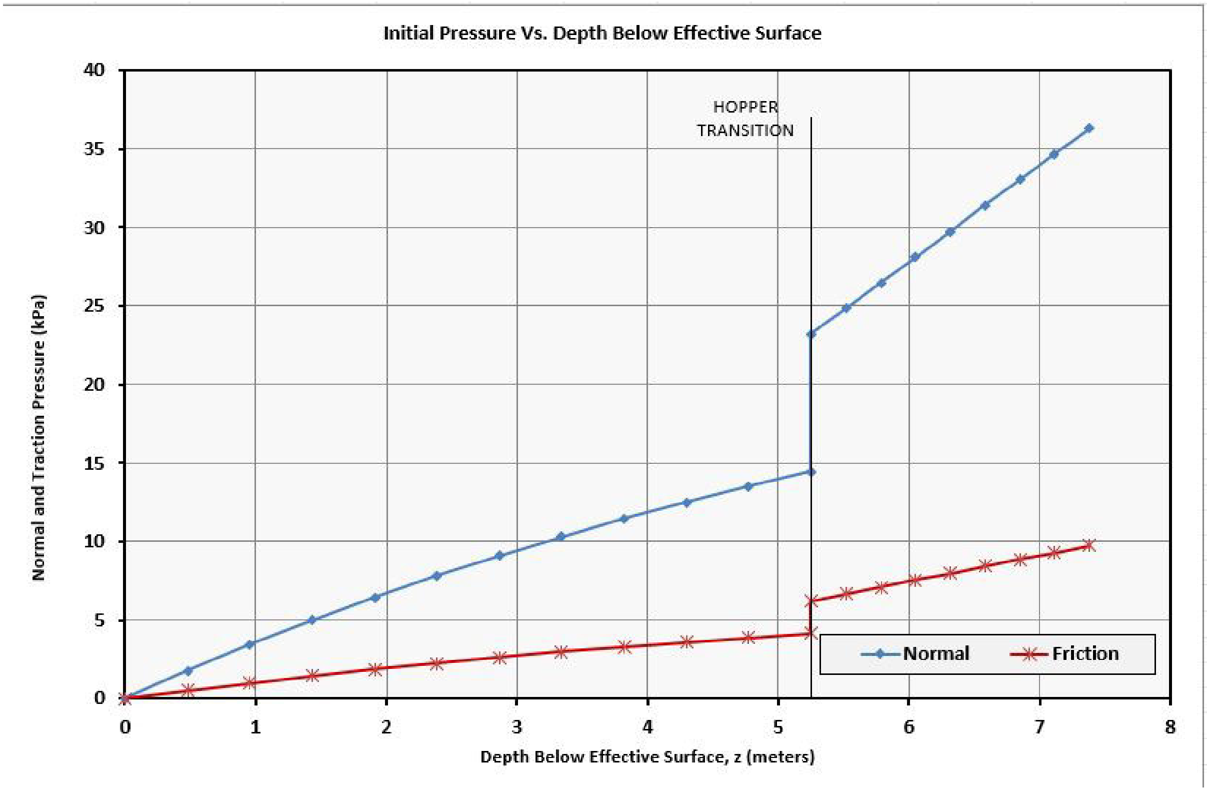
Case	LU

	INITIAL FORCES		FLOW FORCES	
z (m)	Normal kPa	Friction kPa	Normal kPa	Friction kPa
0.00	0.00	0.00	0.00	0.00
0.48	1.47	0.42	2.24	0.51
0.95	2.86	0.82	4.36	0.98
1.43	4.17	1.20	6.37	1.44
1.91	5.43	1.56	8.28	1.87
2.39	6.61	1.90	10.10	2.28
2.86	7.74	2.22	11.82	2.67
3.34	8.81	2.53	13.45	3.04
3.82	9.82	2.82	15.00	3.39
4.30	10.79	3.10	16.47	3.72
4.77	11.70	3.36	17.86	4.04
5.25	12.57	3.61	19.19	4.33
5.25	19.86	9.26	28.64	13.35
5.52	21.19	9.88	28.34	13.22
5.78	22.52	10.50	27.86	12.99
6.05	23.84	11.12	27.18	12.68
6.32	25.17	11.74	26.28	12.26
6.58	26.49	12.35	25.12	11.71
6.85	27.82	12.97	23.66	11.03
7.12	29.15	13.59	21.84	10.18
7.38	30.47	14.21	19.58	9.13

Table 16 – Upper/Lower Bound Load Table (3.6m Dia. Wheat – 6 Sheets)

Case	UL			
	INITIAL FORCES		FLOW FORCES	
z (m)	Normal kPa	Friction kPa	Normal kPa	Friction kPa
0.00	0.00	0.00	0.00	0.00
0.48	2.40	1.15	3.66	1.38
0.95	4.46	2.14	6.81	2.57
1.43	6.23	2.99	9.52	3.59
1.91	7.76	3.73	11.85	4.47
2.39	9.07	4.36	13.85	5.23
2.86	10.20	4.90	15.57	5.88
3.34	11.17	5.37	17.06	6.44
3.82	12.01	5.77	18.33	6.92
4.30	12.73	6.11	19.43	7.34
4.77	13.34	6.41	20.37	7.69
5.25	13.87	6.66	21.18	8.00
5.25	15.77	4.22	25.40	6.81
5.52	17.40	4.66	25.32	6.78
5.78	19.04	5.10	25.00	6.70
6.05	20.68	5.54	24.42	6.54
6.32	22.31	5.98	23.56	6.31
6.58	23.95	6.42	22.39	6.00
6.85	25.59	6.86	20.89	5.60
7.12	27.23	7.30	19.00	5.09
7.38	28.86	7.73	16.67	4.47

Figure 38 – Lower/Lower Bound Load Graphs (3.6m Dia. Wheat – 6 Sheets)



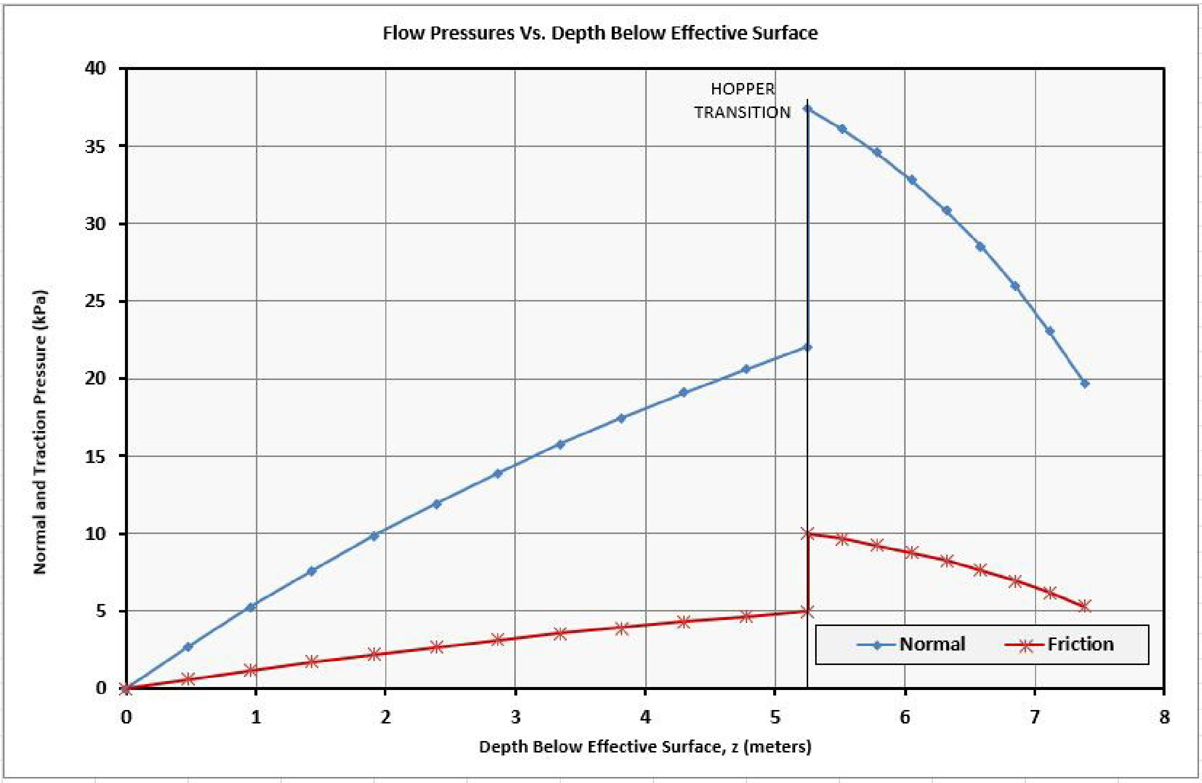
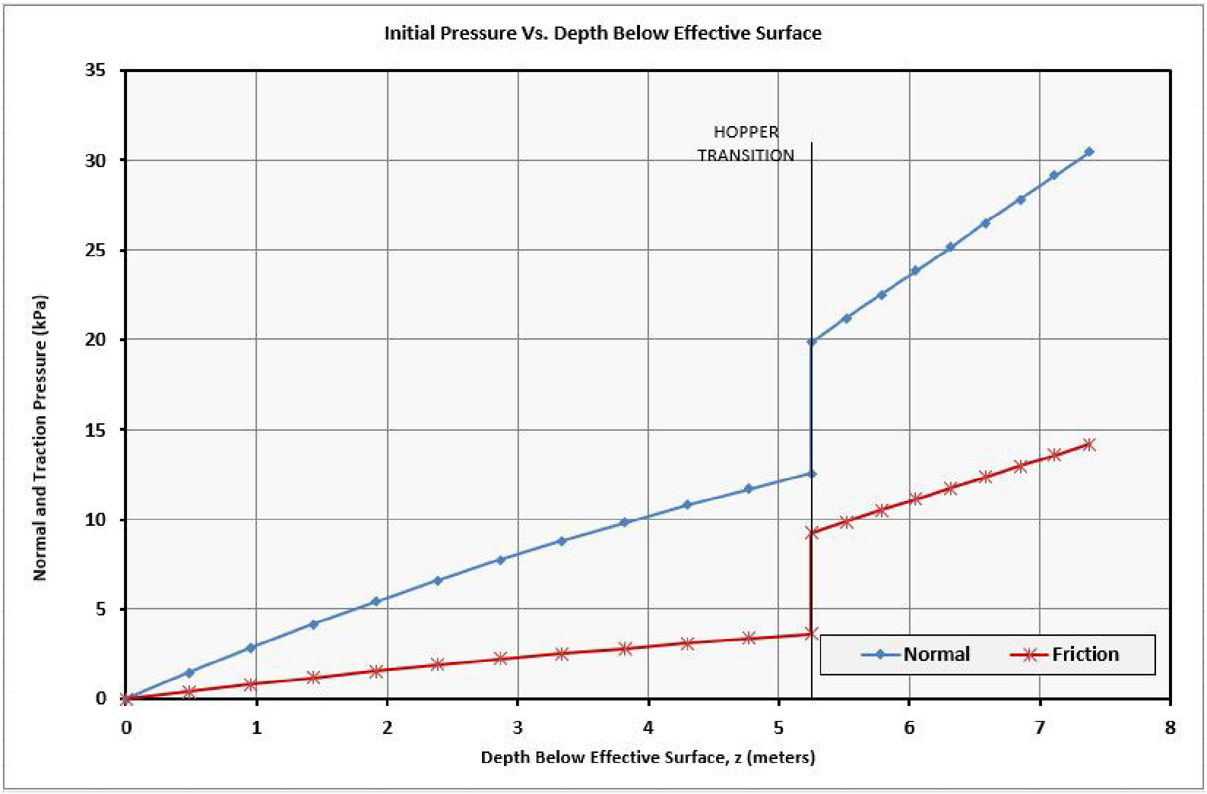


Figure 39 – Lower/Upper Bound Load Graphs (3.6m Dia. Wheat – 6 Sheets)



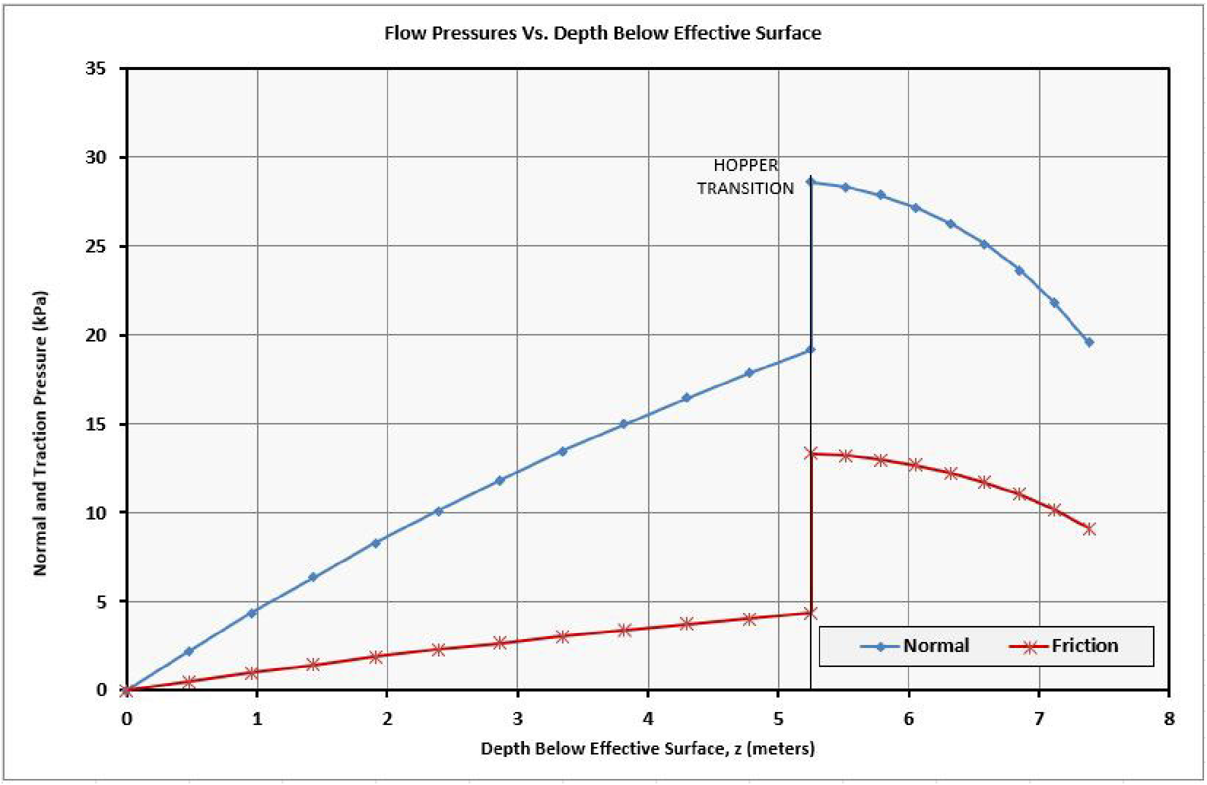
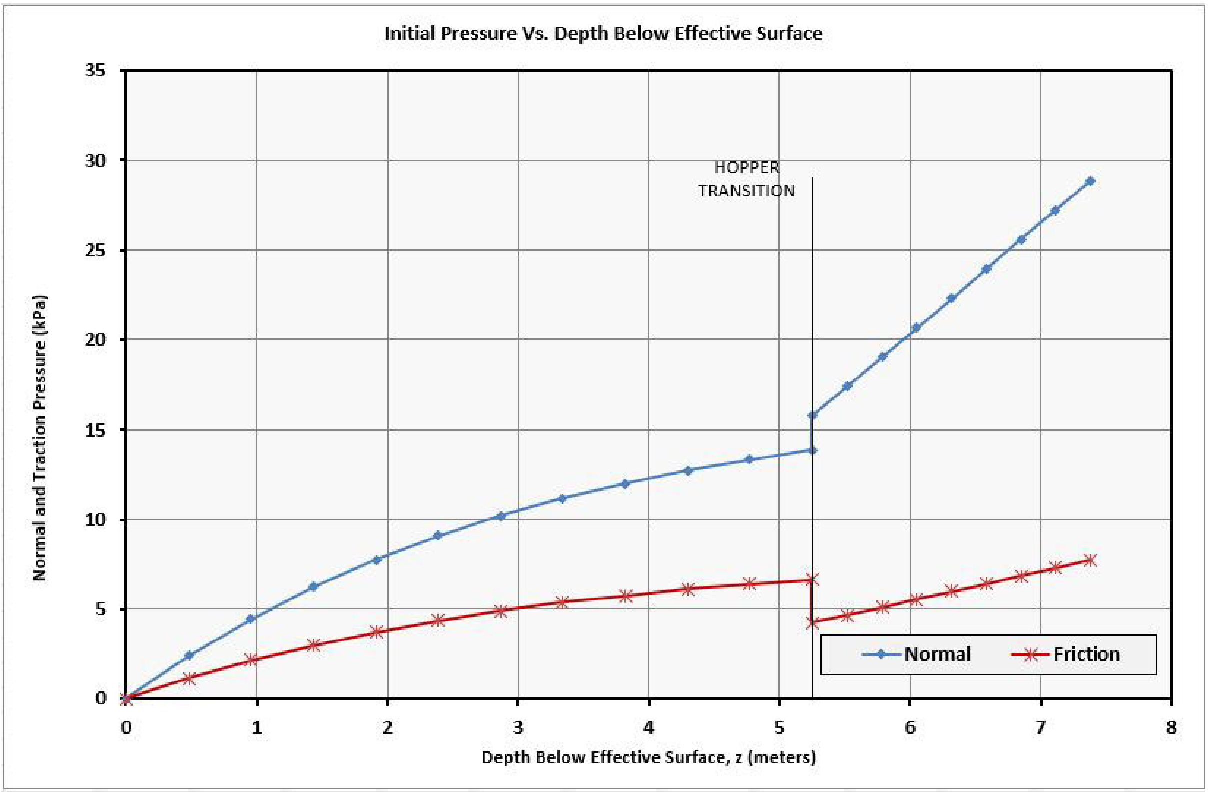
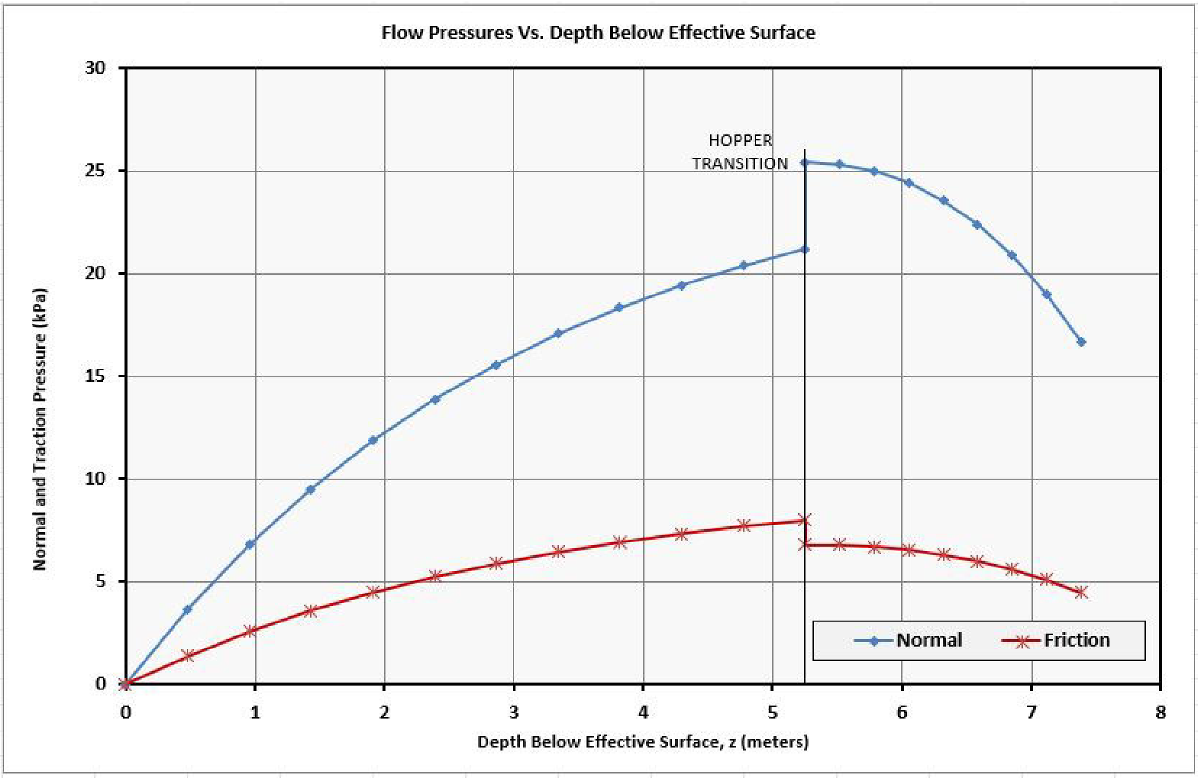


Figure 40 – Upper/Lower Bound Load Graphs (3.6m Dia. Wheat – 6 Sheets)





E.2 3.6m Diameter Silo – Meal – 8 Sheets

Table 17 – Lower/Lower Bound Load Tables (3.6m Dia. Meal – 8 Sheets)

Case	LL			
	INITIAL FORCES		FLOW FORCES	
z (m)	Normal kPa	Friction kPa	Normal kPa	Friction kPa
0.00	0.00	0.00	0.00	0.00
0.61	1.99	0.56	3.21	0.67
1.22	3.81	1.07	6.15	1.29
1.83	5.47	1.54	8.82	1.85
2.44	6.98	1.97	11.26	2.36
3.05	8.36	2.36	13.49	2.83
3.66	9.62	2.71	15.52	3.25
4.27	10.77	3.03	17.37	3.64
4.88	11.82	3.33	19.06	4.00
5.49	12.77	3.60	20.61	4.32
6.11	13.65	3.85	22.01	4.61
6.72	14.44	4.07	23.30	4.88
6.72	20.22	5.42	30.65	8.21
6.98	21.49	5.76	29.84	8.00
7.25	22.77	6.10	28.86	7.73
7.51	24.04	6.44	27.68	7.42
7.78	25.31	6.78	26.29	7.05
8.05	26.59	7.12	24.67	6.61
8.31	27.86	7.47	22.77	6.10
8.58	29.13	7.81	20.55	5.51
8.85	30.41	8.15	17.95	4.81

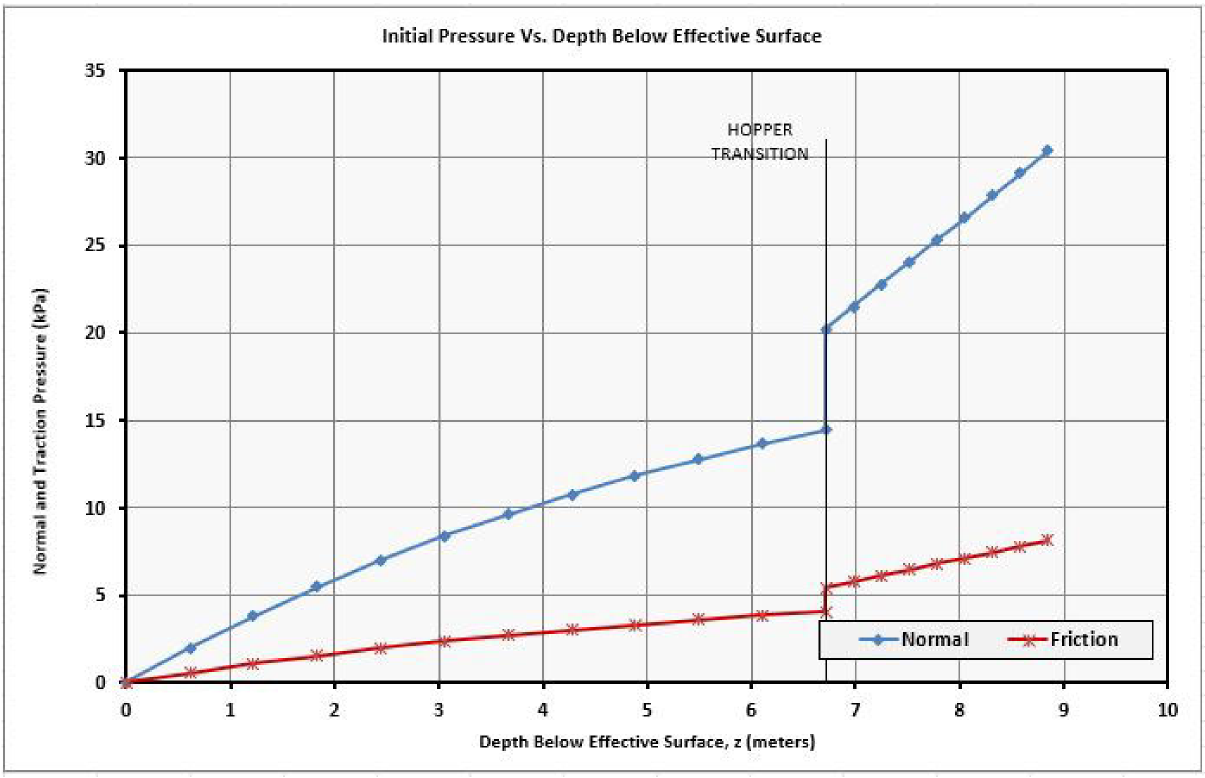
Table 18 – Lower/Upper Bound Load Tables (3.6m Dia. Meal – 8 Sheets)

Case	LU			
	INITIAL FORCES		FLOW FORCES	
z (m)	Normal kPa	Friction kPa	Normal kPa	Friction kPa
0.00	0.00	0.00	0.00	0.00
0.61	1.46	0.41	2.36	0.49
1.22	2.83	0.80	4.56	0.96
1.83	4.11	1.16	6.63	1.39
2.44	5.30	1.49	8.56	1.79
3.05	6.42	1.81	10.36	2.17
3.66	7.47	2.11	12.05	2.53
4.27	8.45	2.38	13.64	2.86
4.88	9.37	2.64	15.12	3.17
5.49	10.23	2.88	16.50	3.46
6.11	11.03	3.11	17.80	3.73
6.72	11.78	3.32	19.01	3.99
6.72	19.22	8.16	28.03	11.90
6.98	20.30	8.61	27.37	11.62
7.25	21.37	9.07	26.56	11.27
7.51	22.44	9.53	25.58	10.86
7.78	23.52	9.98	24.41	10.36
8.05	24.59	10.44	23.04	9.78
8.31	25.67	10.89	21.41	9.09
8.58	26.74	11.35	19.50	8.28
8.85	27.82	11.81	17.23	7.31

Table 19 – Upper/Lower Bound Load Tables (3.6m Dia. Meal – 8 Sheets)

Case	UL			
	INITIAL FORCES		FLOW FORCES	
z (m)	Normal kPa	Friction kPa	Normal kPa	Friction kPa
0.00	0.00	0.00	0.00	0.00
0.61	2.84	1.20	4.58	1.44
1.22	5.14	2.18	8.29	2.62
1.83	7.01	2.98	11.31	3.57
2.44	8.53	3.62	13.76	4.34
3.05	9.76	4.14	15.75	4.97
3.66	10.76	4.57	17.36	5.48
4.27	11.58	4.91	18.68	5.90
4.88	12.24	5.19	19.74	6.23
5.49	12.77	5.42	20.61	6.51
6.11	13.21	5.61	21.31	6.73
6.72	13.56	5.76	21.88	6.91
6.72	12.60	3.38	19.10	5.12
6.98	13.87	3.72	19.29	5.17
7.25	15.15	4.06	19.30	5.17
7.51	16.42	4.40	19.12	5.12
7.78	17.69	4.74	18.72	5.02
8.05	18.97	5.08	18.08	4.85
8.31	20.24	5.42	17.17	4.60
8.58	21.51	5.76	15.92	4.27
8.85	22.79	6.11	14.30	3.83

Figure 41 – Lower/Lower Bound Load Graphs (3.6m Dia. Meal – 8 Sheets)



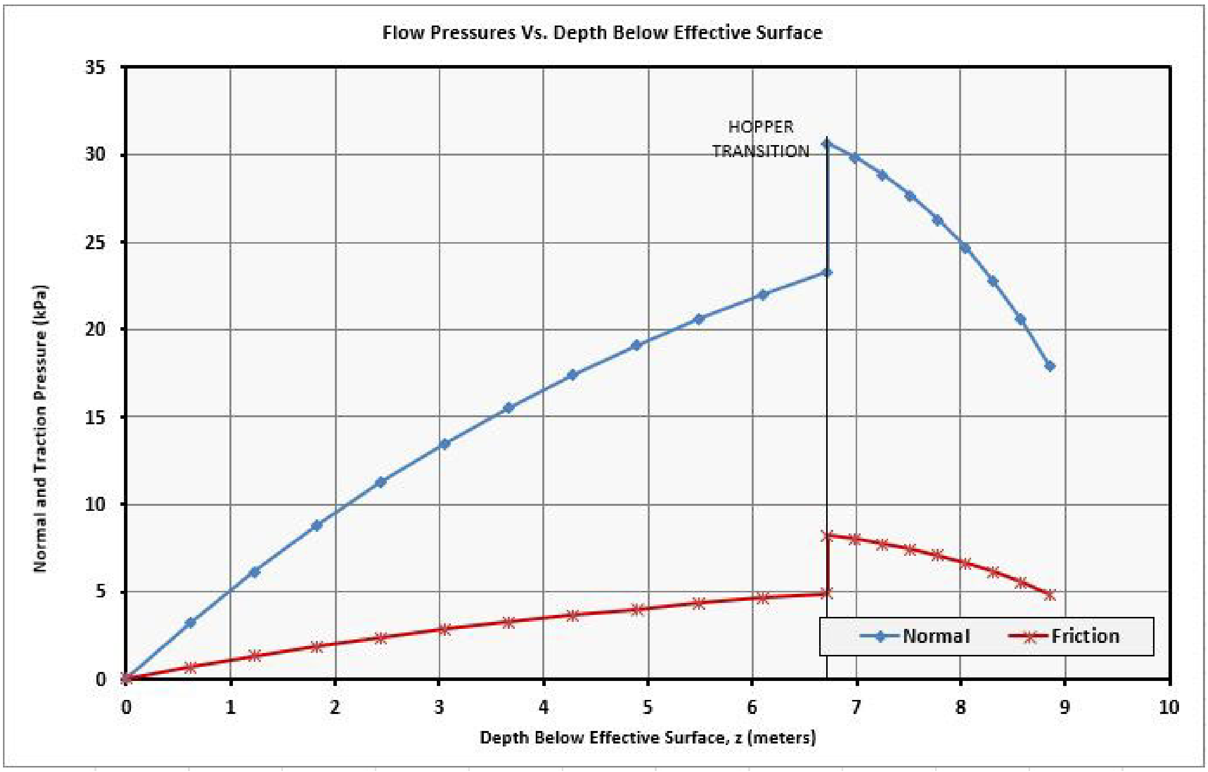


Figure 42 – Lower/Upper Bound Load Graphs (3.6m Dia. Meal – 8 Sheets)

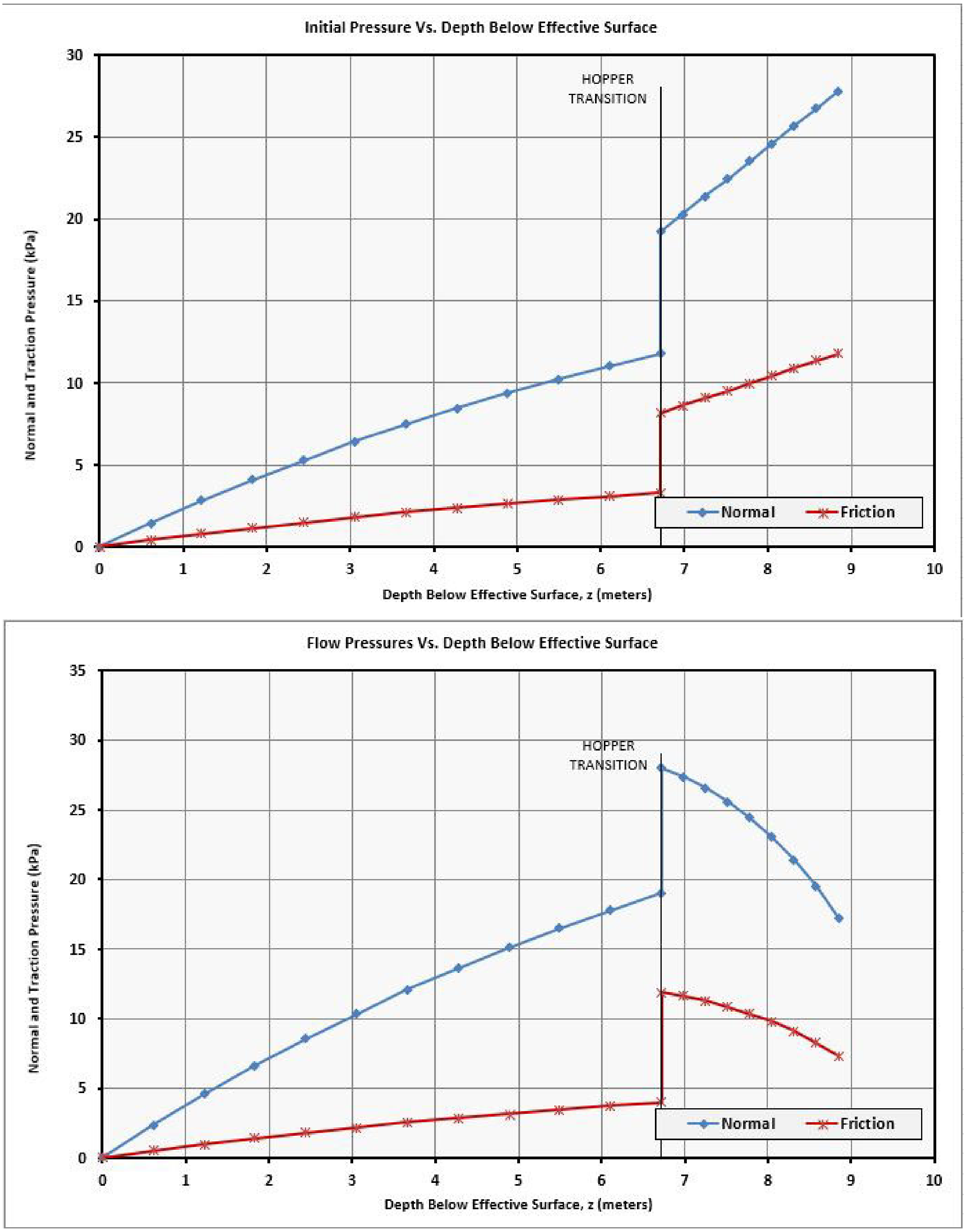
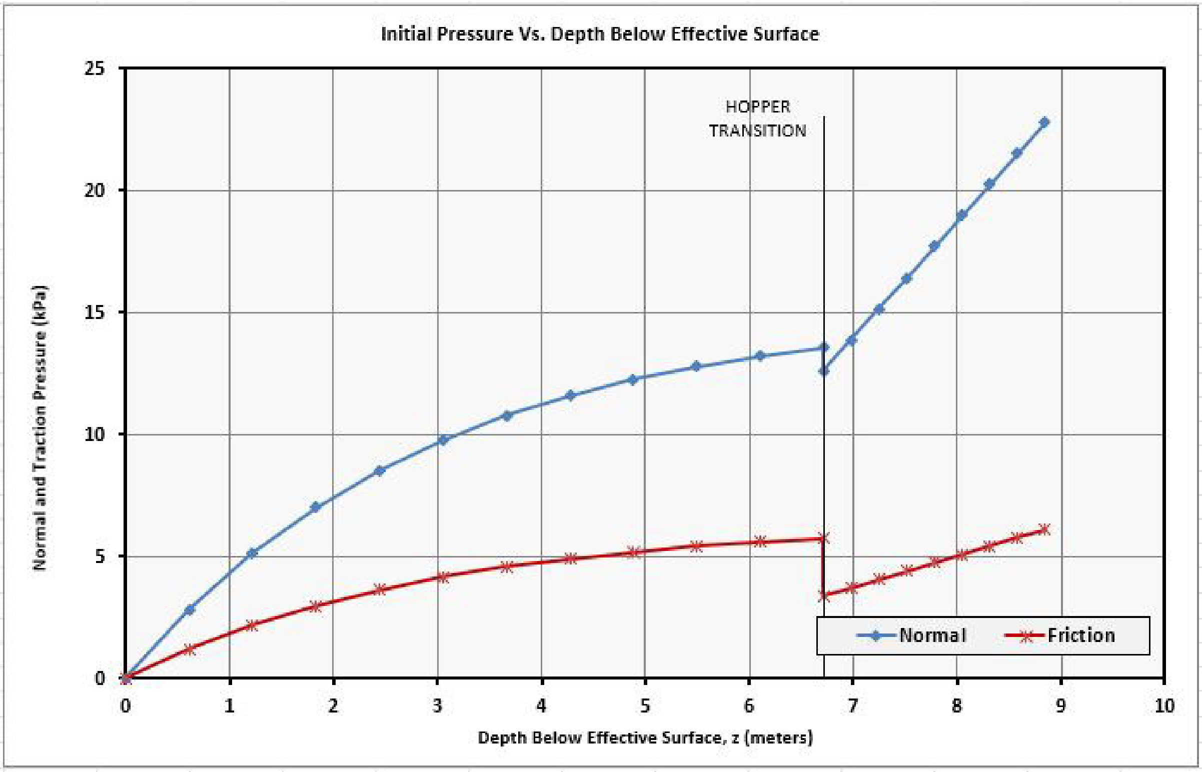
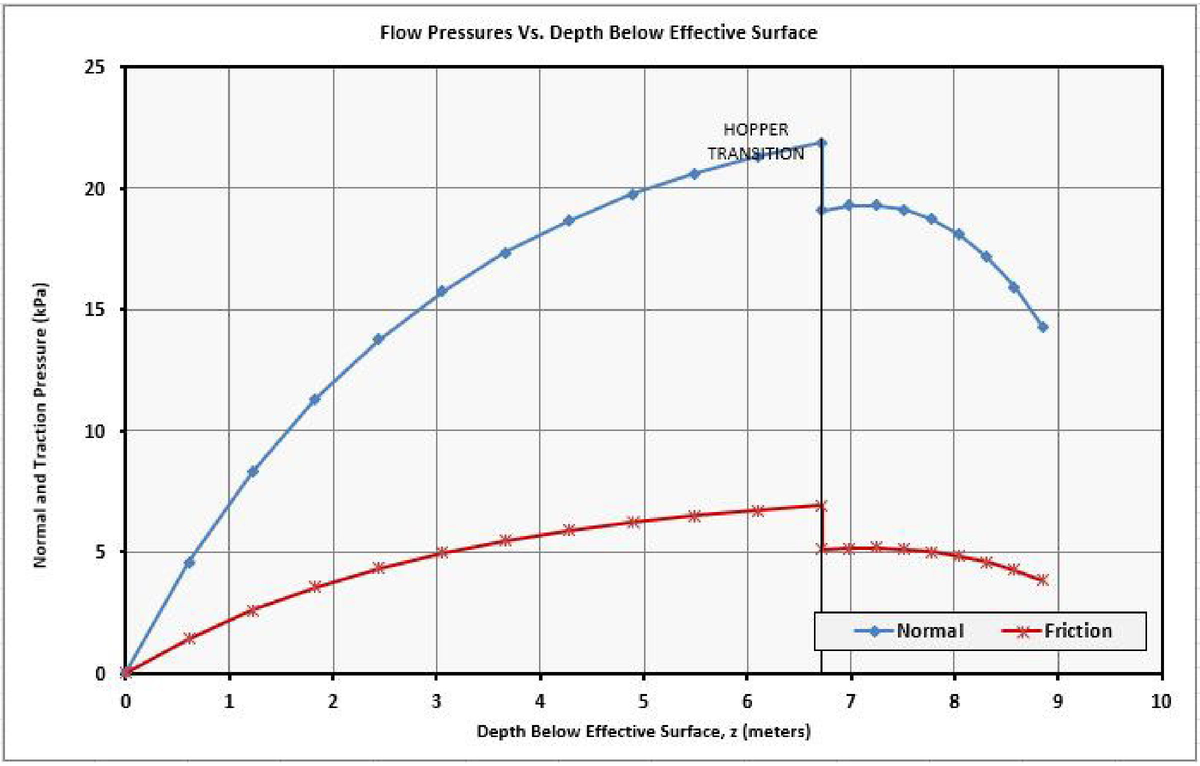


Figure 43 – Upper/Lower Bound Load Graphs (3.6m Dia. Meal – 8 Sheets)





Appendix F – Strand 7 Models & AutoCAD Drawings

F.1 3.6m Diameter Silo – Wheat – 6 Sheets

Figure 44 – Front View 3.6m Diameter Silo – 6 Sheets High (Strand7)

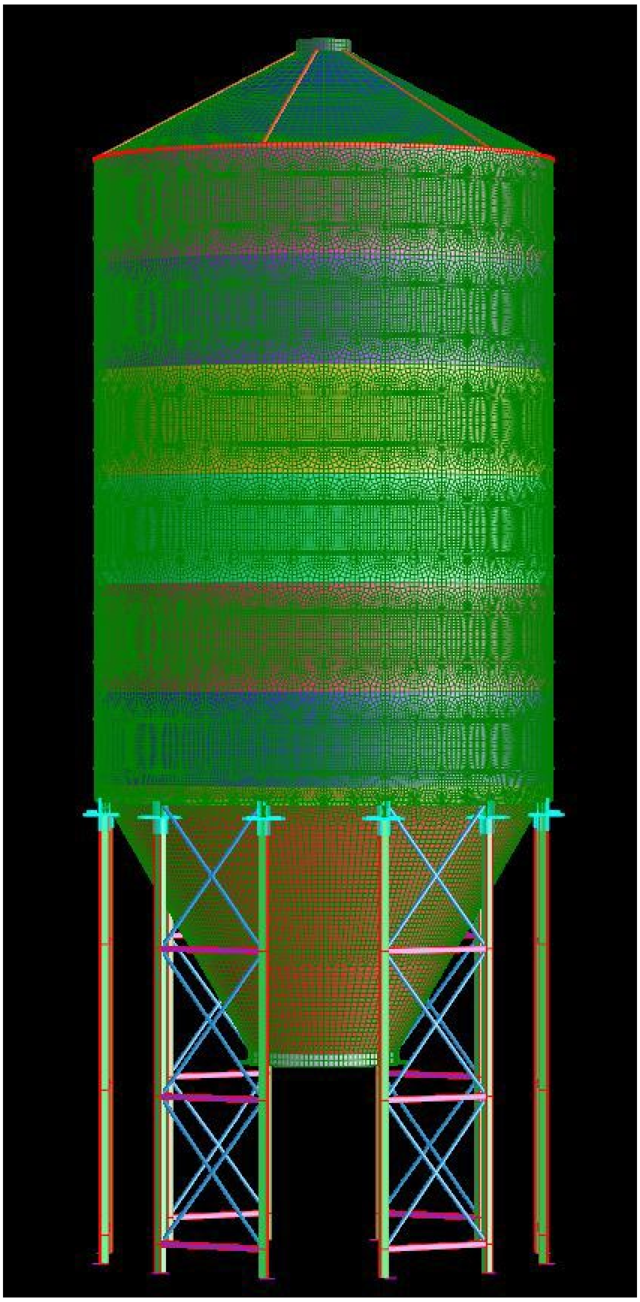
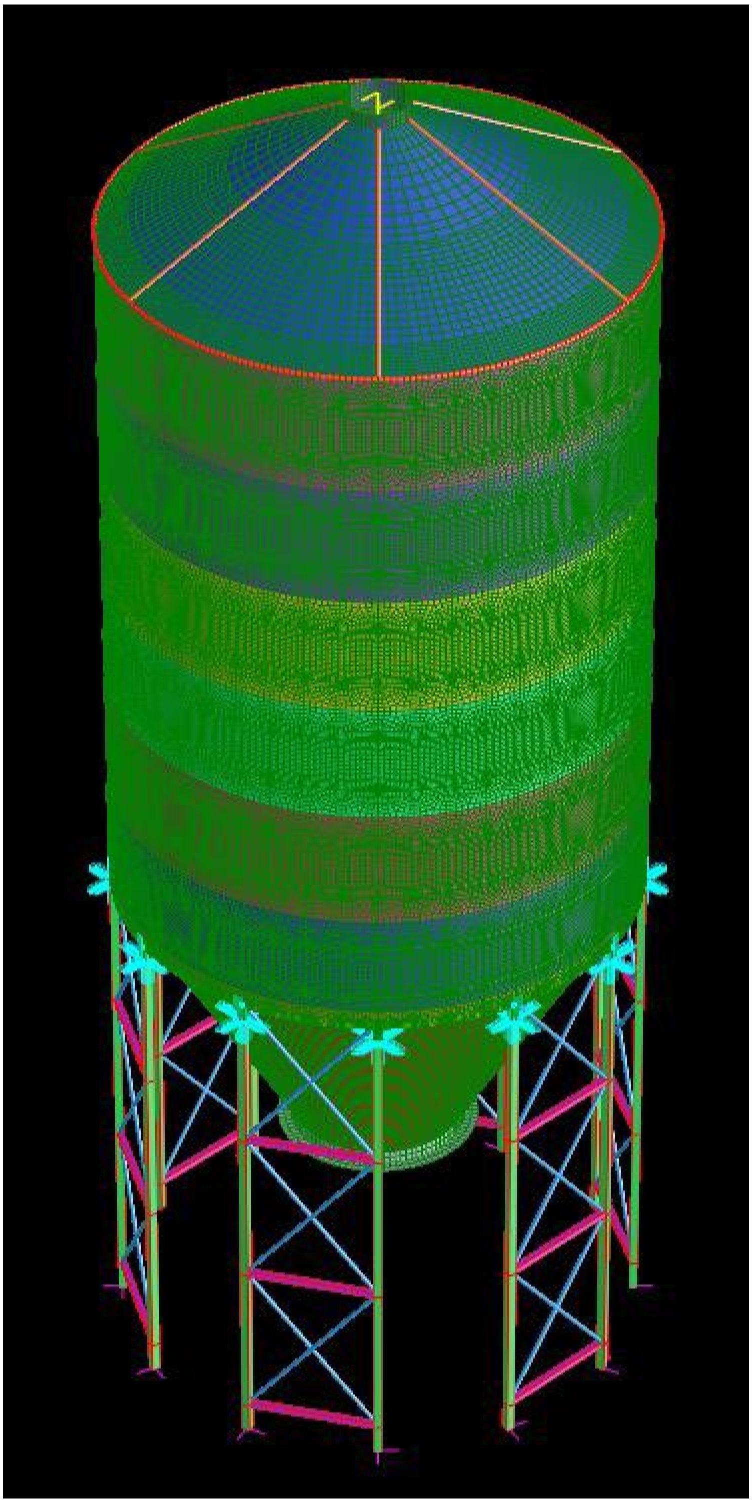


Figure 45 – Isometric View 3.6m Diameter – 6 Sheets High (Strand7)



F.2 3.6m Diameter Silo – Meal – 8 Sheets

Figure 46 – Front View 3.6m Diameter Silo – 6 Sheets High (Strand7)

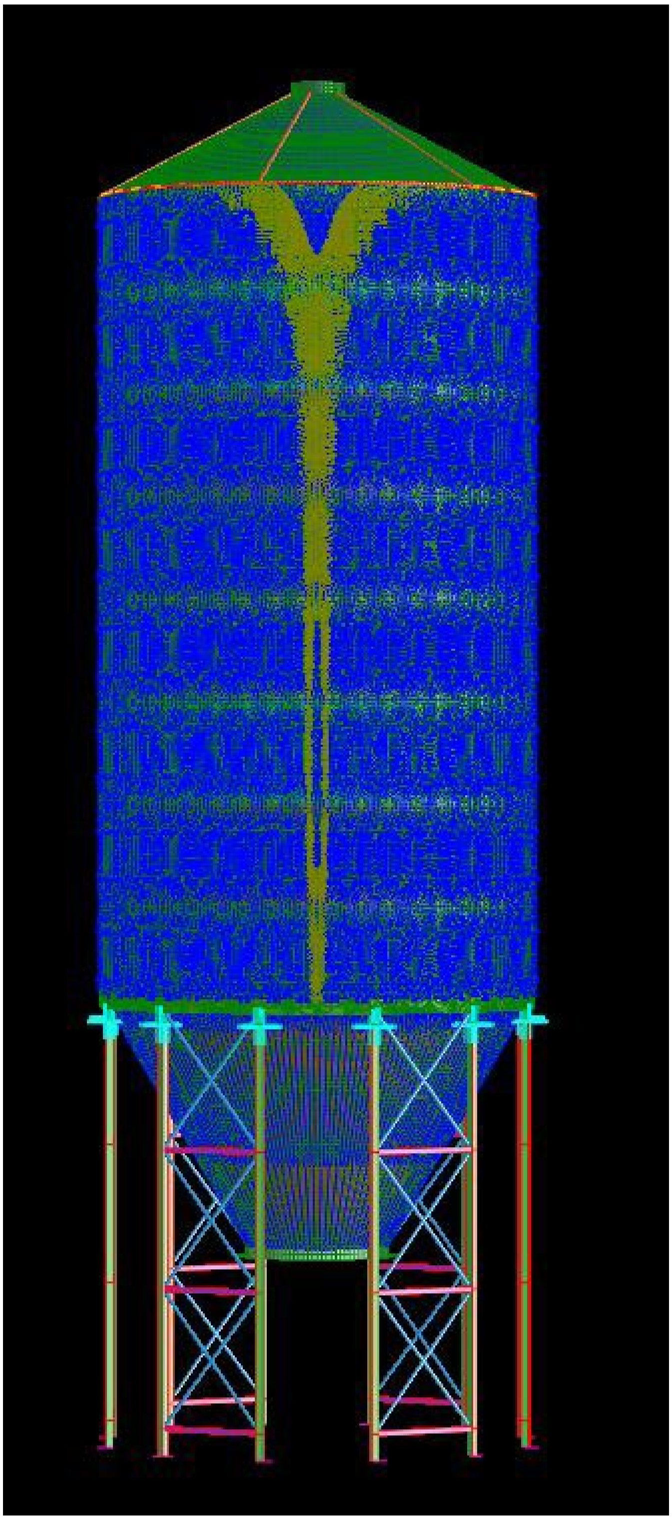


Figure 47 – Isometric View 3.6m Diameter – 6 Sheets High (Strand7)

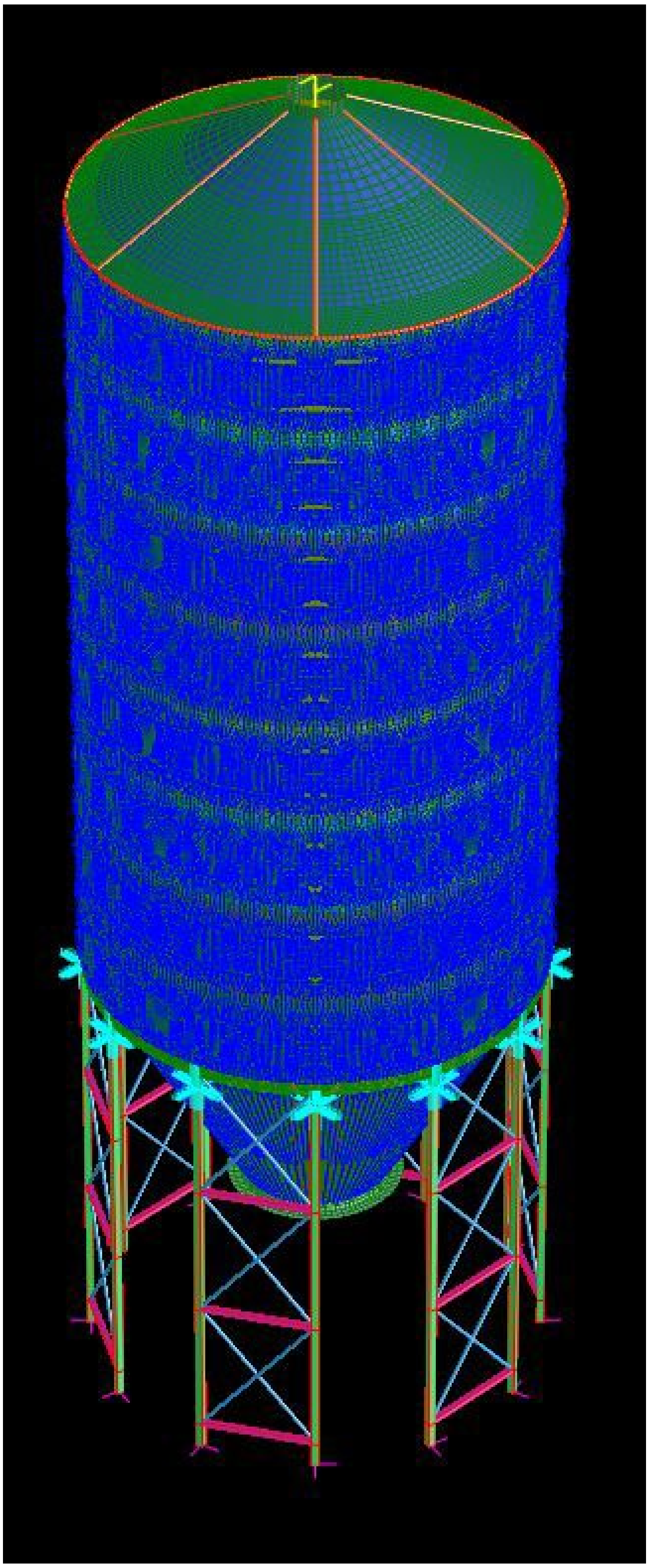


Figure 48 – Silo Design Drawing (AutoCAD)

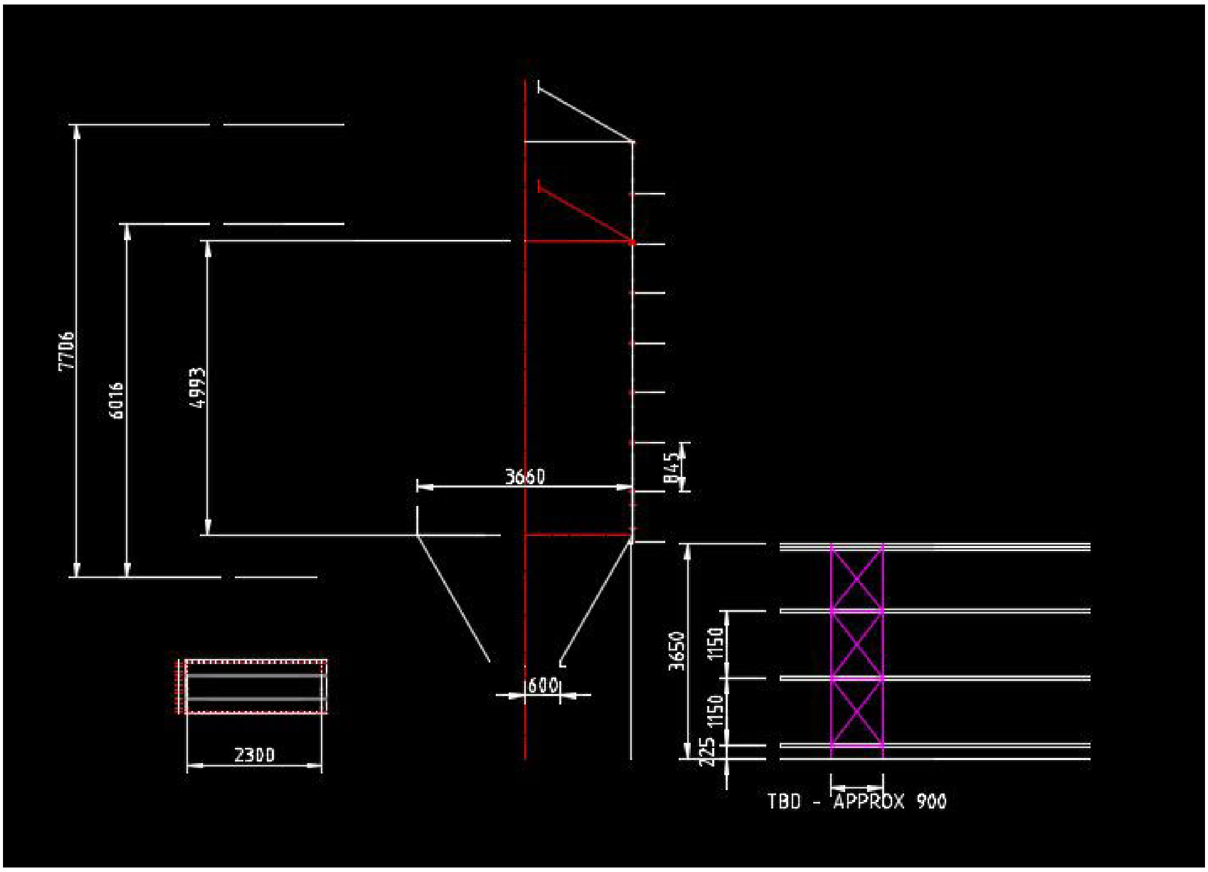
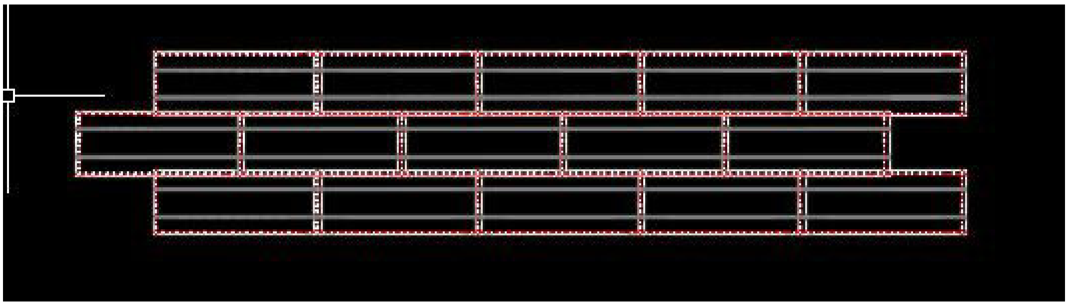


Figure 49 – Silo Design Drawing – Wall Sheeting (AutoCAD)



F.3 2.5m Diameter Silo – Wheat – 6 Sheets – Modified

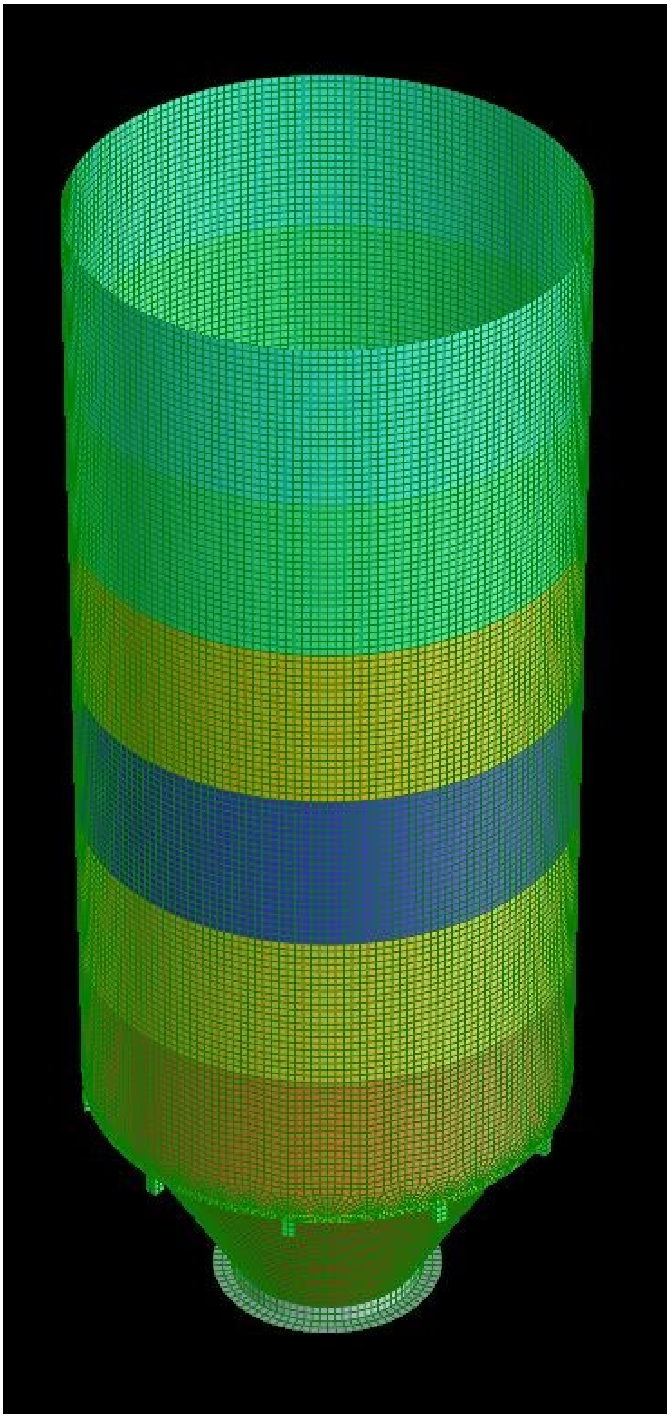


Figure 50 – Isometric view of the flat wall corrugation.

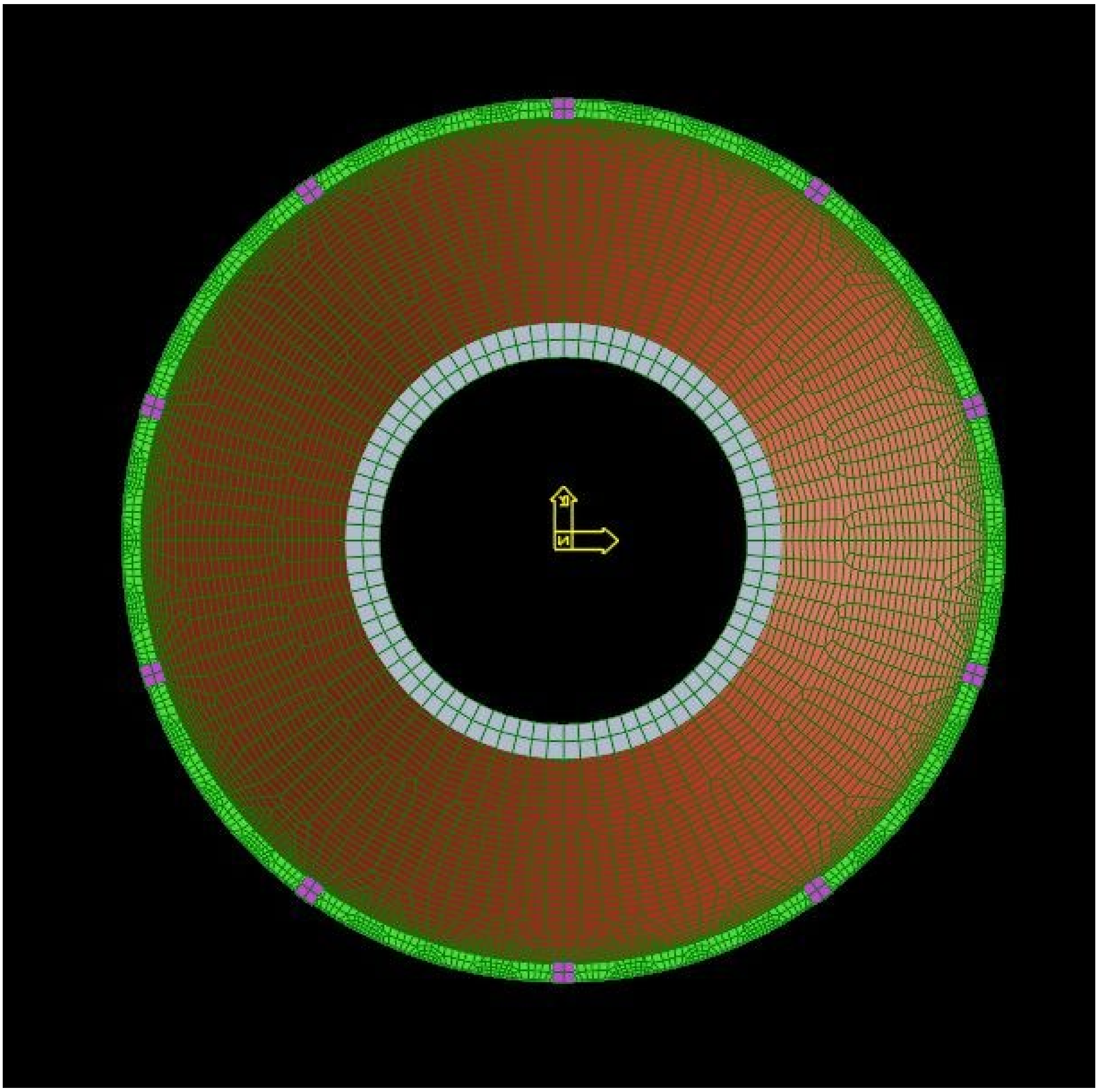


Figure 51 – Bottom view of the flat wall corrugation.

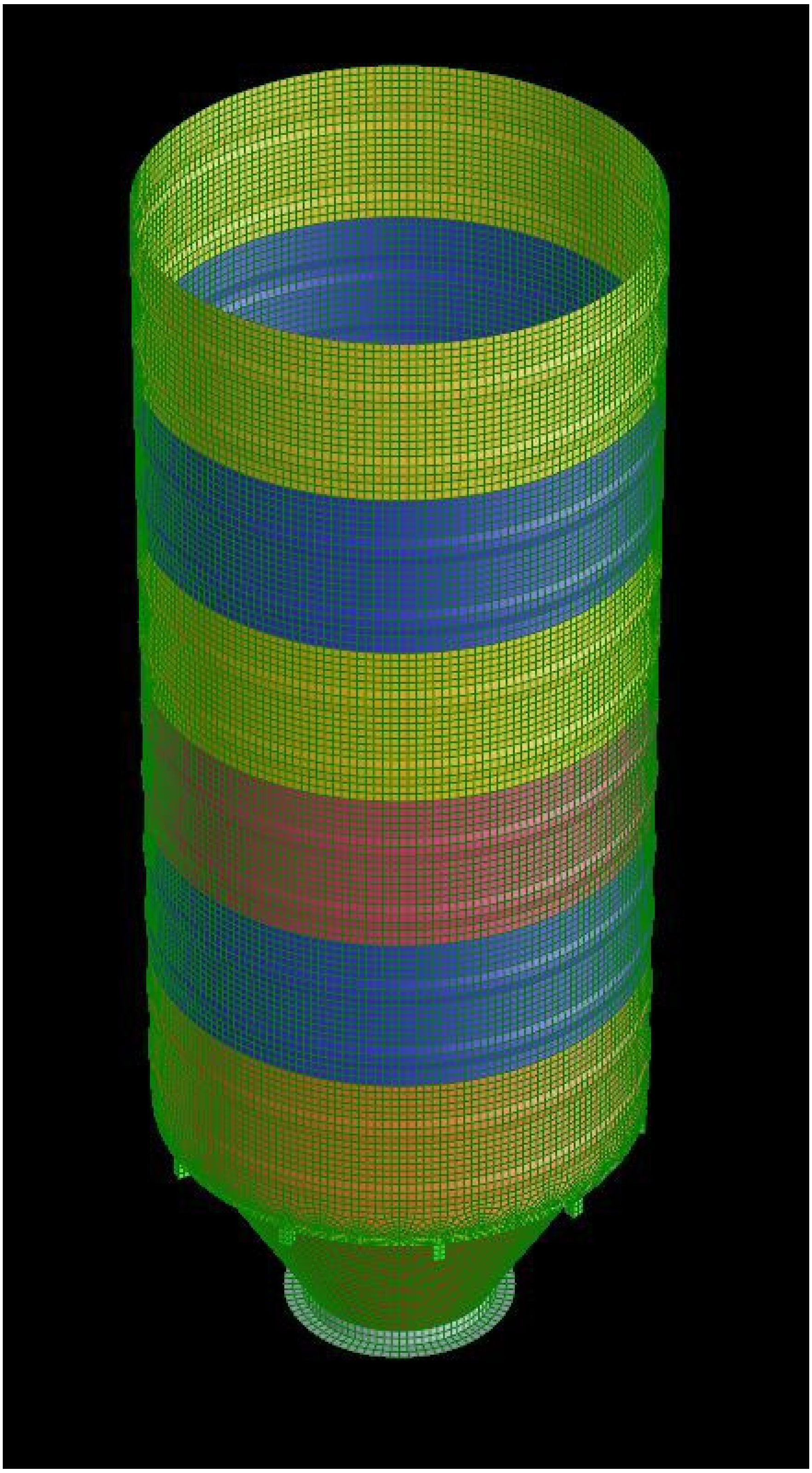


Figure 52 – Isometric view of the larger ribbed wall corrugation.

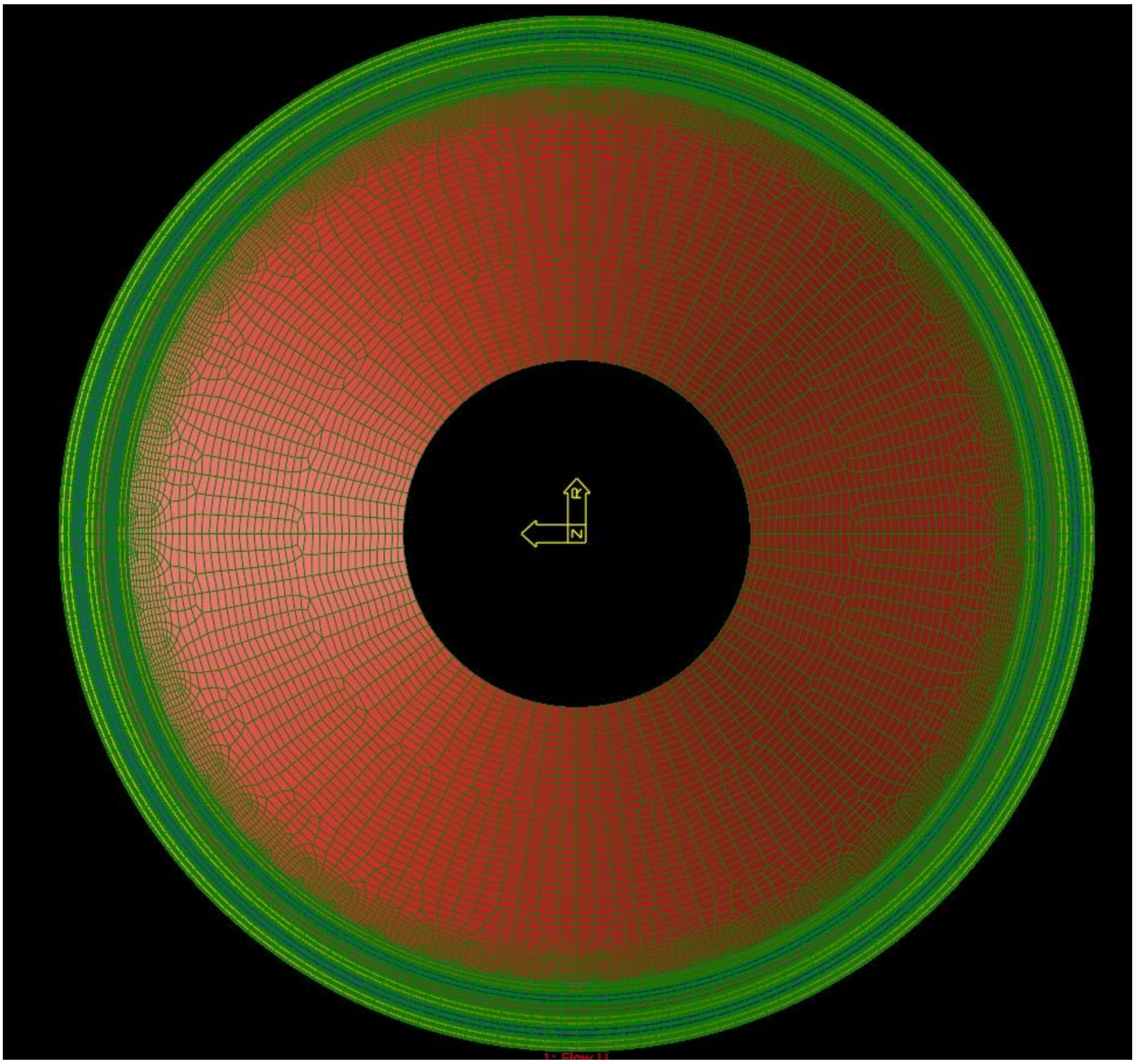


Figure 53 – Top view of the larger ribbed wall corrugation.

Appendix G – Strand7 Model Results

G.1 2.5m Diameter Wheat Silo

G.1.1 1.0mm Thickness

Figure 54: Lower-lower case for 1.0mm thickness, 2.5m diameter wheat silo.

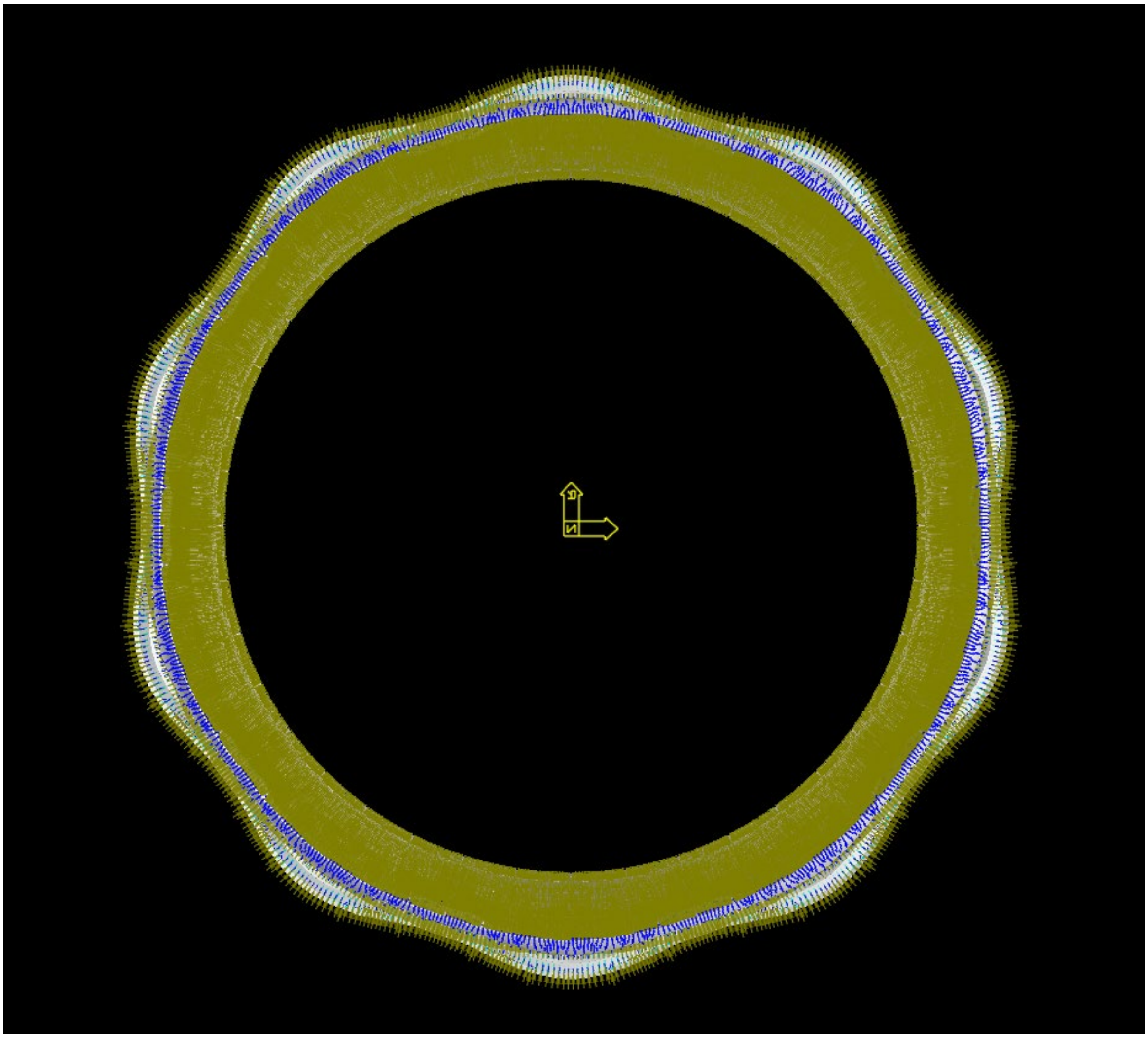


Figure 55: Lower-upper case for 1.0mm thickness, 2.5m diameter wheat silo. Bottom view.

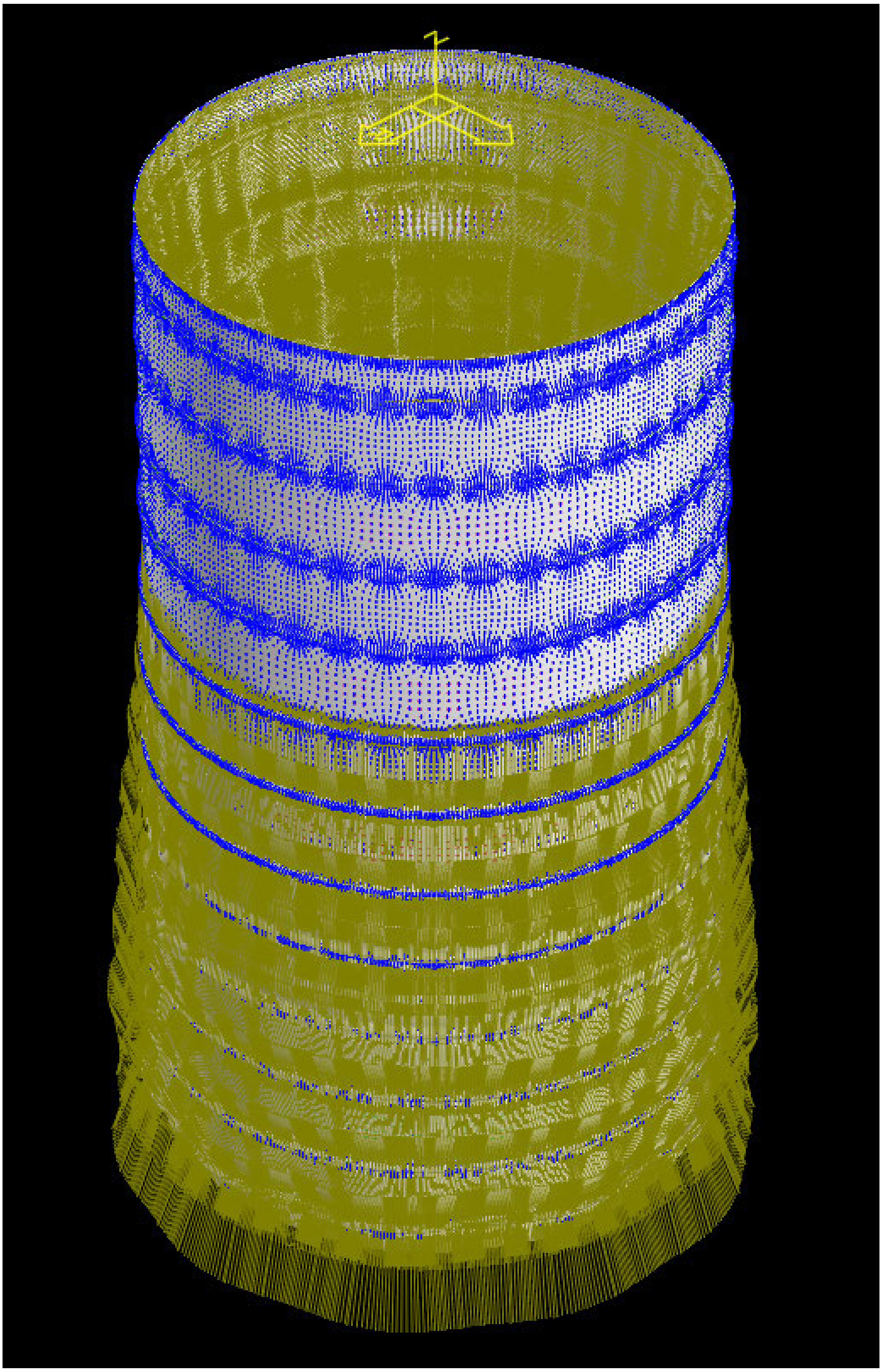


Figure 56: Upper-upper case for 1.0mm thickness, 2.5m diameter wheat silo. Isometric View.

G.1.2 1.2mm Thickness

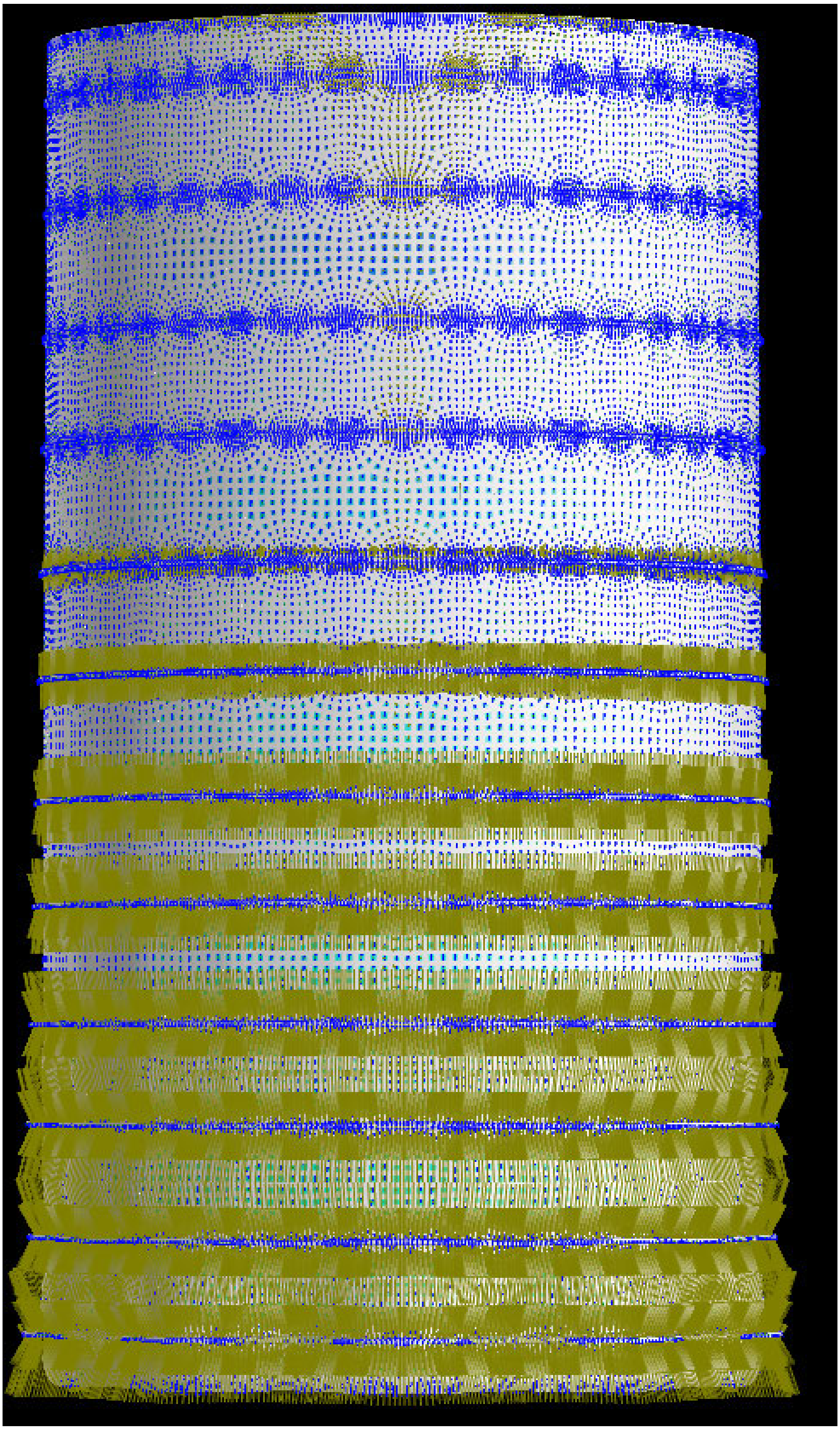


Figure 57: Lower-lower case for 1.2mm thickness, 2.5m diameter wheat silo.

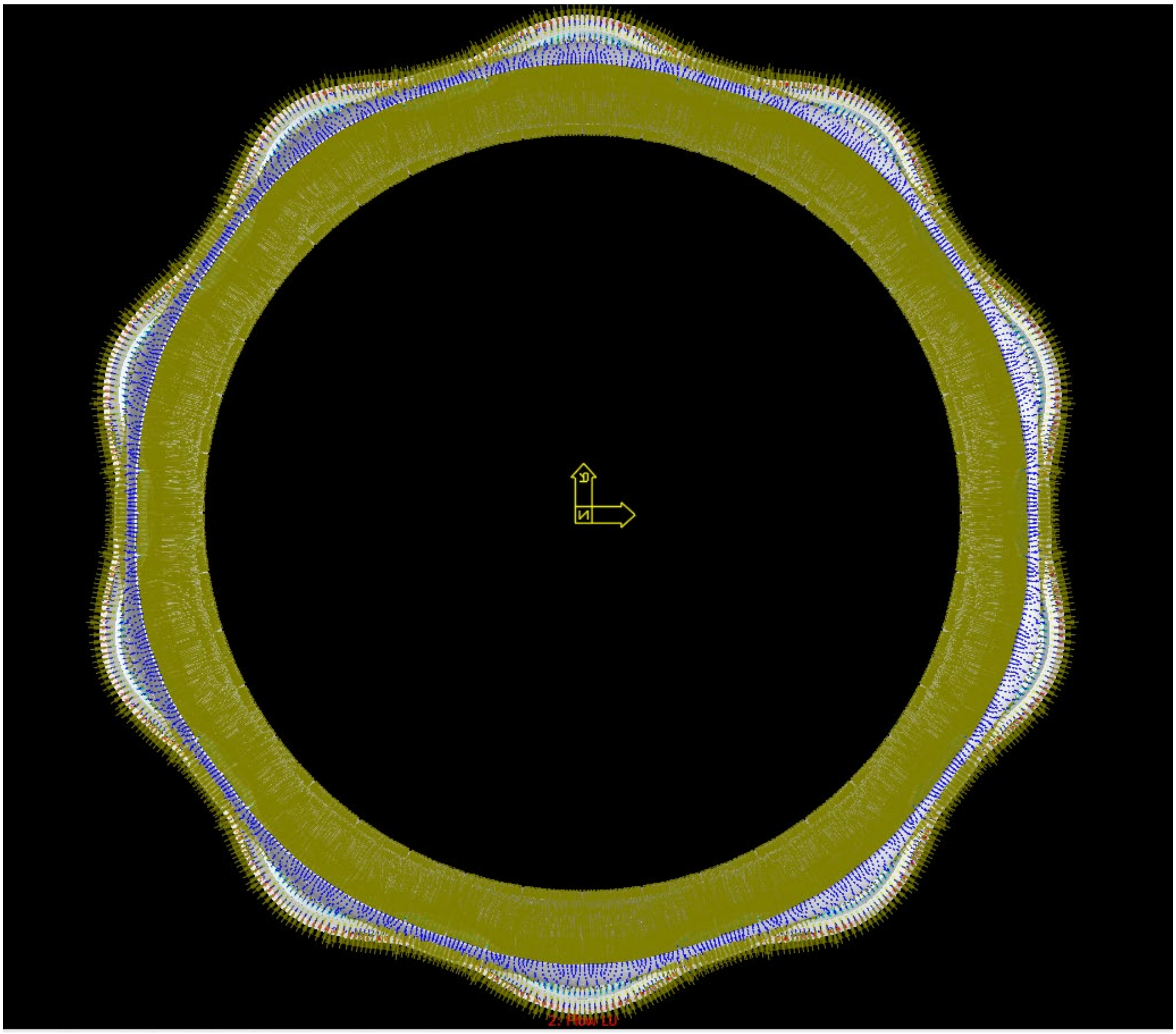


Figure 58: Lower-upper case for 1.2mm thickness, 2.5m diameter wheat silo. Bottom view.

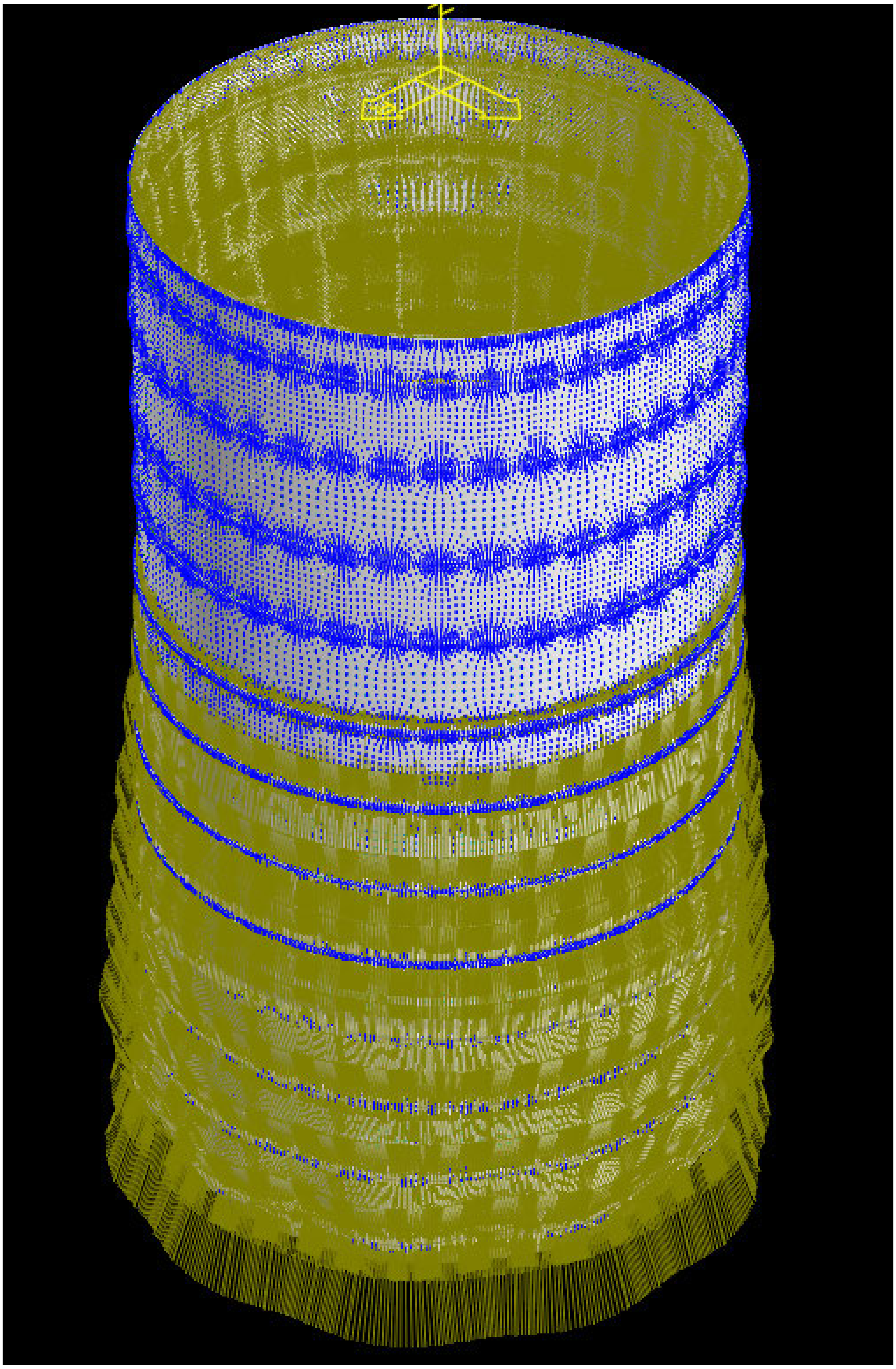


Figure 59: The upper-upper case for 1.2mm thickness, 2.5m diameter wheat silo. Isometric View.

G.1.3 1.35mm Thickness

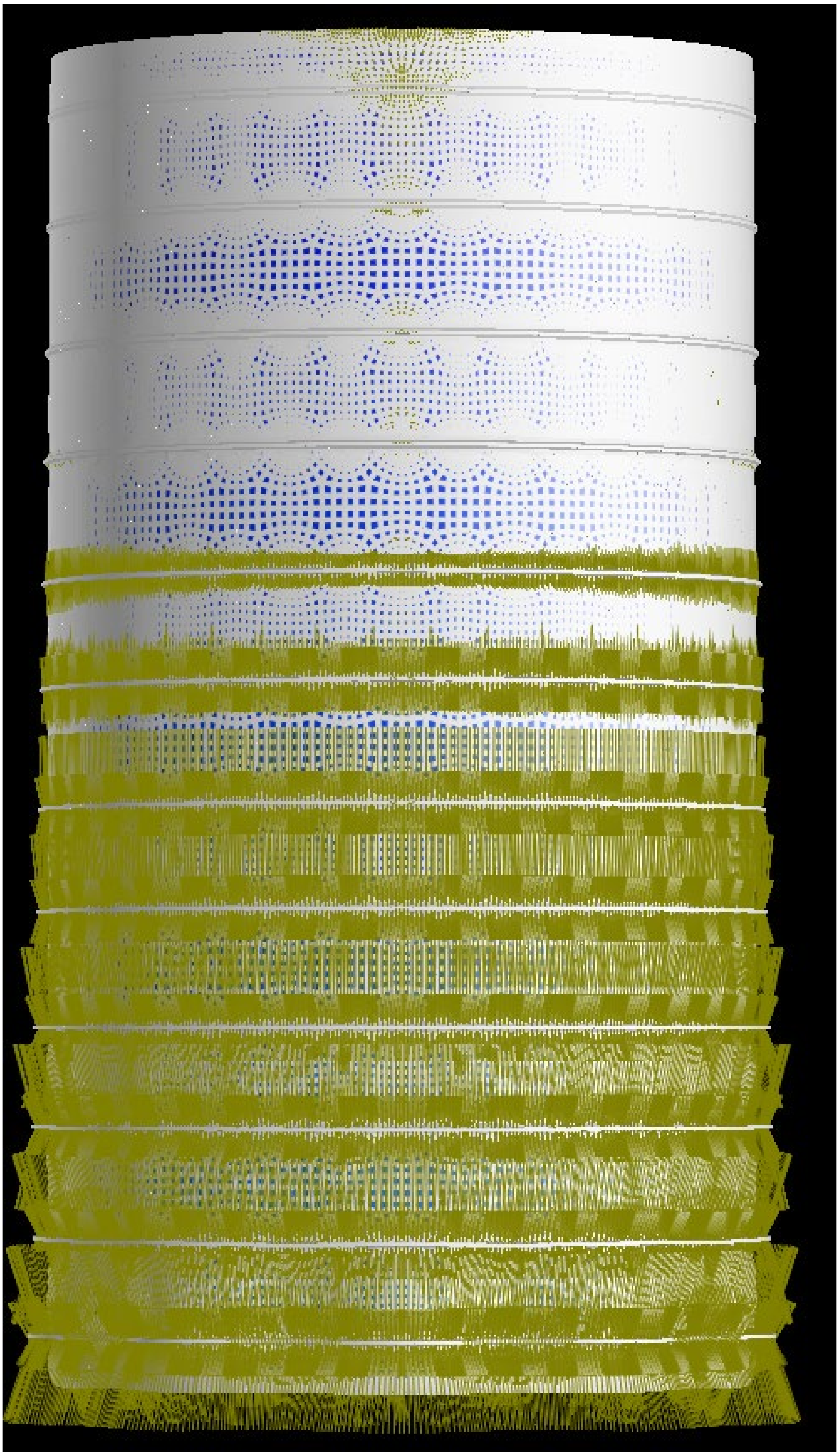


Figure 60: Lower-lower case for 1.35mm thickness, 2.5m diameter wheat silo.

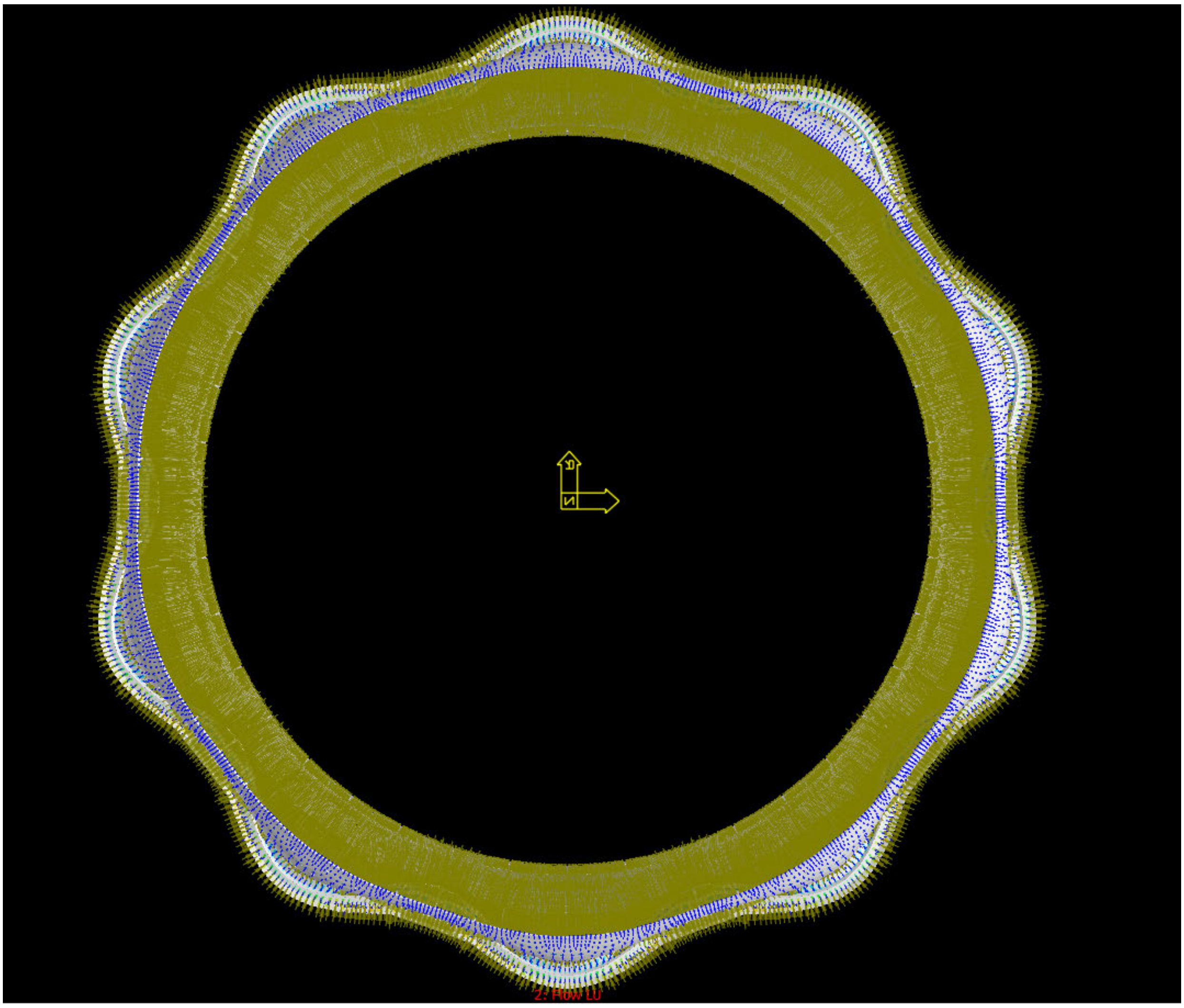


Figure 61: Lower-upper case for 1.35mm thickness, 2.5m diameter wheat silo. Bottom view.

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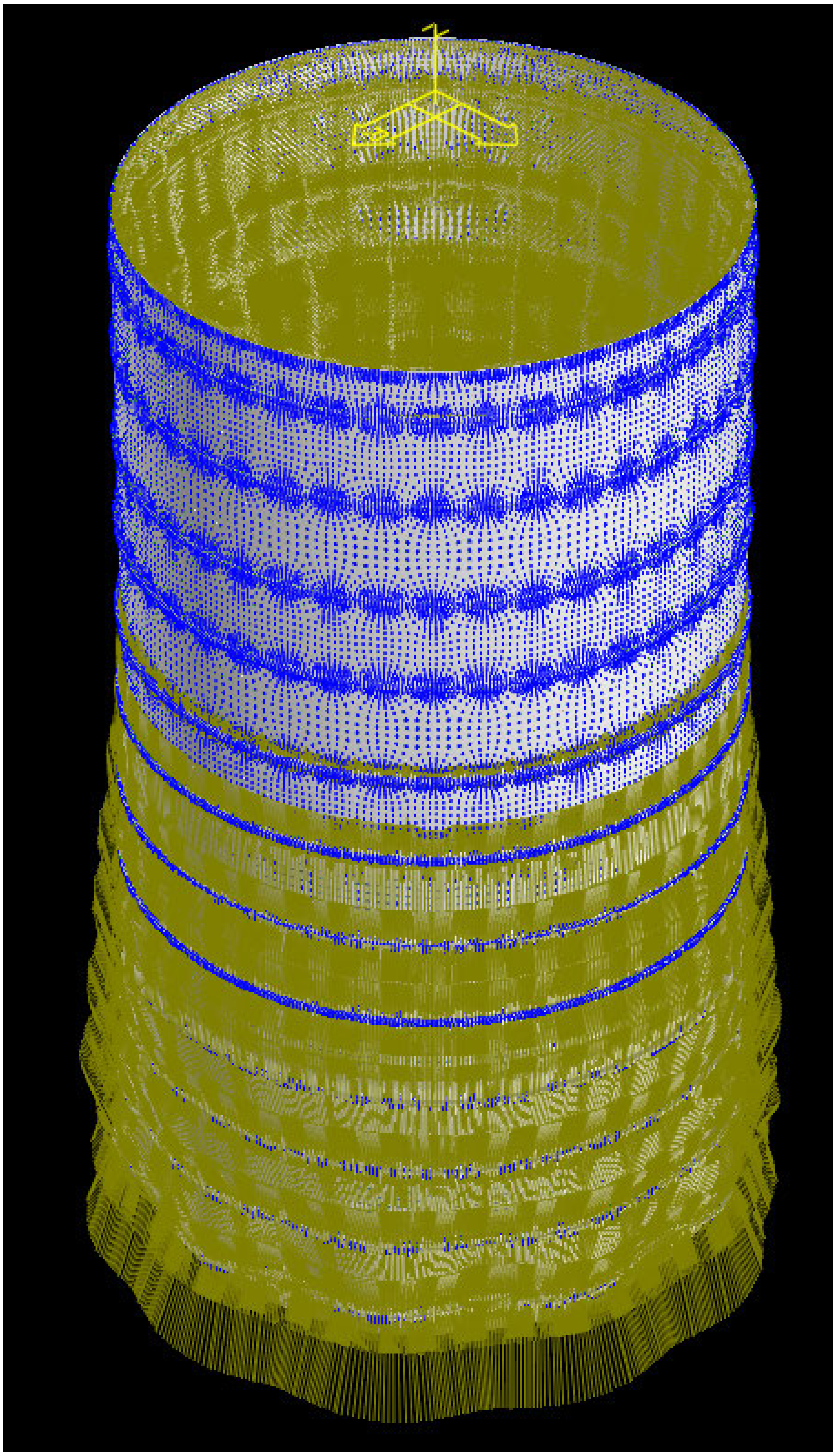


Figure 62: Upper-upper case for 1.35mm thickness, 2.5m diameter wheat silo. Isometric View.

G.1.4 1.5mm Thickness (Initial)

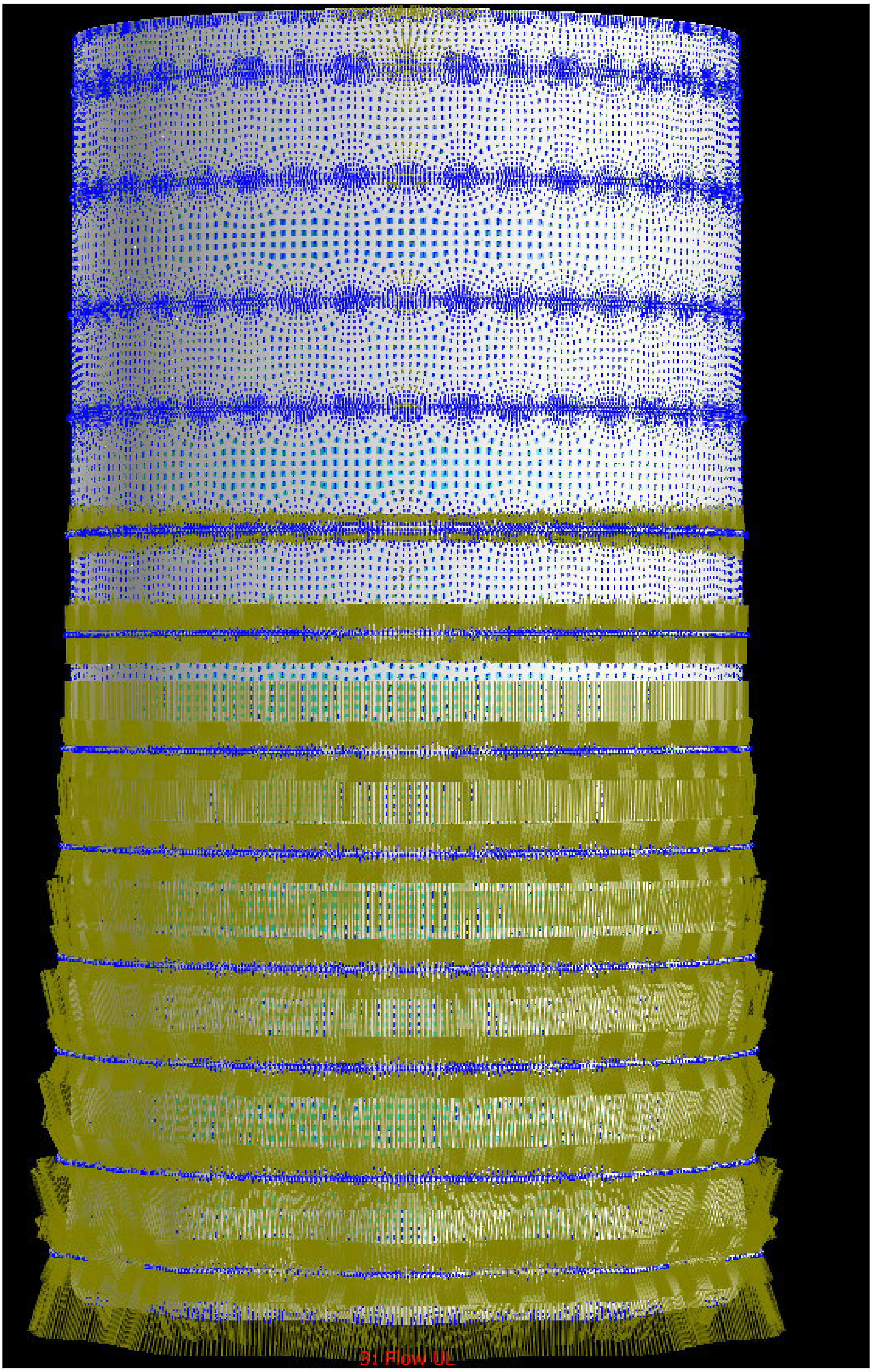


Figure 63: Upper-lower case for 1.5mm thickness, 2.5m diameter wheat silo.

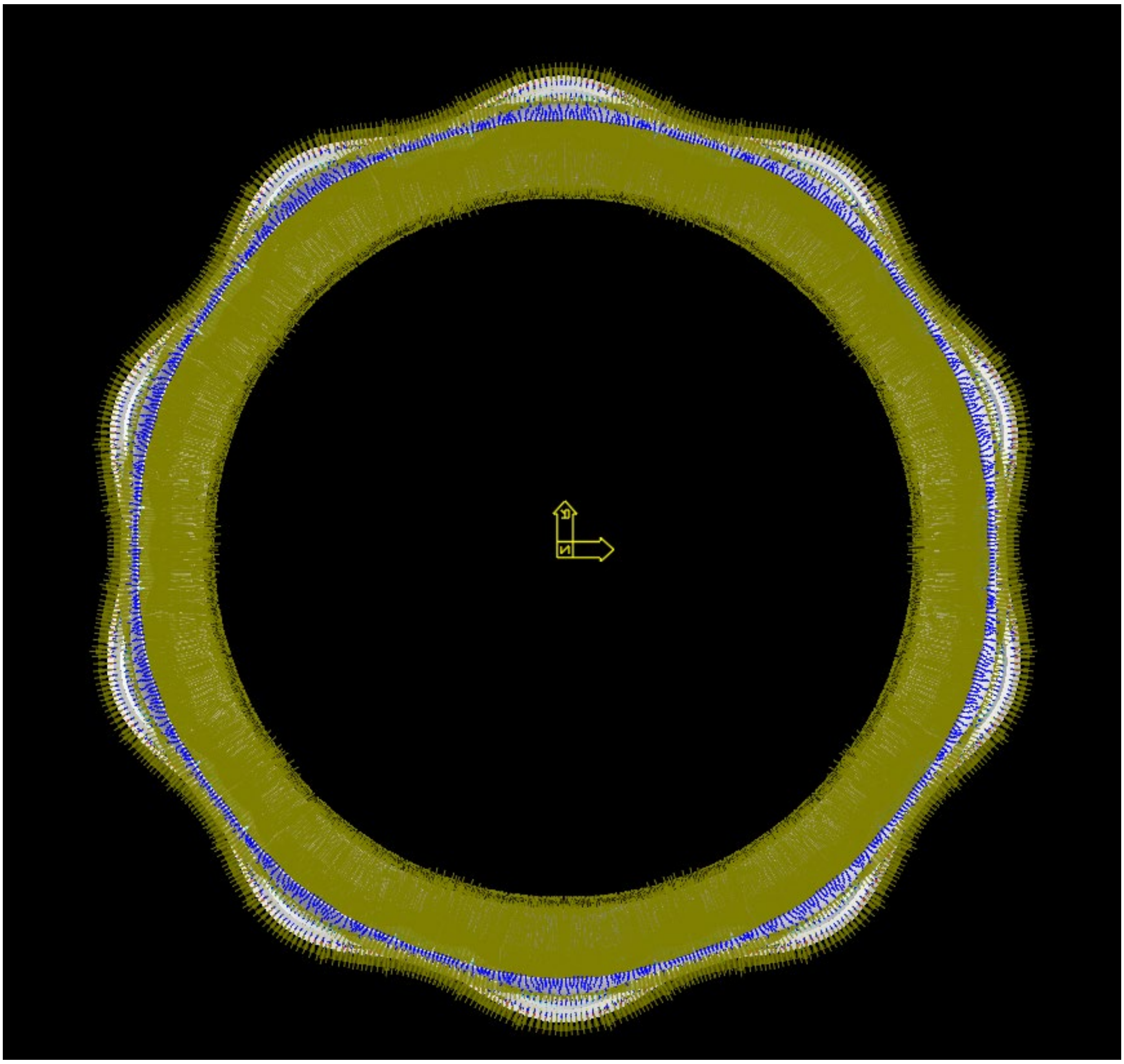


Figure 64: Upper-lower case for 1.5mm thickness, 2.5m diameter wheat silo. Bottom view.

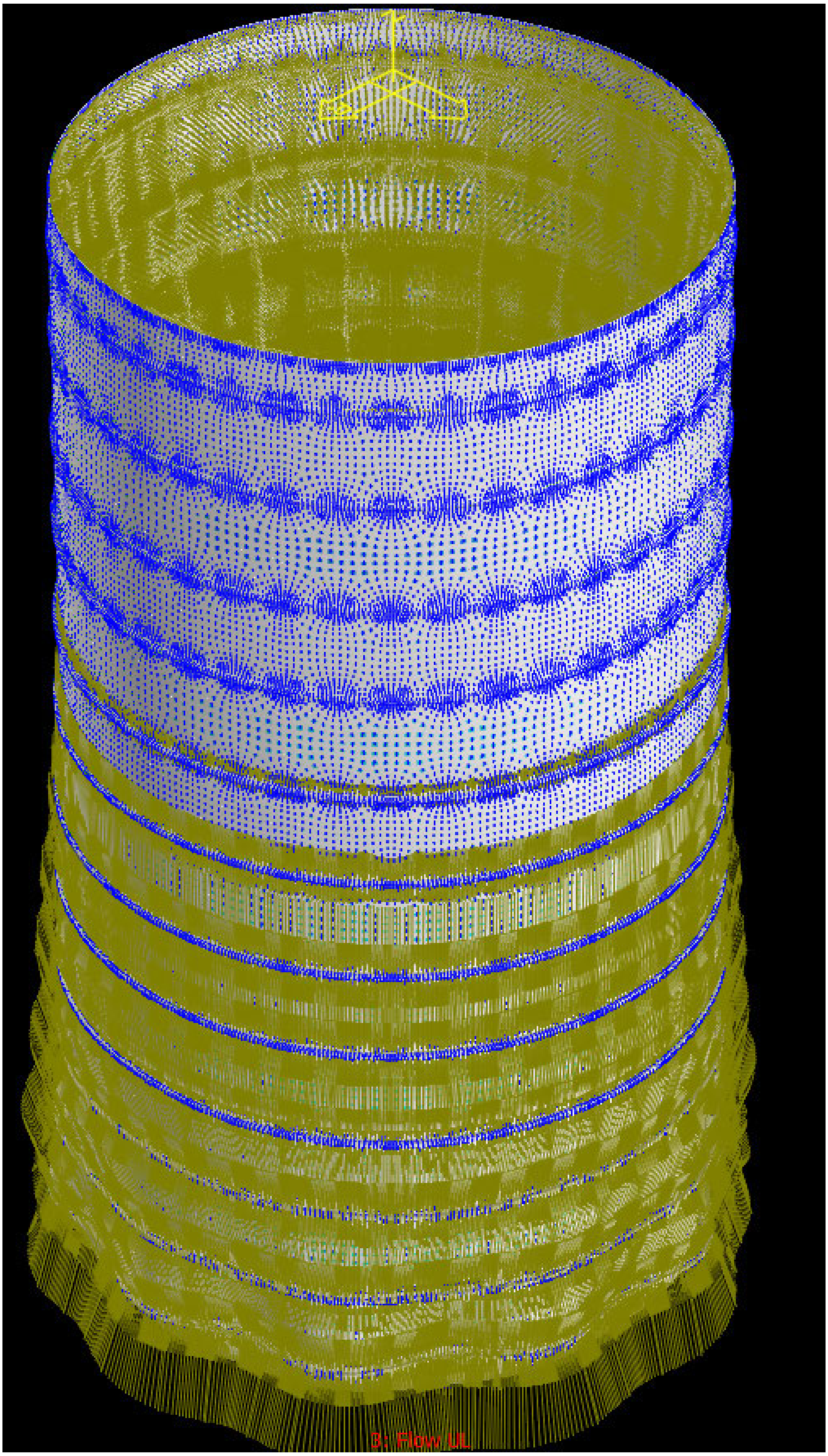


Figure 65: Upper-upper case for 1.5mm thickness, 2.5m diameter wheat silo. Isometric View.

G.1.5 Modified Corrugation Shape

G.1.5.1 Larger Ribbed Corrugation 1.5mm Thick

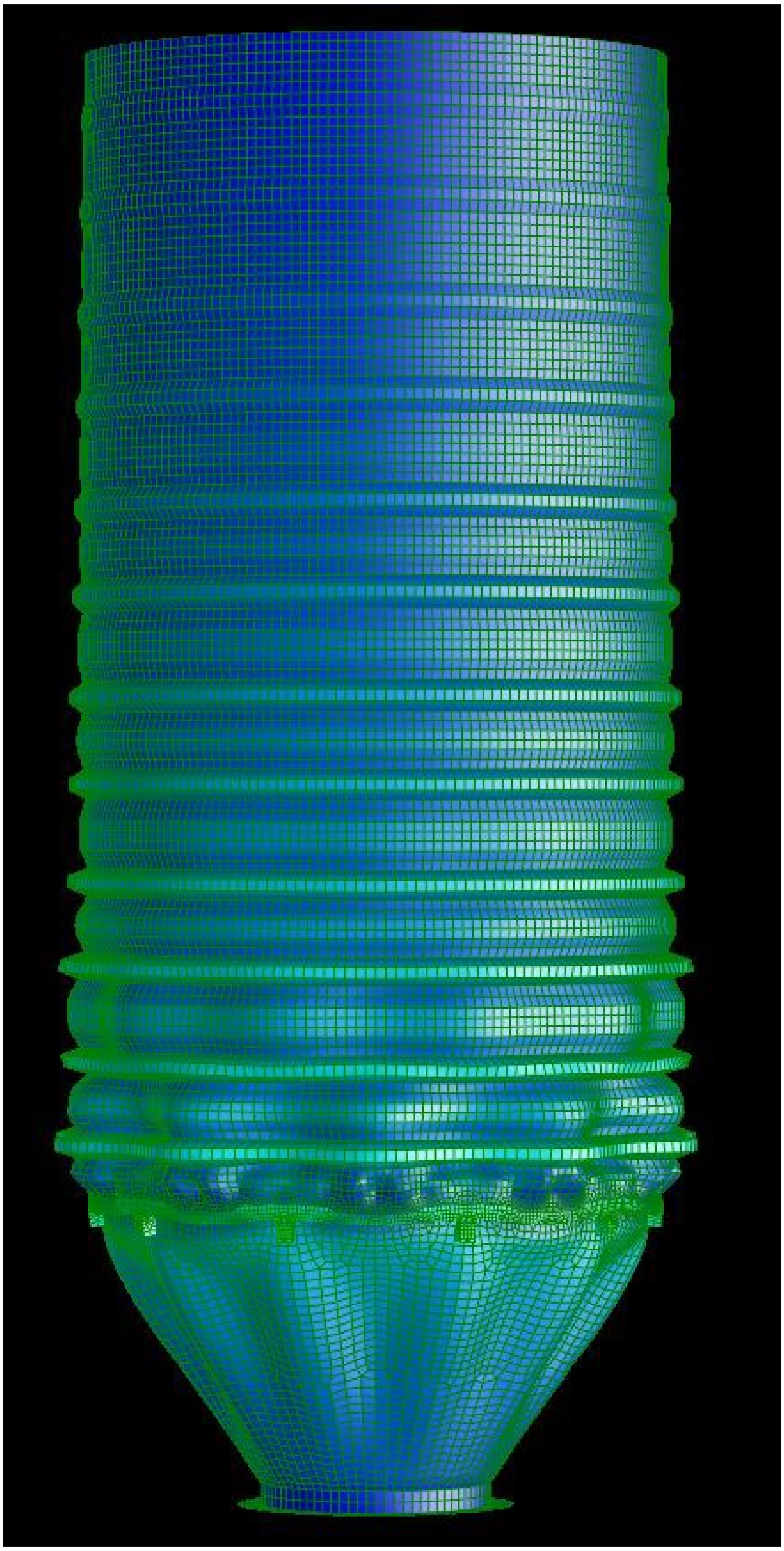


Figure 66: Front View of Lower-Lower load case. 1.5mm thick.

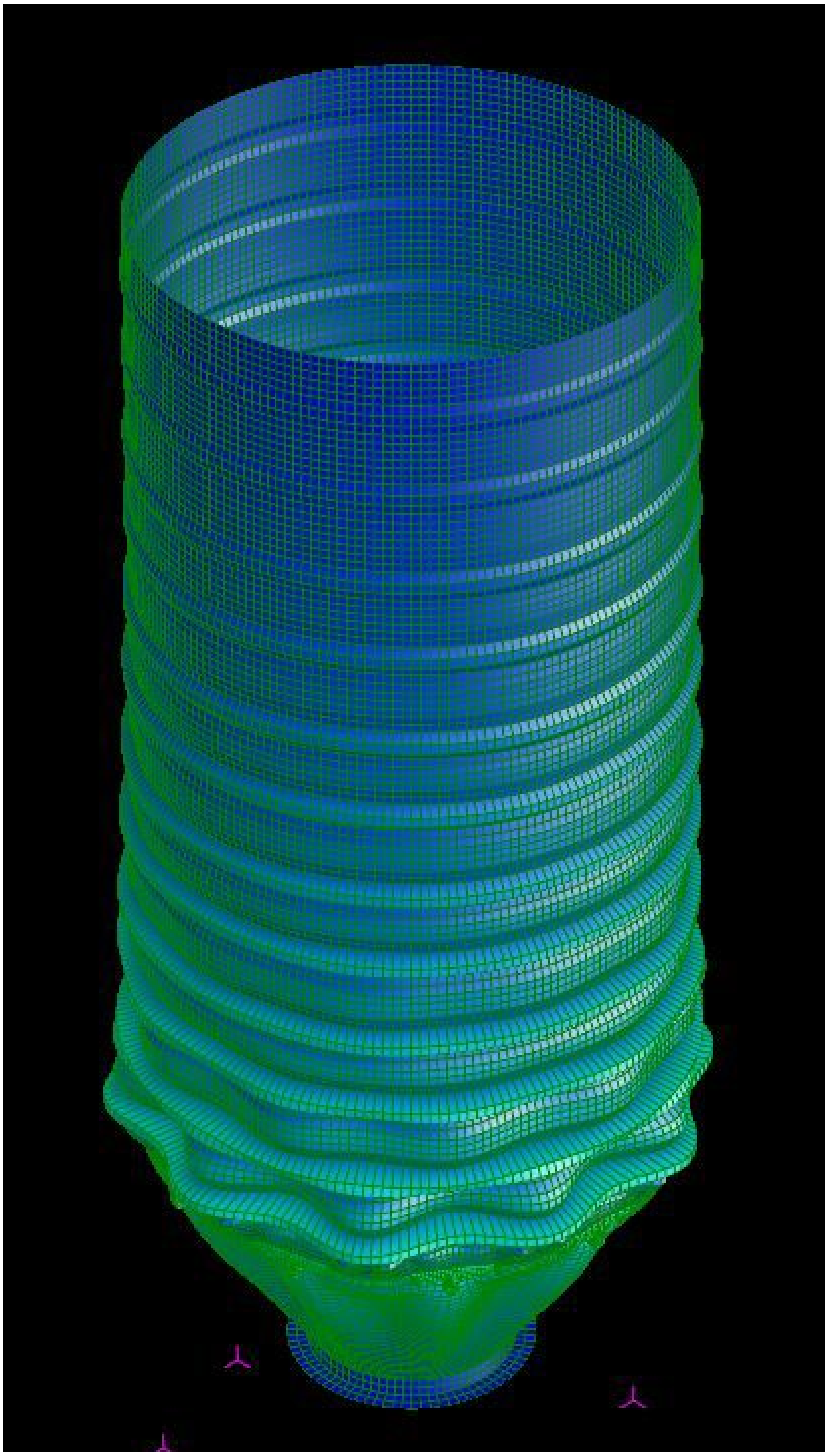


Figure 67: Isometric view of the Lower-Lower load case. 1.5mm thick.

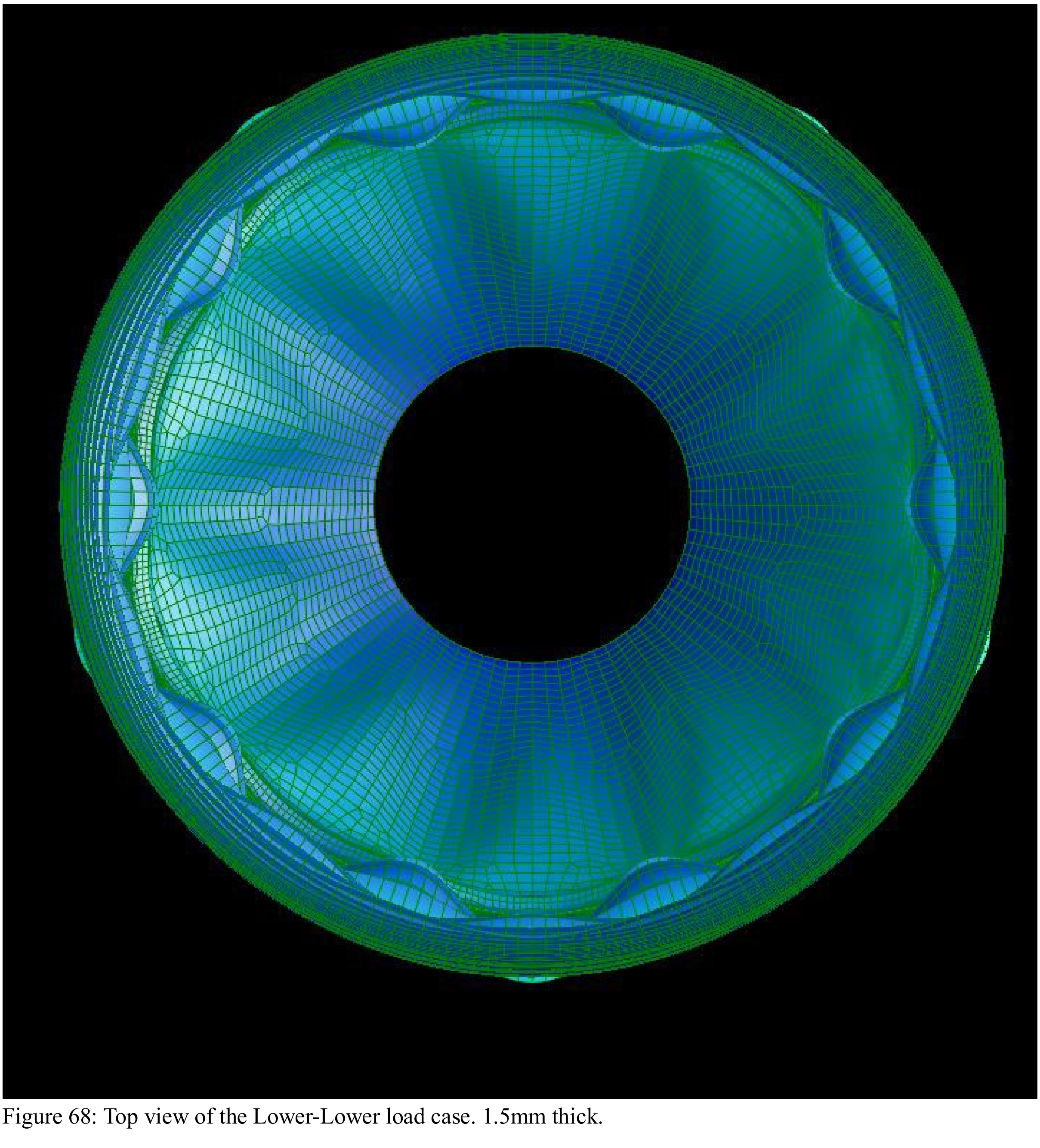


Figure 68: Top view of the Lower-Lower load case. 1.5mm thick.

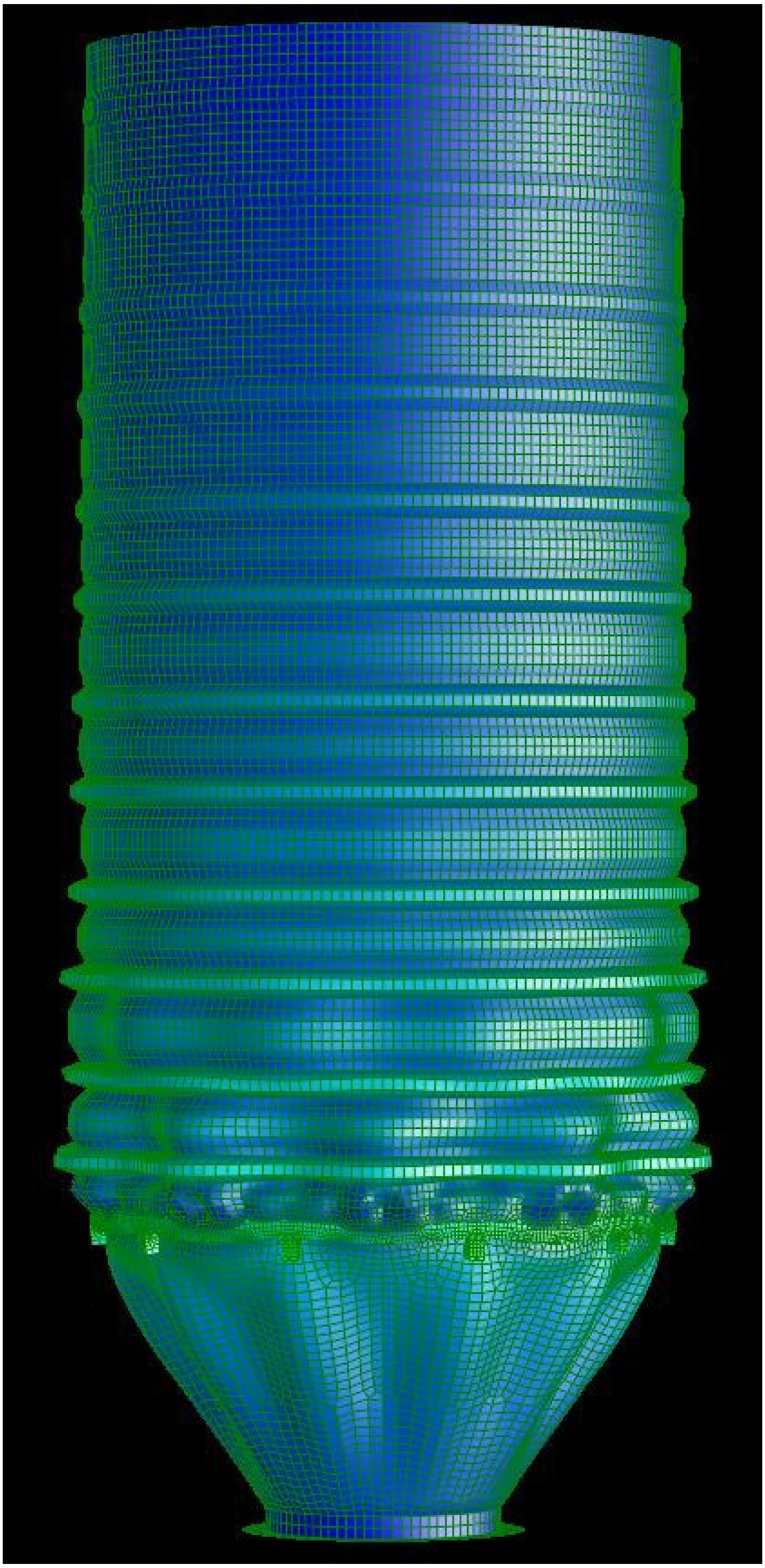


Figure 69: Front View of Lower-Upper load case. 1.5mm thick.

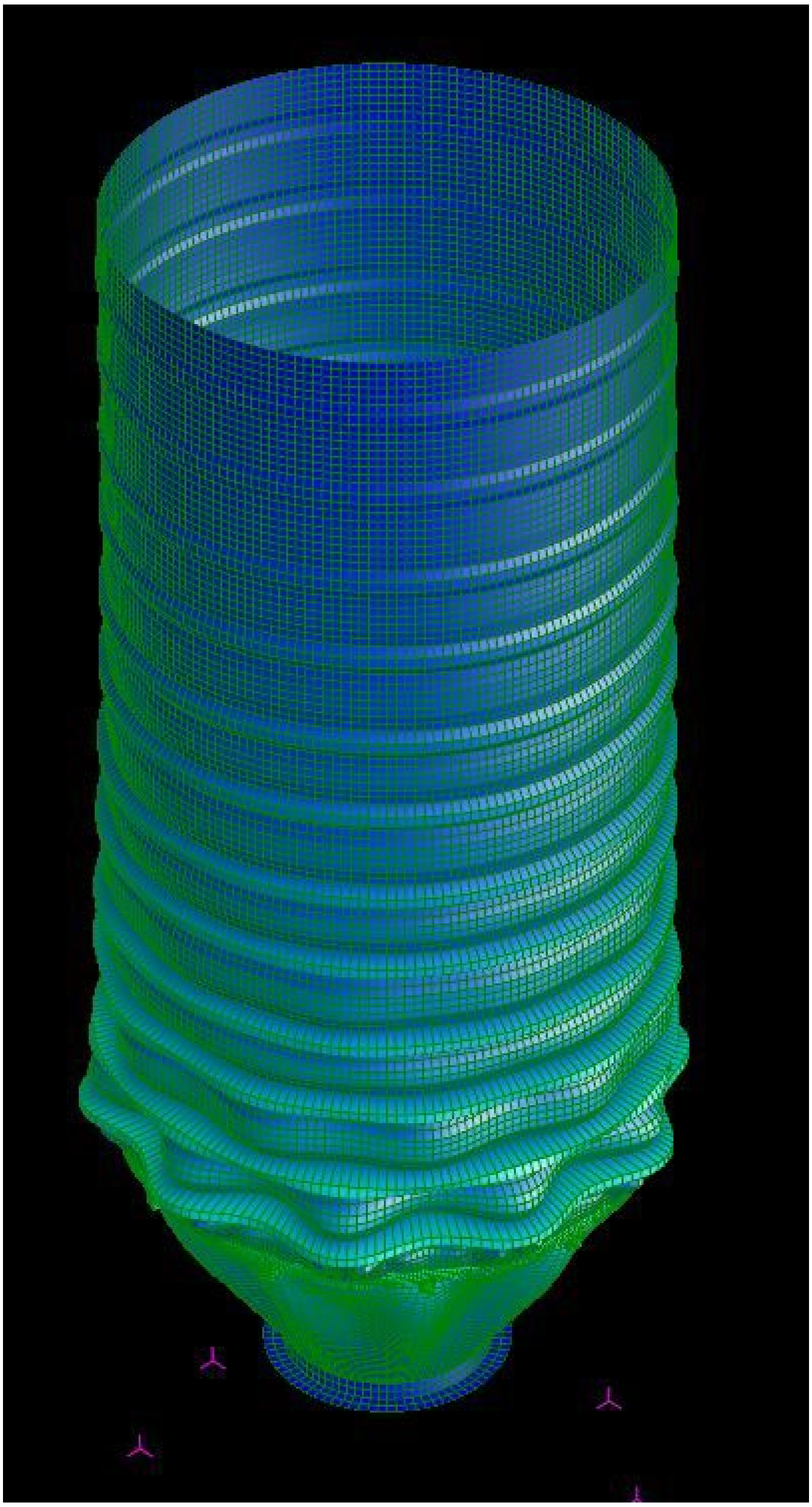


Figure 70: Isometric view of the Lower-Upper load case. 1.5mm thick.

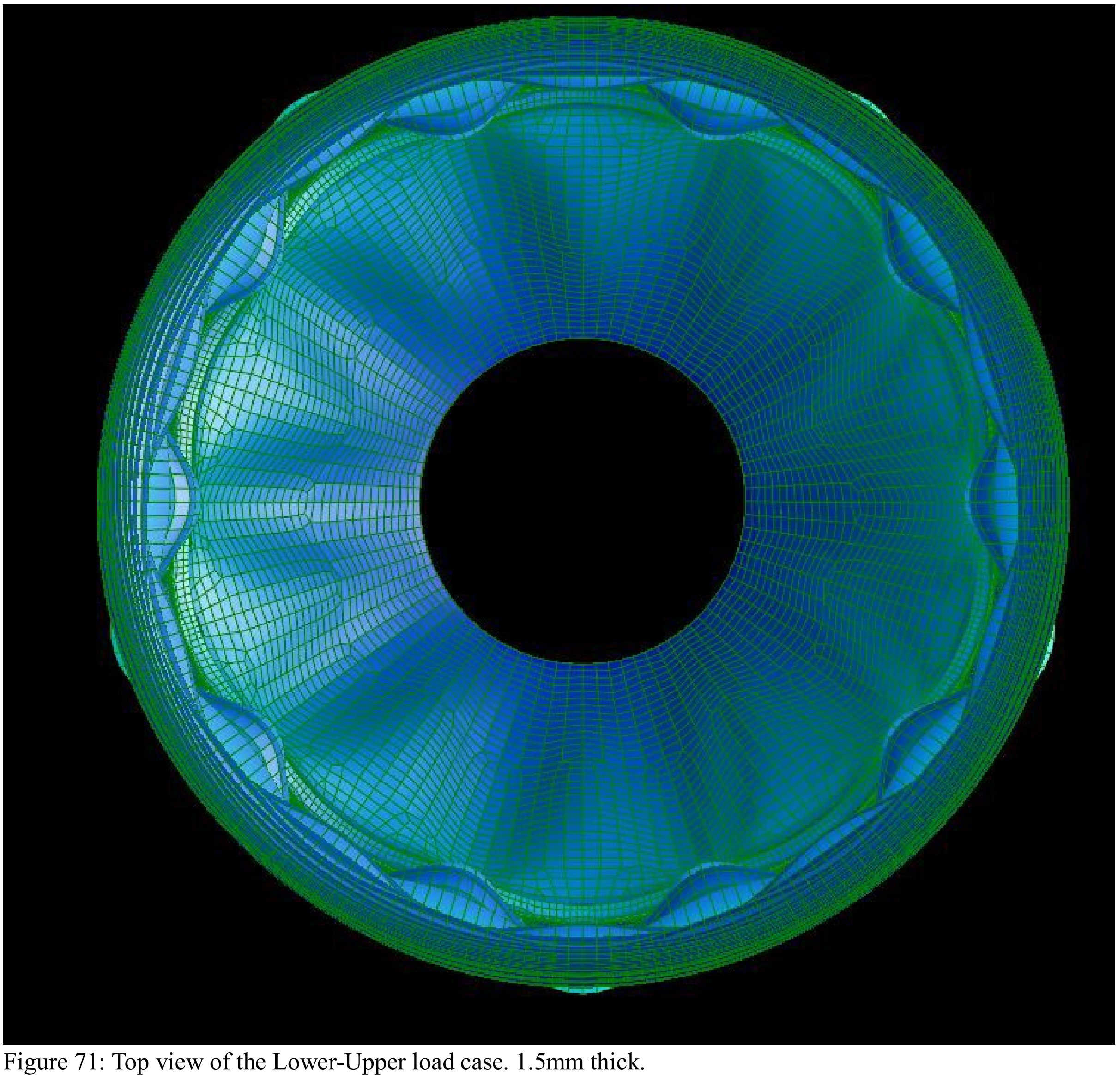


Figure 71: Top view of the Lower-Upper load case. 1.5mm thick.

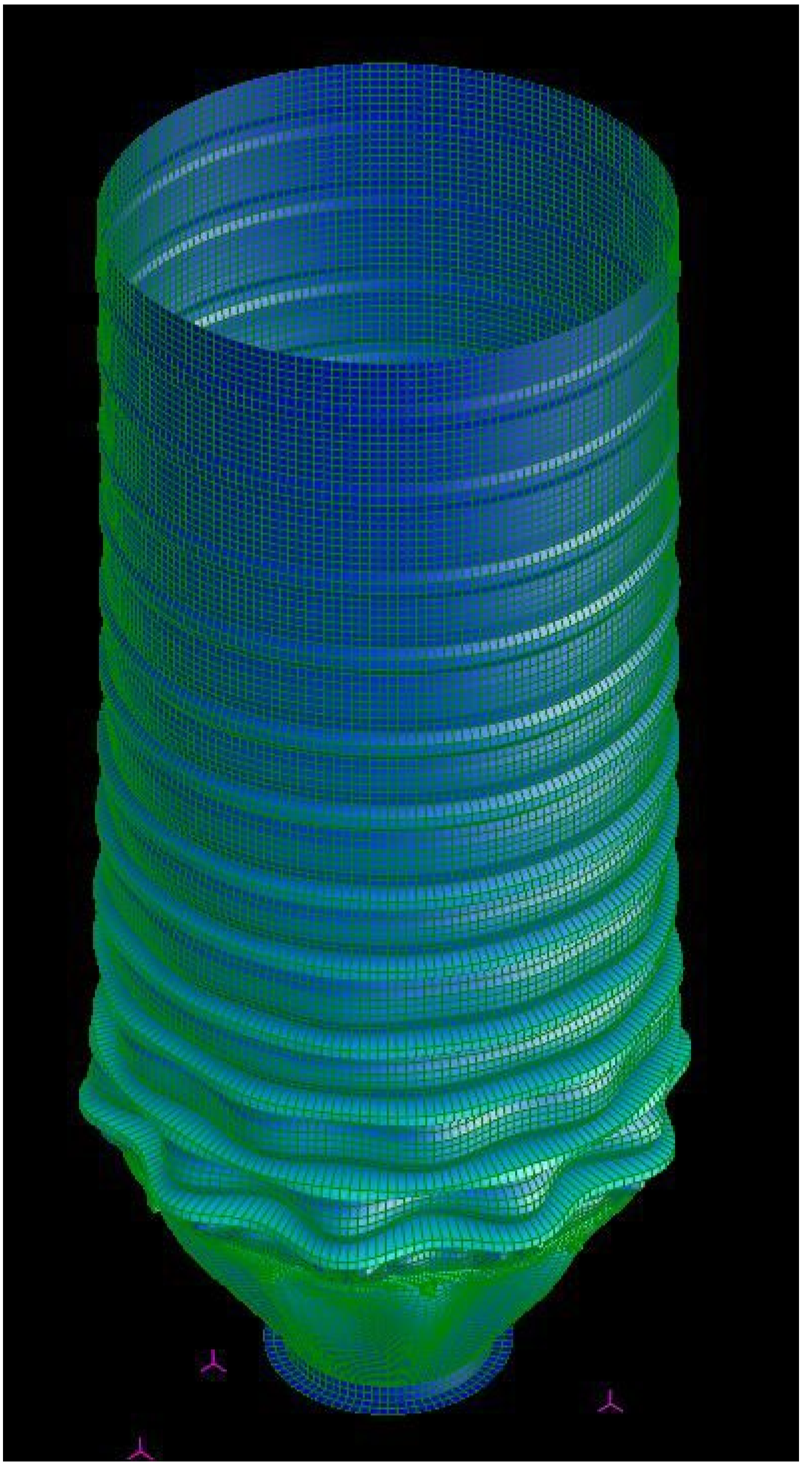


Figure 72: Isometric view of the Upper-Lower load case. 1.5mm thick.

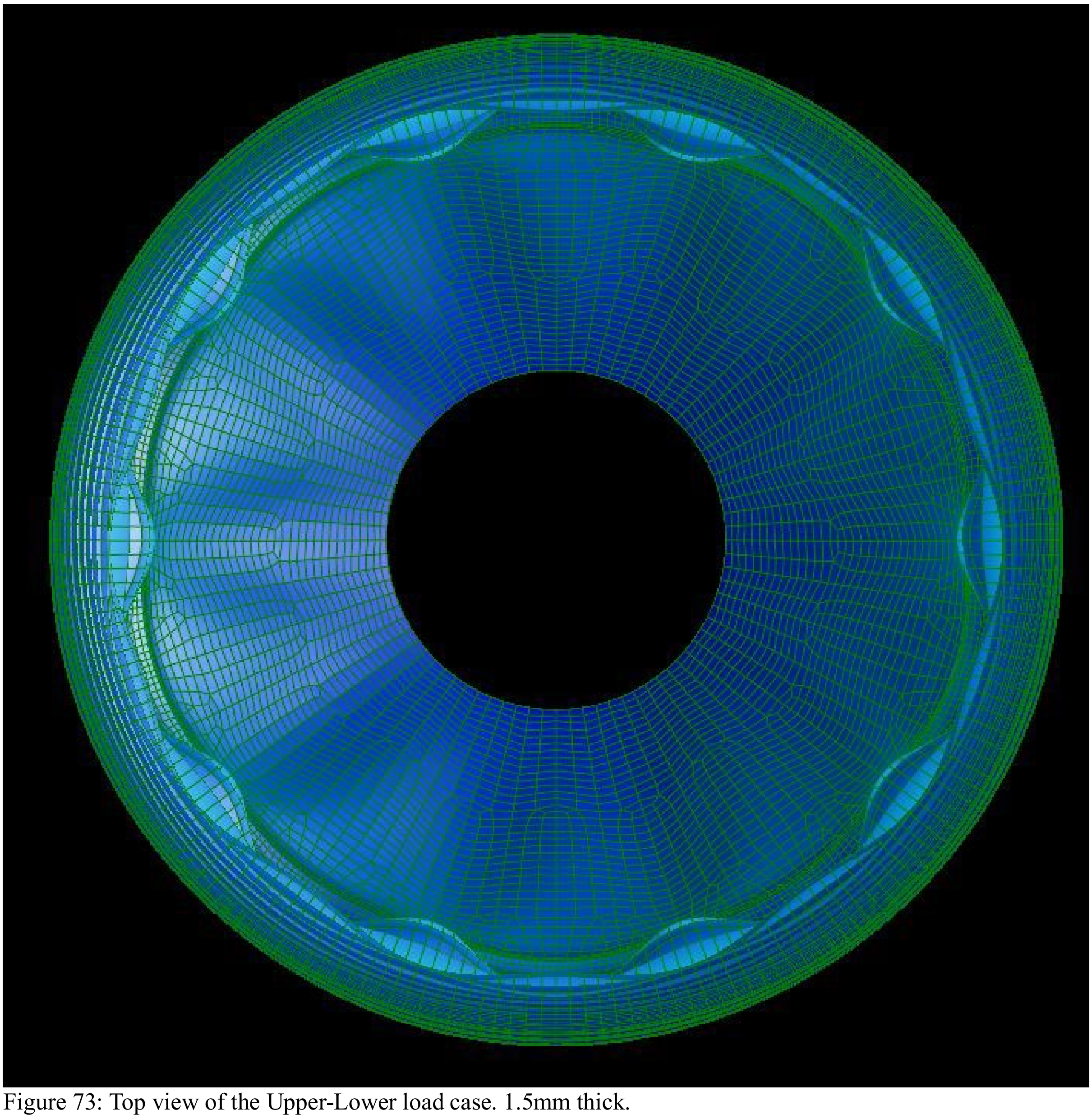


Figure 73: Top view of the Upper-Lower load case. 1.5mm thick.

G.1.5.2 Larger Ribbed Corrugation 1.2mm Thick

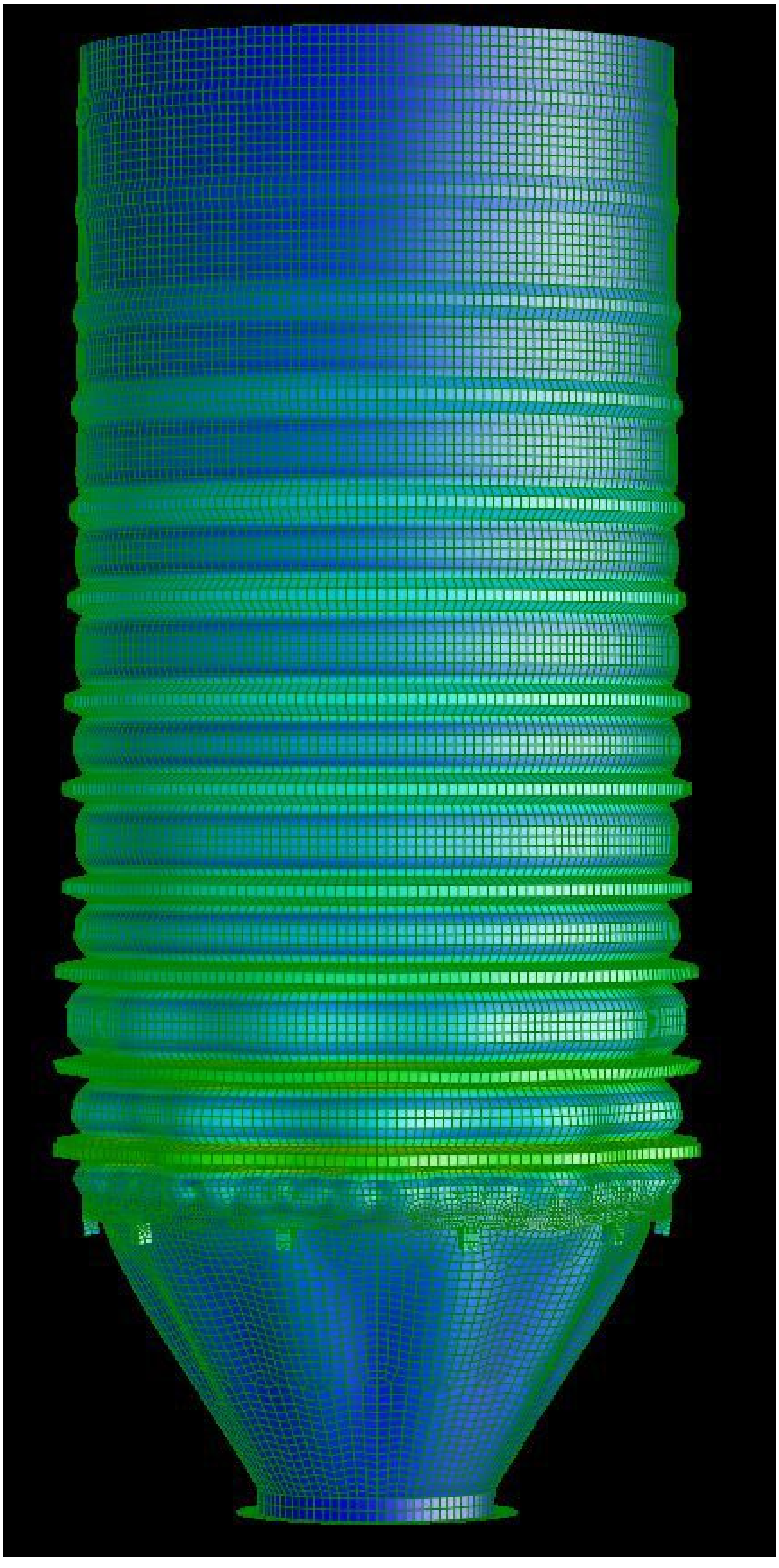


Figure 74: Top view of the Lower-Upper load case. 1.2mm thick.

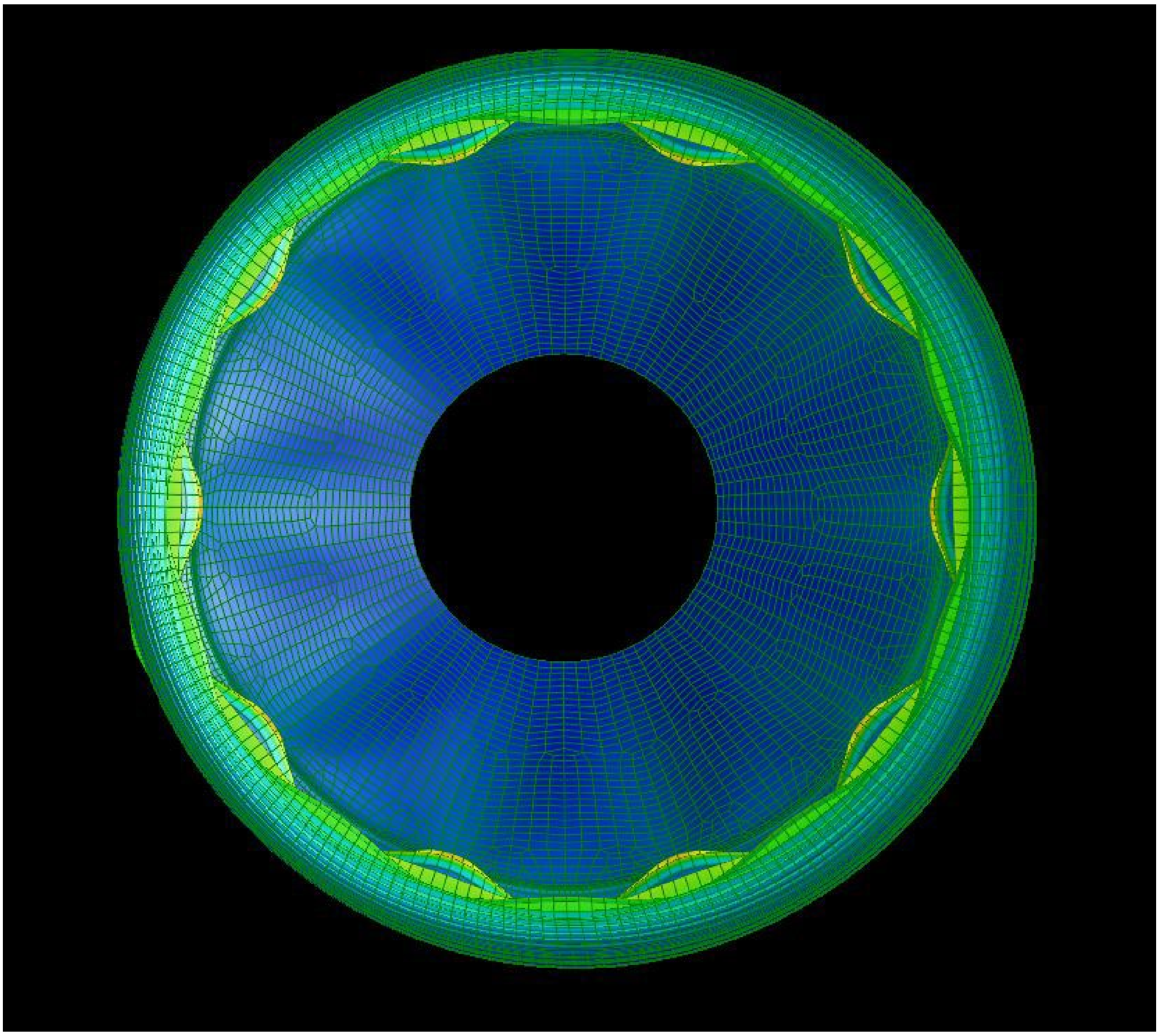


Figure 75: Top view of the Upper-Lower load case. 1.2mm thick.

G.1.5.3 Flat-Walled 1.5mm Thick

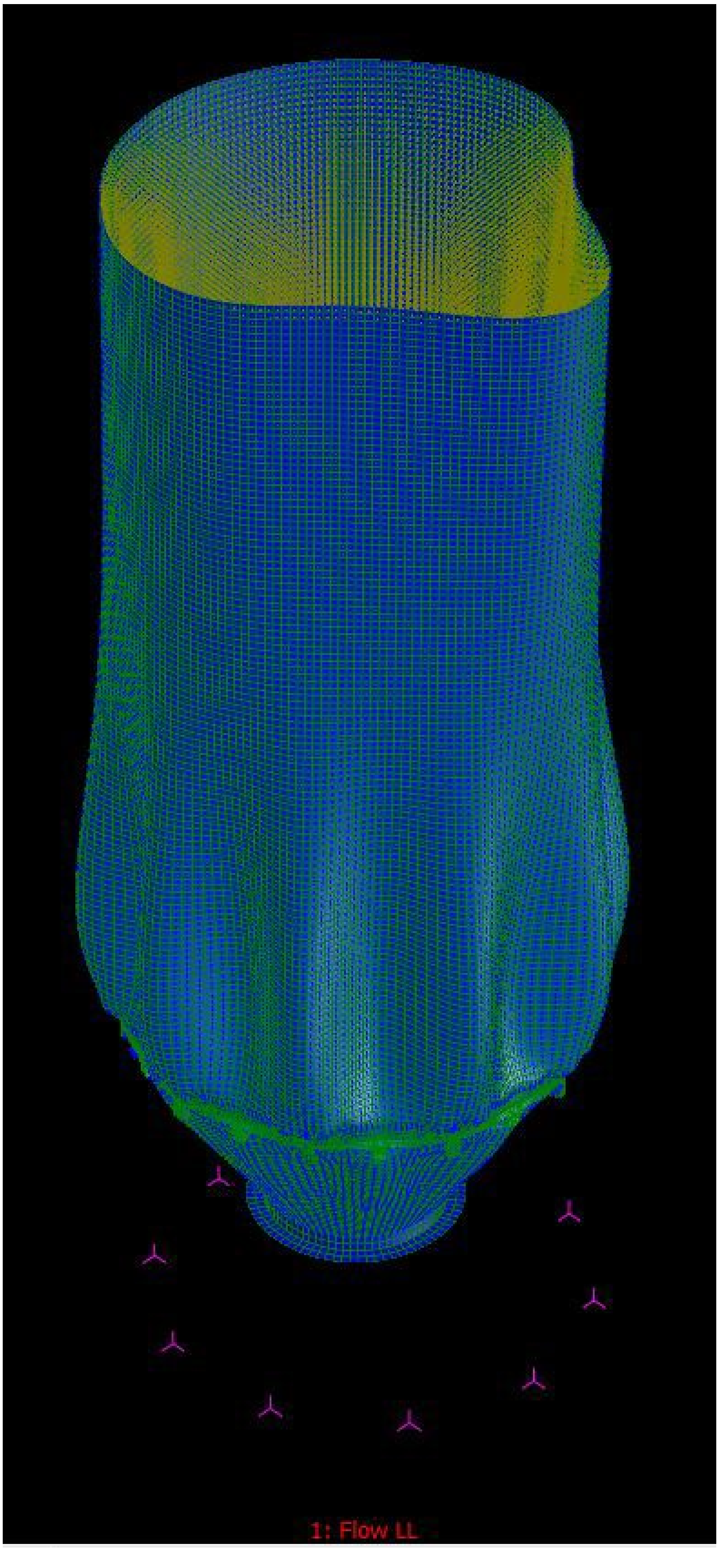


Figure 76: Isometric view of the Lower-Lower load case. 1.5mm thick.

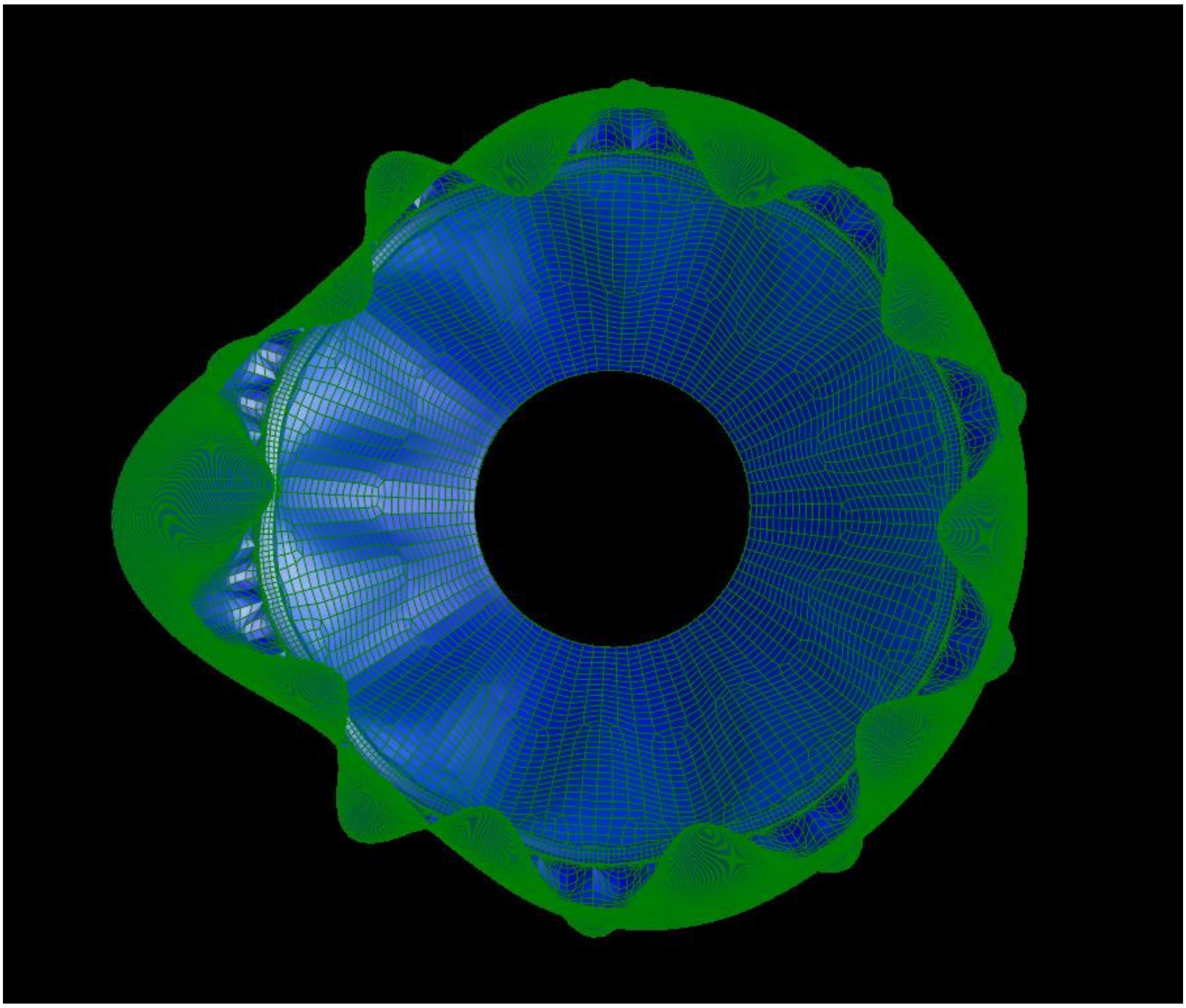


Figure 77: Top view of the Lower-Lower load case. 1.5mm thick.

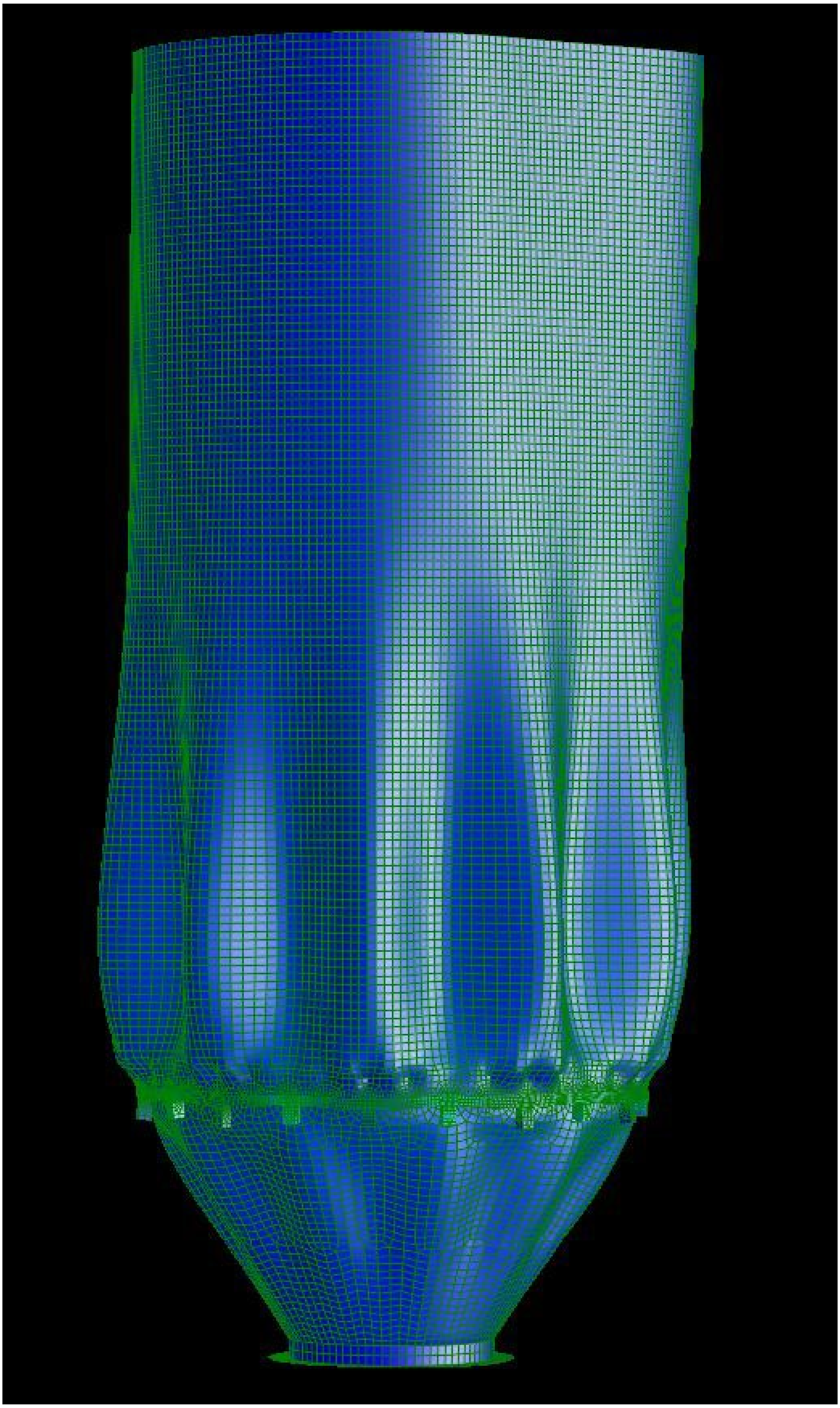


Figure 78: Front view of the Lower-Upper load case. 1.5mm thick.

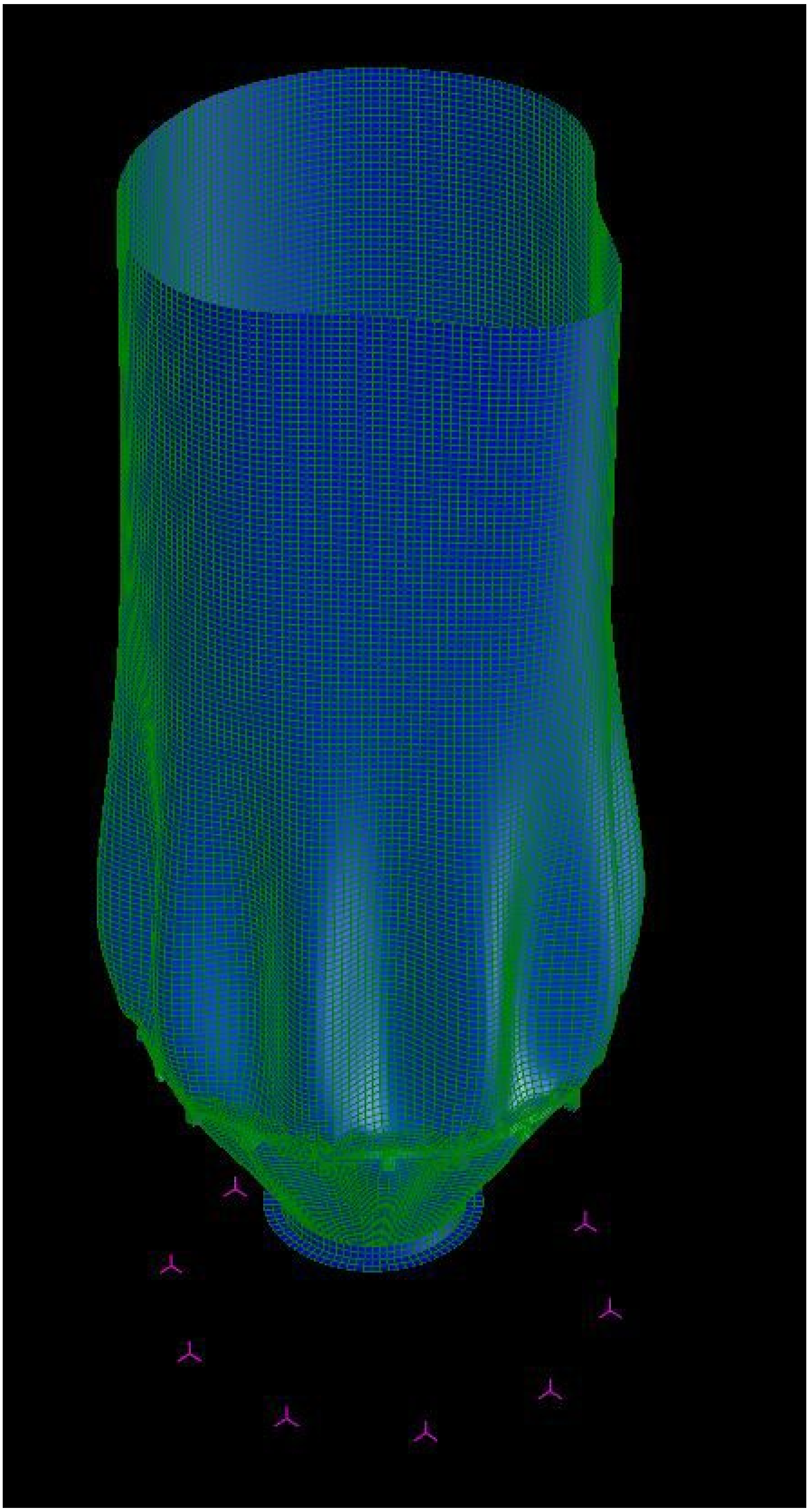


Figure 79: Isometric view of the Lower- Upper load case. 1.5mm thick.

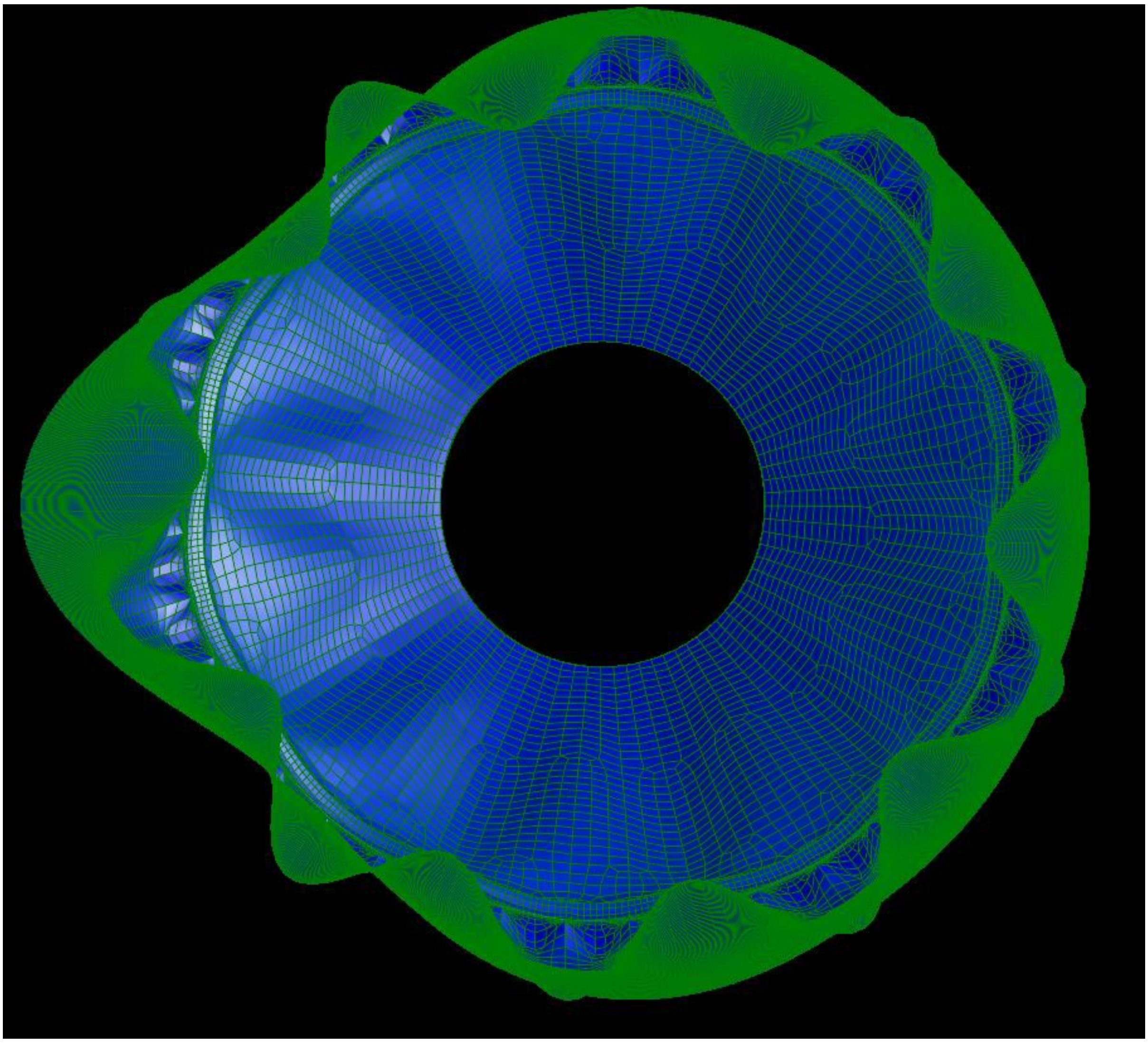


Figure 80: Top view of the Lower-Upper load case. 1.5mm thick.

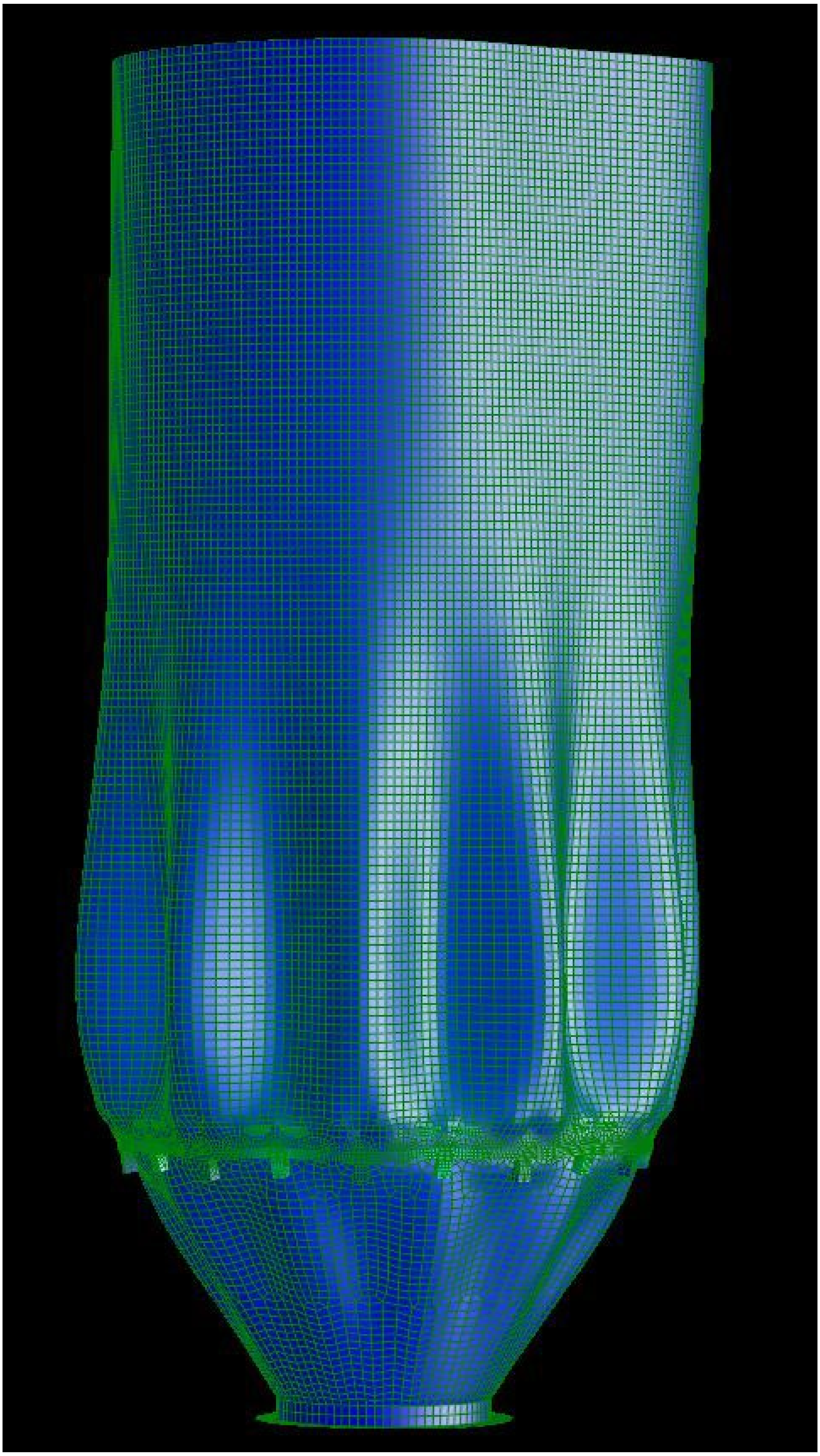


Figure 81: Front view of the Upper-Lower load case. 1.5mm thick.

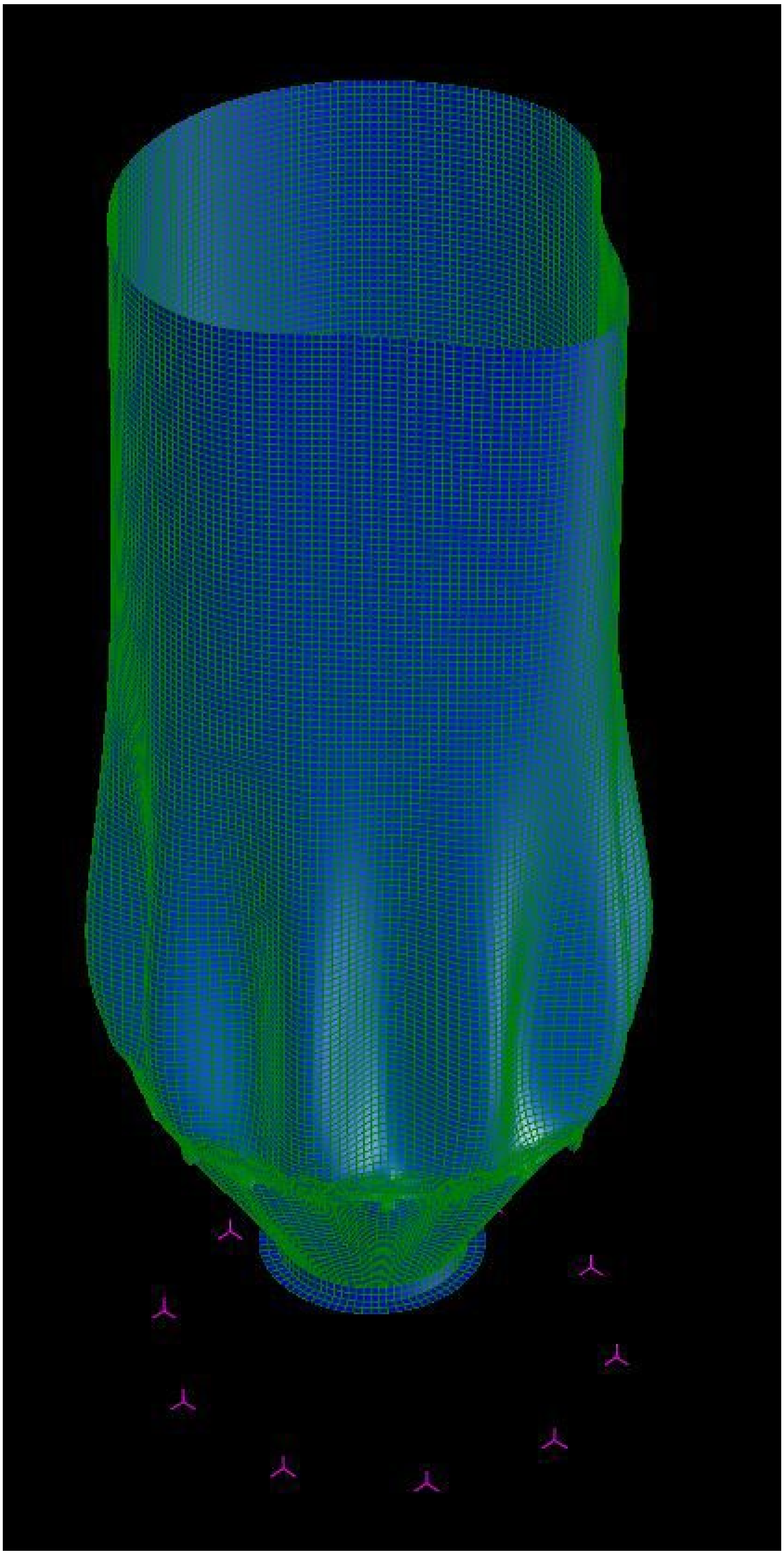


Figure 82: Isometric view of the Upper-Lower load case. 1.5mm thick.

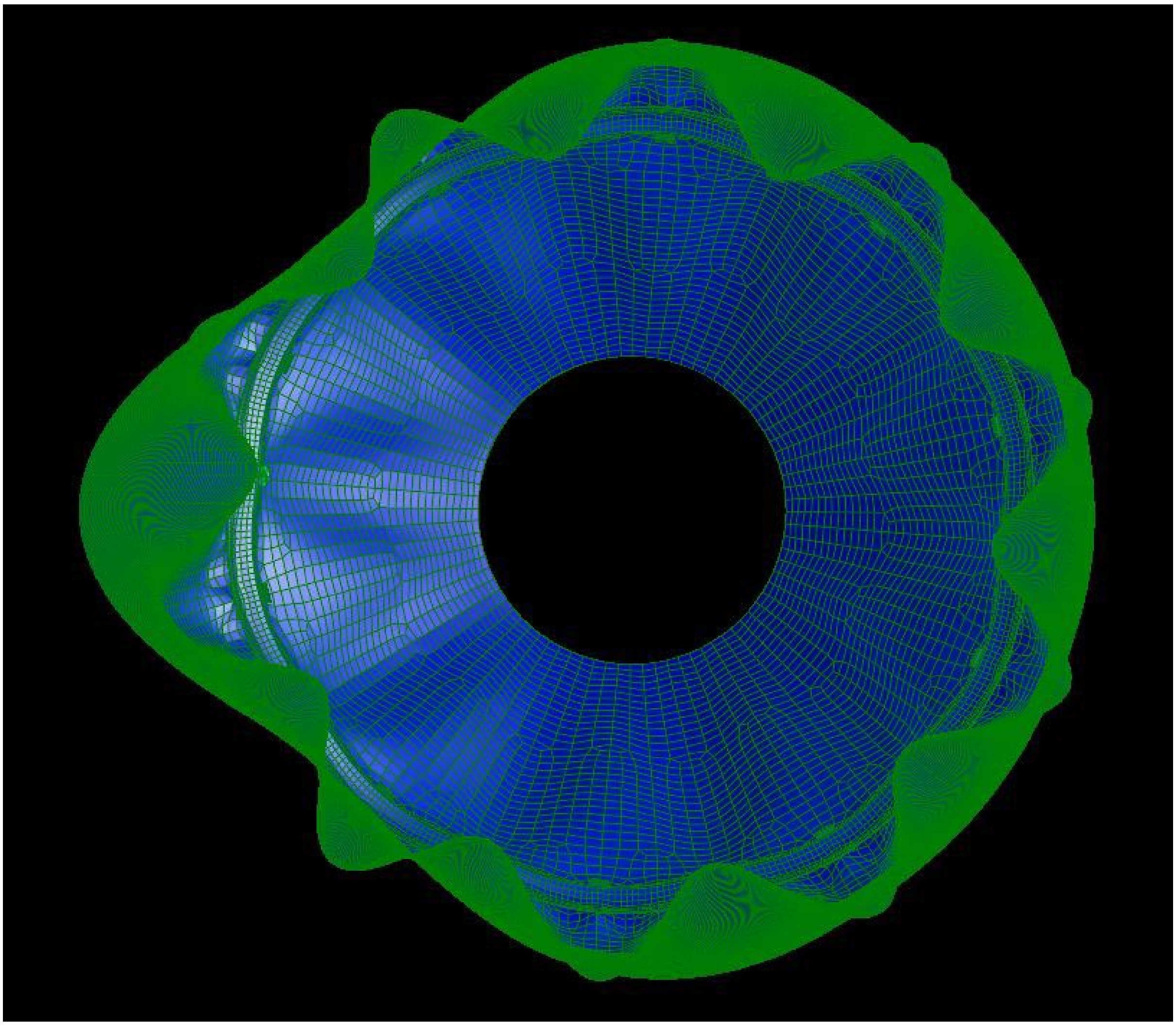


Figure 83: Top view of the Upper-Lower load case. 1.5mm thick.

G.2 3.6m Diameter Wheat Silo

G.2.1 1.0mm Thickness

These models can be found in chapter 5.1 of the report.

G.2.2 1.2mm Thickness

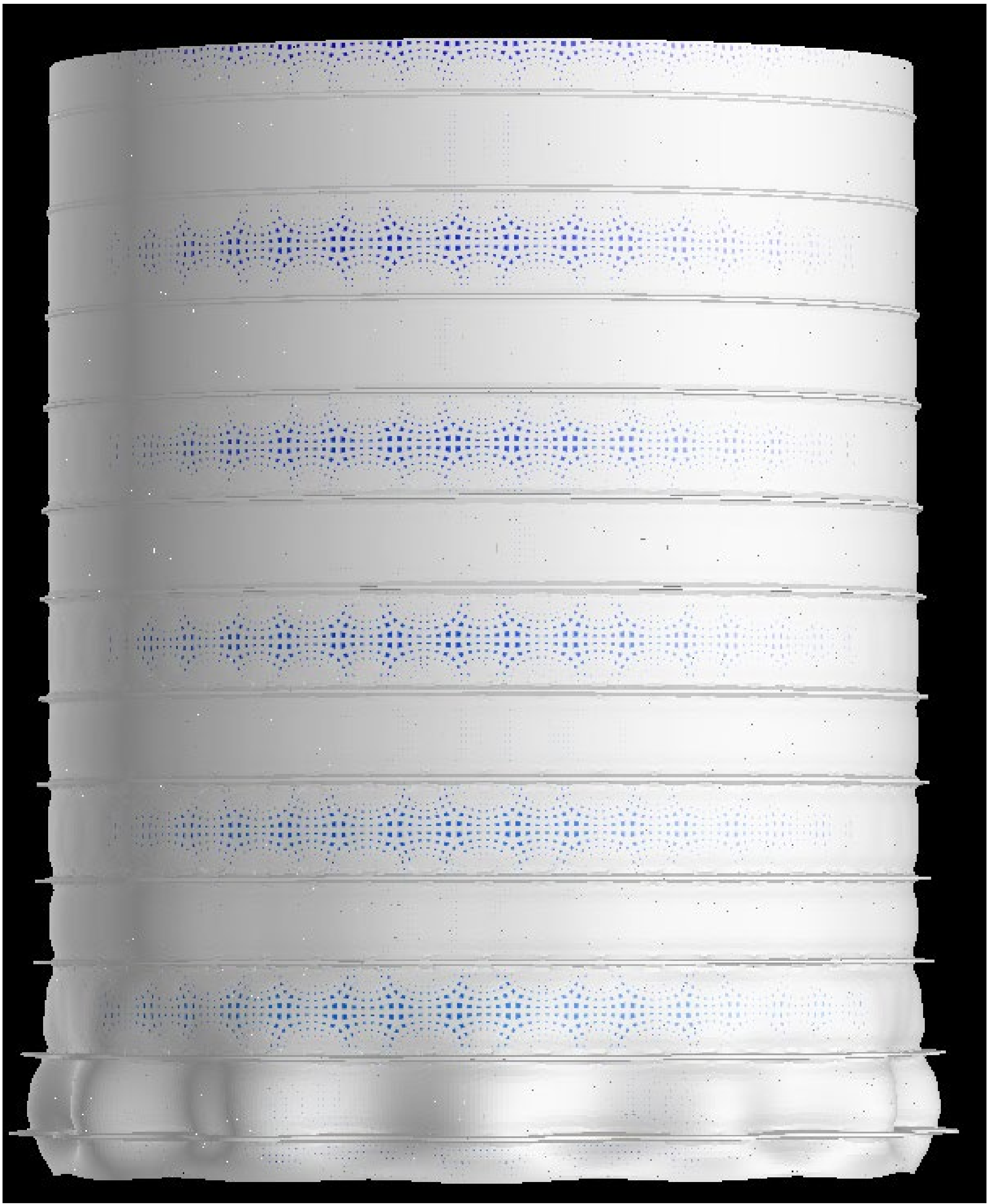


Figure 84: Upper-lower case for 1.2mm thickness, 3.6m diameter wheat silo.

Figure 85: Upper-lower case for 1.2mm thickness, 3.6m diameter wheat silo. Isometric View.

G.2.3 1.35mm Thickness

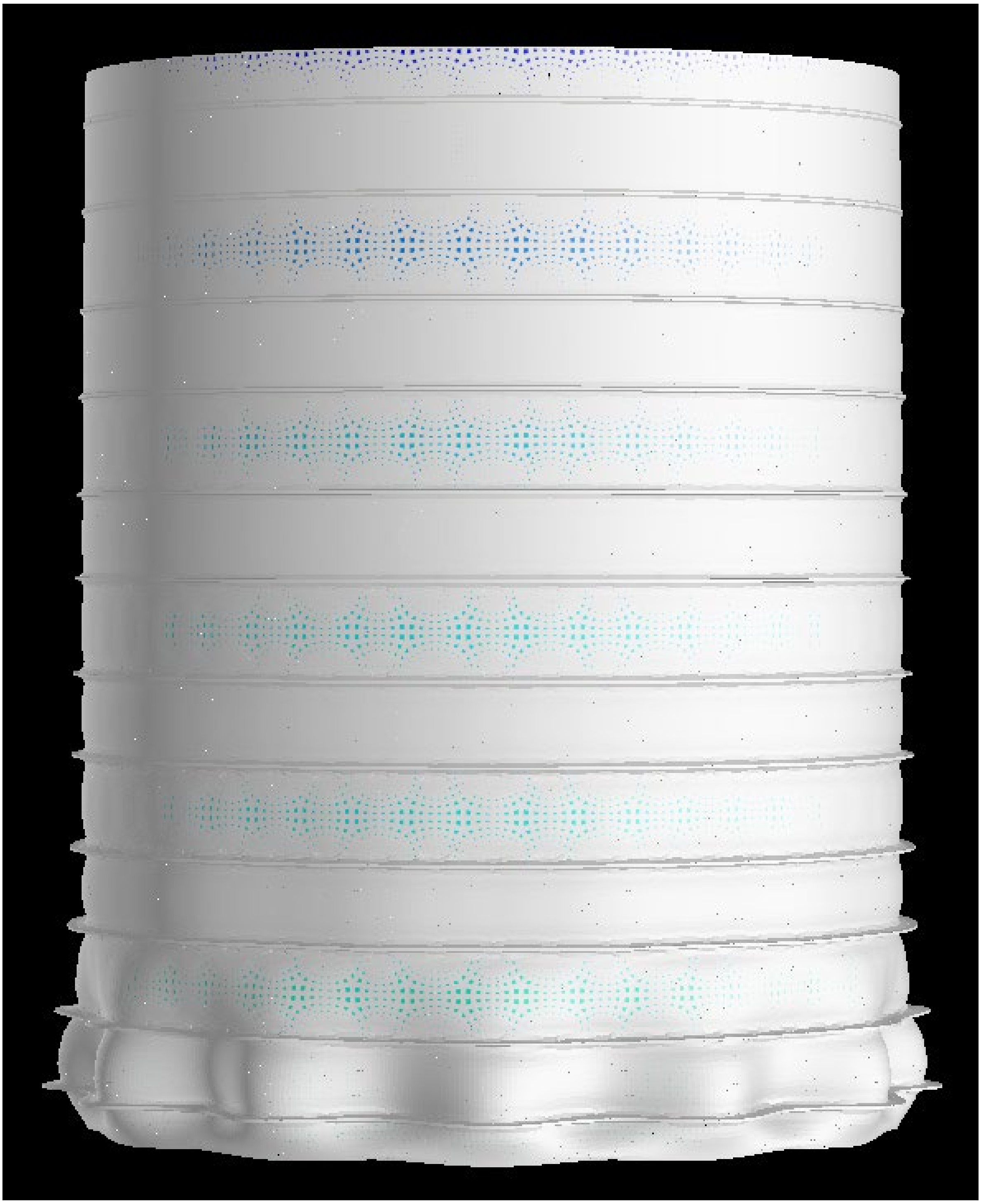


Figure 86: Upper-lower case for 1.35mm thickness, 3.6m diameter wheat silo.

Figure 87: Upper-lower case for 1.35mm thickness, 3.6m diameter wheat silo. Isometric View.

G.2.4 1.4mm Thickness

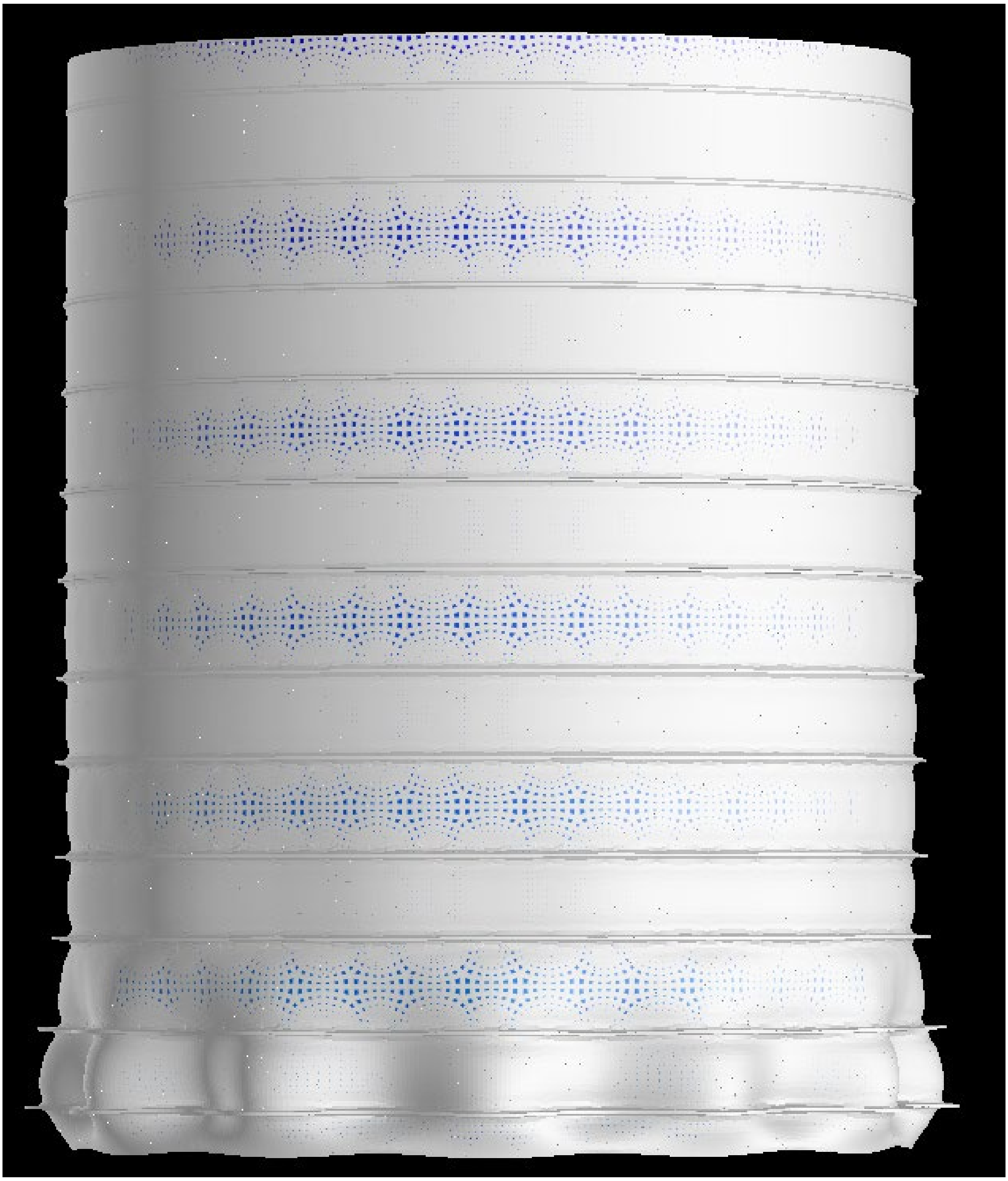


Figure 88: Upper-lower case for 1.4mm thickness, 3.6m diameter wheat silo.

Figure 89: Upper-lower case for 1.4mm thickness, 3.6m diameter wheat silo. Isometric View.

G.2.5 1.5mm Thickness (Initial)

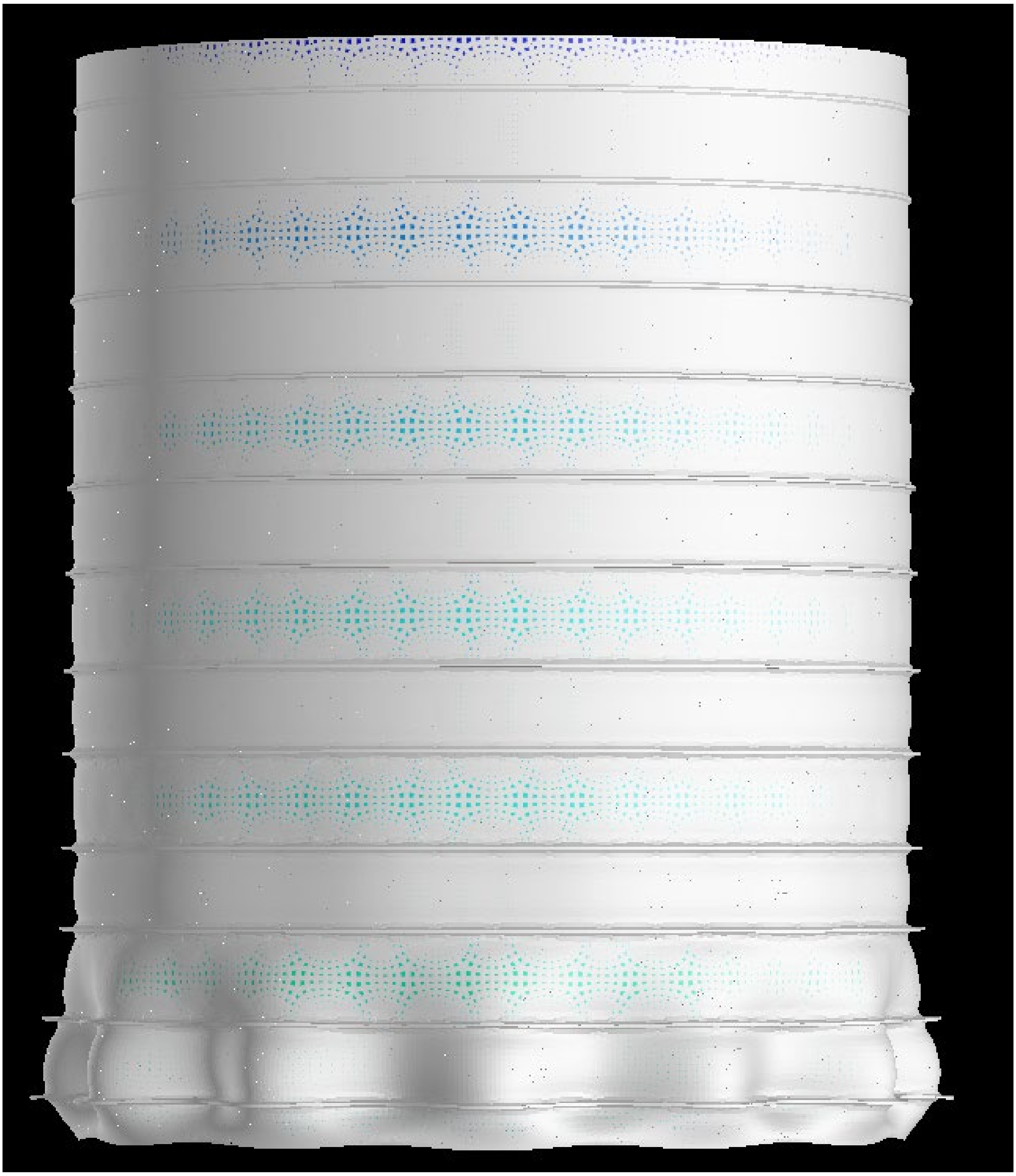


Figure 90: Upper-lower case for 1.5mm thickness, 3.6m diameter wheat silo.

Figure 91: Upper-lower case for 1.5mm thickness, 3.6m diameter wheat silo. Isometric View.

G.3 3.6m Diameter Meal Silo

G.3.1 1.0mm Thickness

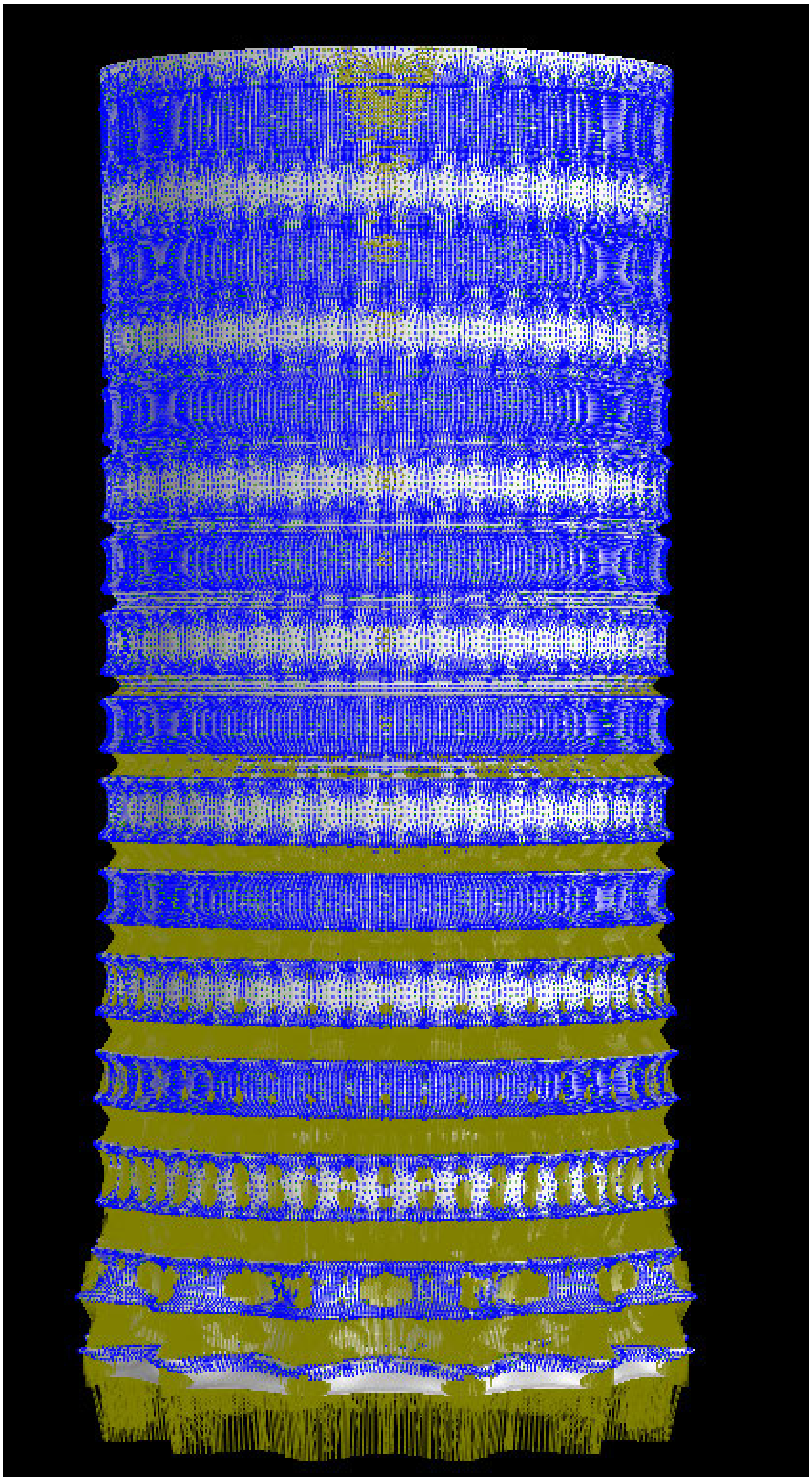


Figure 92: Upper-lower case for 1.0mm thickness, 3.6m diameter meal silo.

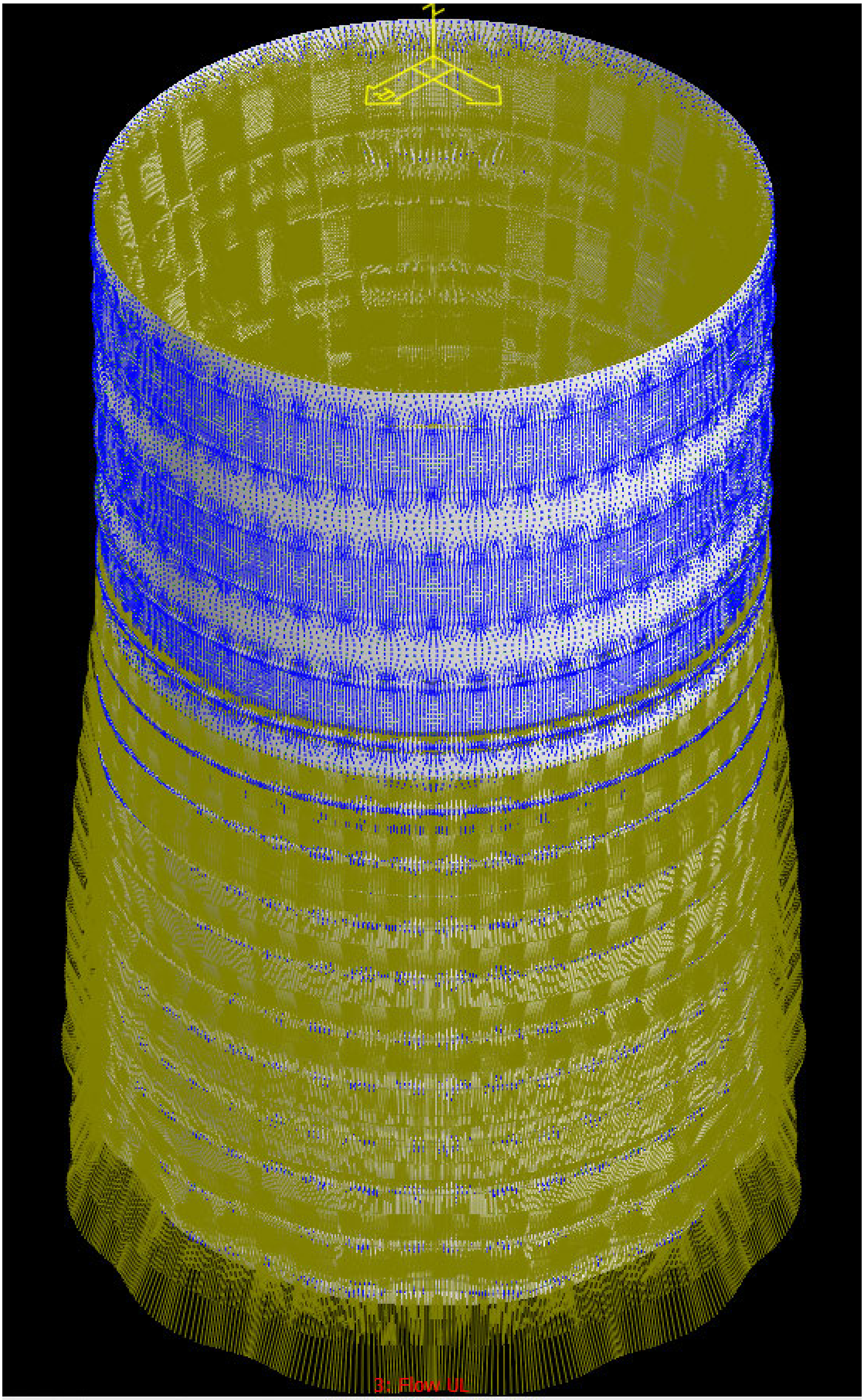


Figure 93: Upper-lower case for 1.0mm thickness, 3.6m diameter meal silo. Isometric View.

G.3.2 1.2mm Thickness

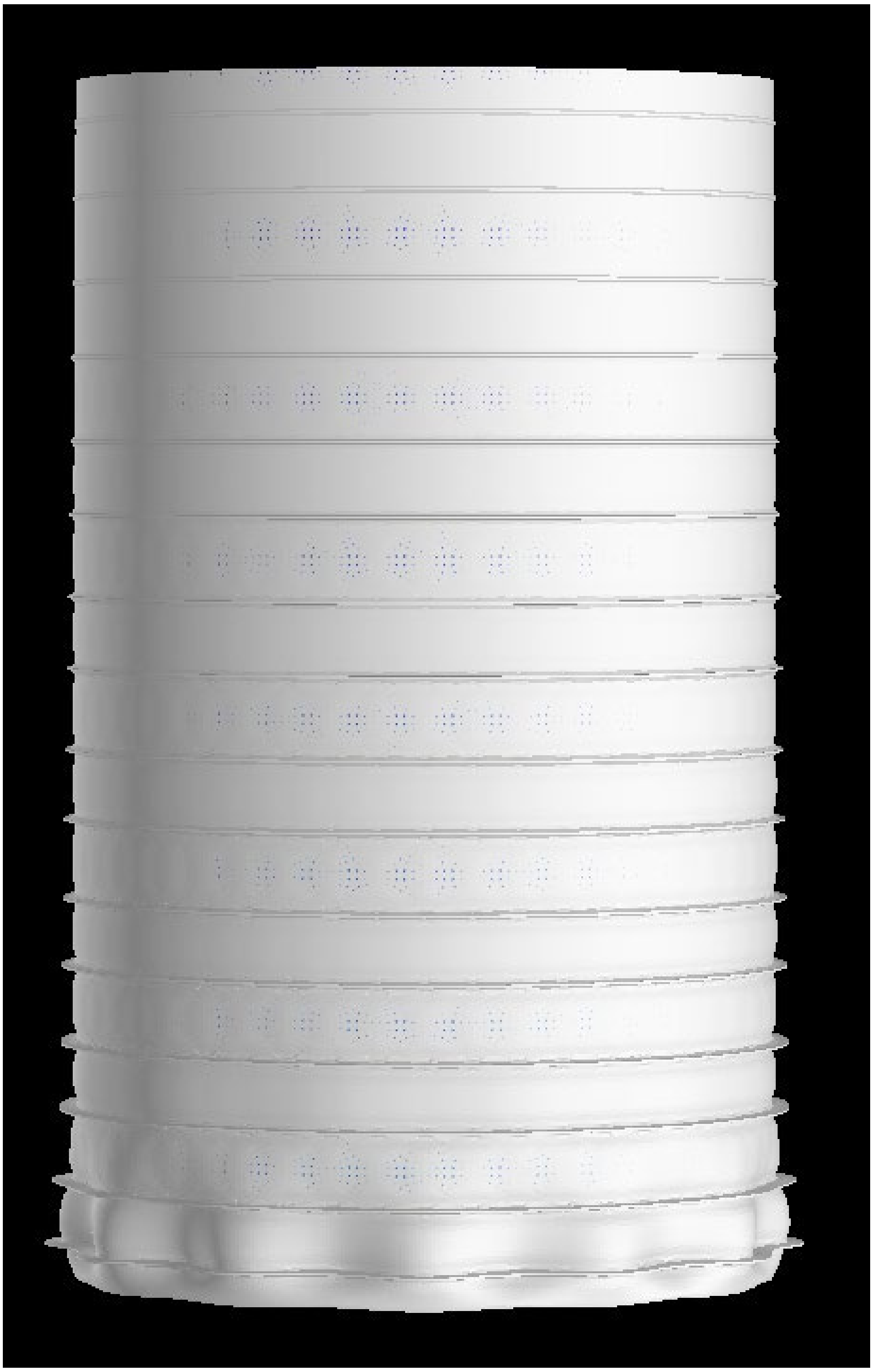


Figure 94: Upper-lower case for 1.2mm thickness, 3.6m diameter meal silo.

Figure 95: Upper-lower case for 1.2mm thickness, 3.6m diameter meal silo. Isometric View.

G.3.3 1.4mm Thickness

Figure 96: Upper-lower case for 1.4mm thickness, 3.6m diameter meal silo.

Figure 97: Upper-lower case for 1.4mm thickness, 3.6m diameter meal silo. Isometric View.

G.3.4 1.5mm Thickness (Initial)

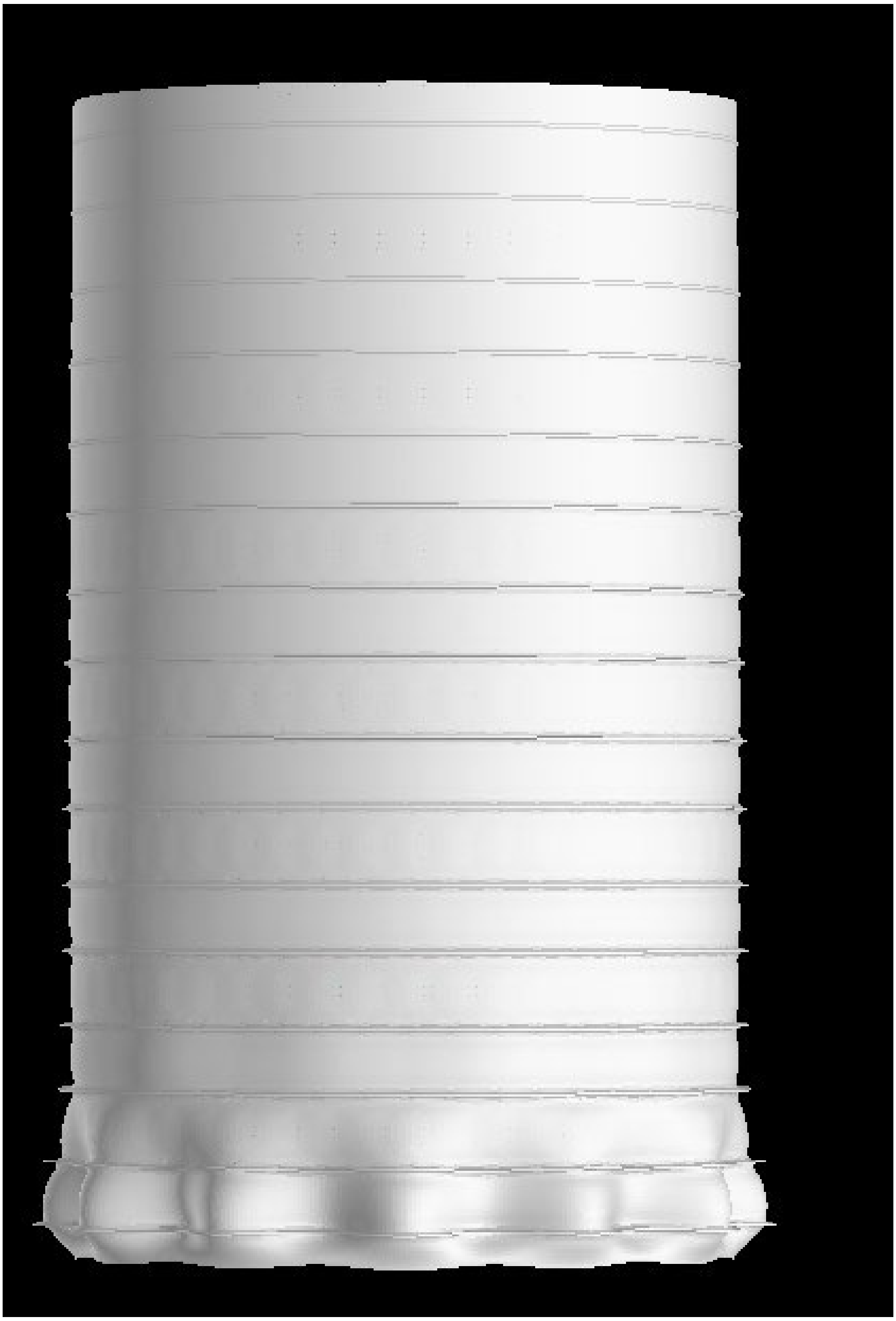
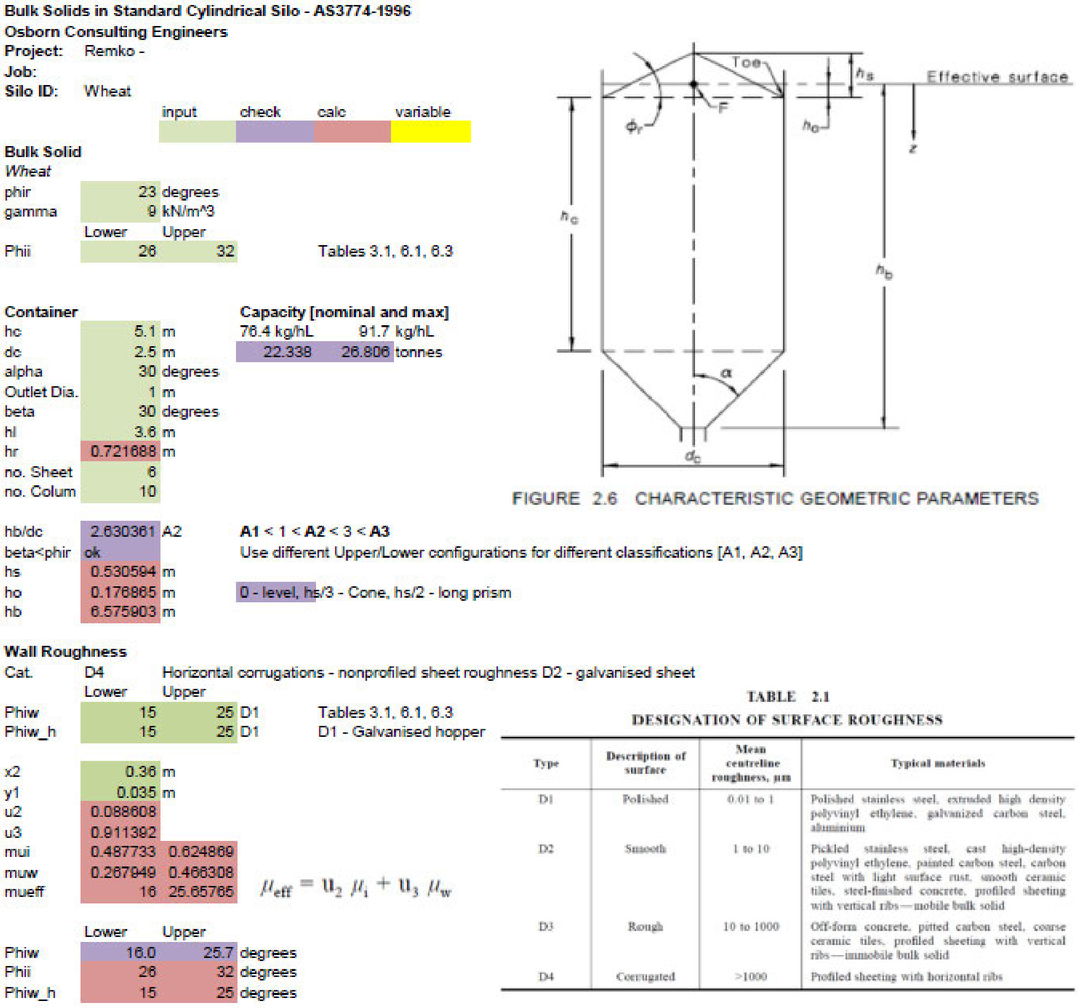


Figure 98: Upper-lower case for 1.5mm thickness, 3.6m diameter meal silo.

Figure 99: Upper-lower case for 1.5mm thickness, 3.6m diameter meal silo. Isometric View.

Appendix H – Excel Spreadsheets

H.1 2.5m Diameter Wheat Silo Spreadsheet



Bulk Solids in Standard Cylindrical Silo - AS3774-1996
Osborn Consulting Engineers
Project: Remko -
Job:
Silo ID: Wheat

input	check	calc	variable
🟩	🟪	🟥	🟨

Bulk Solid
Wheat

phir	23	degrees	
gamma	9	kN/m^3	
	Lower	Upper	
Phii	26	32	Tables 3.1, 6.1, 6.3

Container

hc	5.1	m	76.4 kg/hL	91.7 kg/hL	
dc	2.5	m	22.338	26.806	tonnes
alpha	30	degrees			
Outlet Dia.	1	m			
beta	30	degrees			
hl	3.6	m			
hr	0.721688	m			
no. Sheet	6				
no. Colum	10				

Capacity [nominal and max]

FIGURE 2.6 CHARACTERISTIC GEOMETRIC PARAMETERS

hb/dc	2.630361	A2	**A1** < 1 < **A2** < 3 < **A3**
beta<phir	ok		Use different Upper/Lower configurations for different classifications [A1, A2, A3]
hs	0.530594	m	
ho	0.176865	m	0 - level, hs/3 - Cone, hs/2 - long prism
hb	6.575903	m	

Wall Roughness

Cat.	D4	Horizontal corrugations - nonprofiled sheet roughness D2 - galvanised sheet		
	Lower	Upper		
Phiw	15	25	D1	Tables 3.1, 6.1, 6.3
Phiw_h	15	25	D1	D1 - Galvanised hopper

TABLE 2.1

DESIGNATION OF SURFACE ROUGHNESS

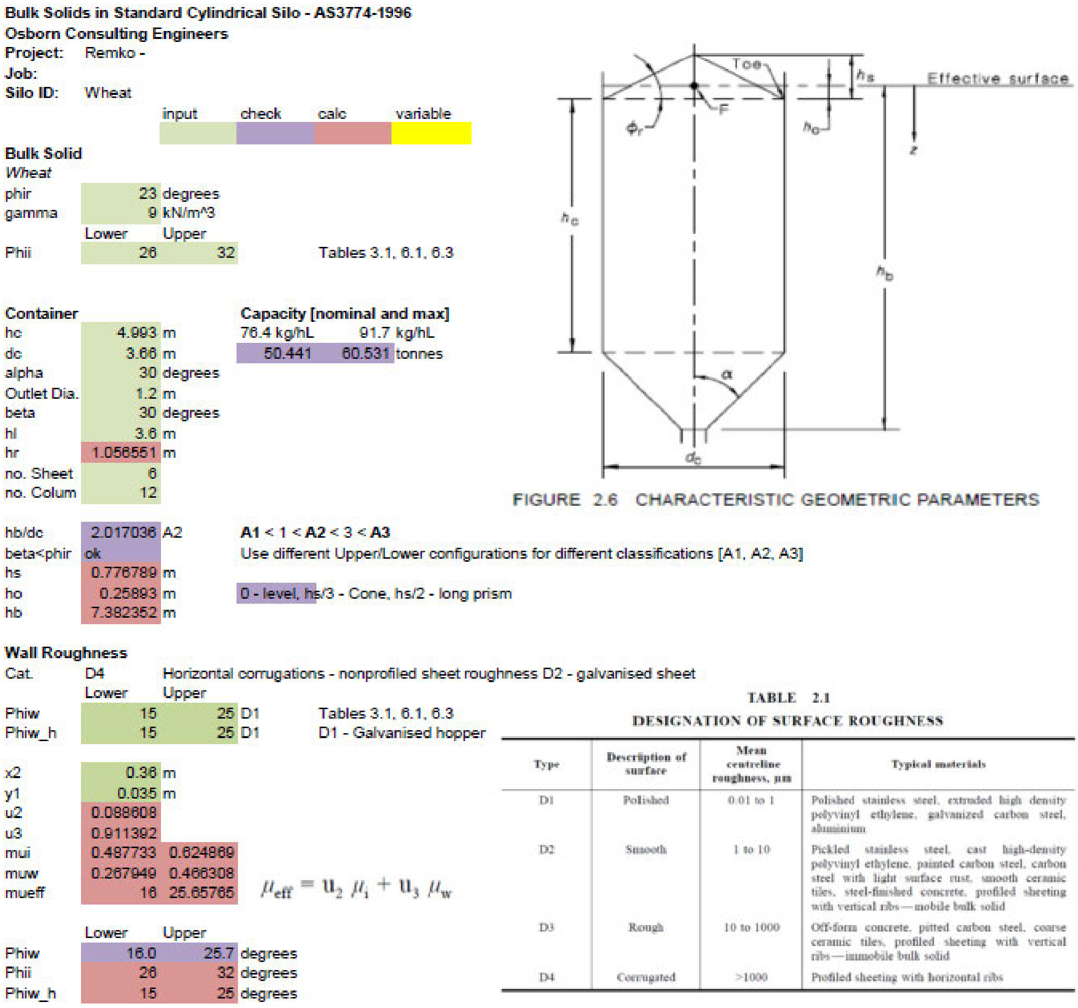
Type	Description of surface	Mean centreline roughness, μm	Typical materials
D1	Polished	0.01 to 1	Polished stainless steel, extruded high density polyvinyl ethylene, galvanized carbon steel, aluminium
D2	Smooth	1 to 10	Pickled stainless steel, cast high-density polyvinyl ethylene, painted carbon steel, carbon steel with light surface rust, smooth ceramic tiles, steel-finished concrete, profiled sheeting with vertical ribs—mobile bulk solid
D3	Rough	10 to 1000	Off-form concrete, pitted carbon steel, coarse ceramic tiles, profiled sheeting with vertical ribs—immobile bulk solid
D4	Corrugated	>1000	Profiled sheeting with horizontal ribs

x2	0.36	m	
y1	0.035	m	
u2	0.088608		
u3	0.911392		
mui	0.487733	0.624869	
muw	0.267949	0.466308	
mueff	16	25.65765	

$$\mu_{eff} = u_2\ \mu_i + u_3\ \mu_w$$

	Lower	Upper	
Phiw	16.0	25.7	degrees
Phii	26	32	degrees
Phiw_h	15	25	degrees

H.2 3.6m Diameter Wheat Silo Spreadsheet



Bulk Solids in Standard Cylindrical Silo - AS3774-1996
Osborn Consulting Engineers
Project: Remko -
Job:
Silo ID: Wheat

input	check	calc	variable
🟩	🟪	🟥	🟨

Bulk Solid
Wheat

	Lower	Upper	
phir	23	degrees	
gamma	9	kN/m^3	
Phii	26	32	Tables 3.1, 6.1, 6.3

Container

hc	4.993	m
dc	3.66	m
alpha	30	degrees
Outlet Dia.	1.2	m
beta	30	degrees
hl	3.6	m
hr	1.056551	m
no. Sheet	6	
no. Colum	12	

Capacity [nominal and max]

76.4 kg/hL	91.7 kg/hL	
50.441	60.531	tonnes

hb/dc	2.017036	A2
beta<phir	ok	
hs	0.776789	m
ho	0.25893	m
hb	7.382352	m

A1 < 1 < **A2** < 3 < **A3**
Use different Upper/Lower configurations for different classifications [A1, A2, A3]

0 - level, hs/3 - Cone, hs/2 - long prism

FIGURE 2.6 CHARACTERISTIC GEOMETRIC PARAMETERS

Wall Roughness

Cat. D4 Horizontal corrugations - nonprofiled sheet roughness D2 - galvanised sheet

	Lower	Upper		
Phiw	15	25	D1	Tables 3.1, 6.1, 6.3
Phiw_h	15	25	D1	D1 - Galvanised hopper

x2	0.36	m
y1	0.035	m
u2	0.088608	
u3	0.911392	
mui	0.487733	0.624869
muw	0.267949	0.466308
mueff	16	25.65765

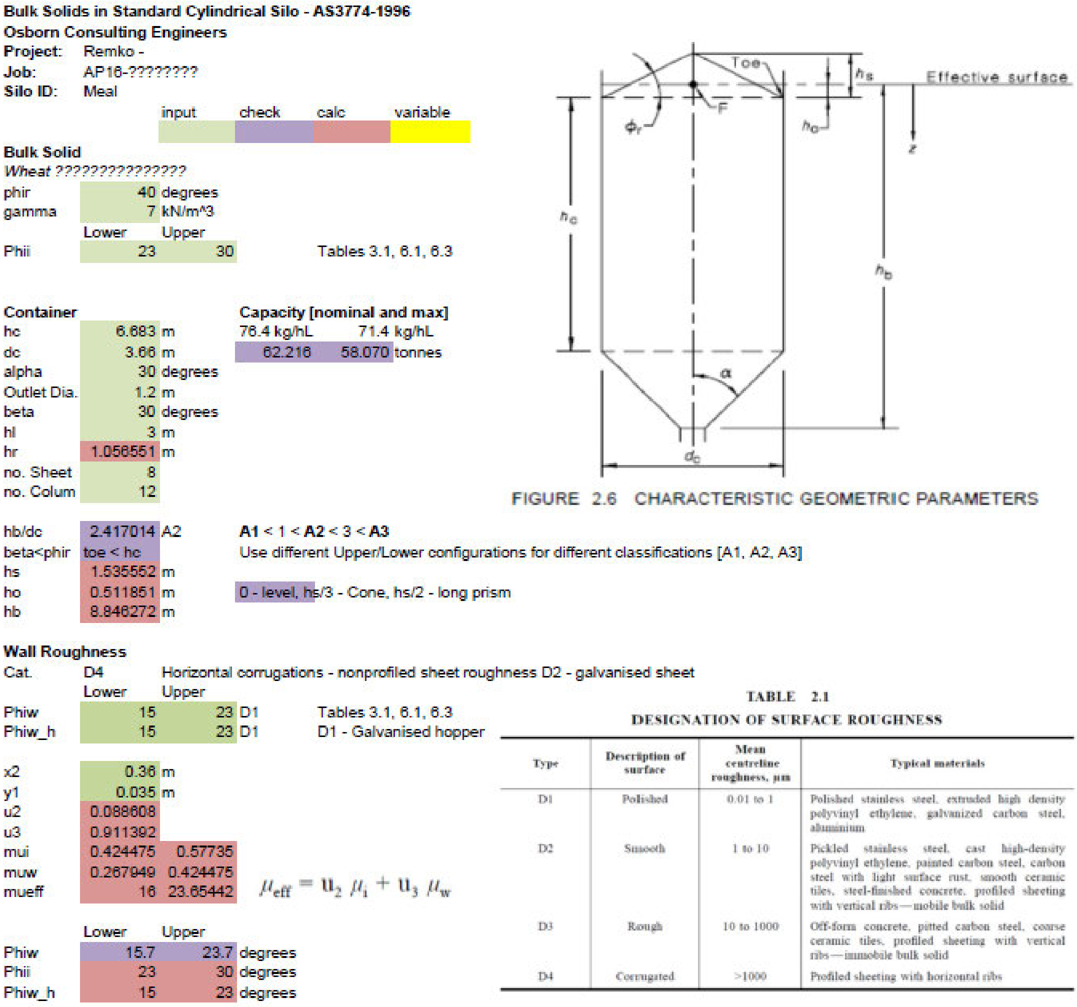
$$\mu_{eff} = u_2\,\mu_i + u_3\,\mu_w$$

	Lower	Upper	
Phiw	16.0	25.7	degrees
Phii	26	32	degrees
Phiw_h	15	25	degrees

TABLE 2.1
DESIGNATION OF SURFACE ROUGHNESS

Type	Description of surface	Mean centreline roughness, µm	Typical materials
D1	Polished	0.01 to 1	Polished stainless steel, extruded high density polyvinyl ethylene, galvanized carbon steel, aluminium
D2	Smooth	1 to 10	Pickled stainless steel, cast high-density polyvinyl ethylene, painted carbon steel, carbon steel with light surface rust, smooth ceramic tiles, steel-finished concrete, profiled sheeting with vertical ribs—mobile bulk solid
D3	Rough	10 to 1000	Off-form concrete, pitted carbon steel, coarse ceramic tiles, profiled sheeting with vertical ribs—immobile bulk solid
D4	Corrugated	>1000	Profiled sheeting with horizontal ribs

H.3 3.6m Diameter Meal Silo Spreadsheet



Bulk Solids in Standard Cylindrical Silo - AS3774-1996
Osborn Consulting Engineers
Project: Remko -
Job: AP16-????????
Silo ID: Meal

input	check	calc	variable
🟩	🟪	🟥	🟨

Bulk Solid

Wheat ???????????????

phir	40	degrees		
gamma	7	kN/m^3		
	Lower	Upper		
Phii	23	30		Tables 3.1, 6.1, 6.3

Container

hc	6.683	m
dc	3.66	m
alpha	30	degrees
Outlet Dia.	1.2	m
beta	30	degrees
hl	3	m
hr	1.056551	m
no. Sheet	8	
no. Colum	12	

Capacity [nominal and max]

76.4 kg/hL	71.4 kg/hL	
62.216	58.070	tonnes

FIGURE 2.6 CHARACTERISTIC GEOMETRIC PARAMETERS

hb/dc	2.417014	A2
beta<phir	toe < hc	
hs	1.535552	m
ho	0.511851	m
hb	8.846272	m

A1 < 1 < **A2** < 3 < **A3**

Use different Upper/Lower configurations for different classifications [A1, A2, A3]

0 - level, hs/3 - Cone, hs/2 - long prism

Wall Roughness

Cat. D4 Horizontal corrugations - nonprofiled sheet roughness D2 - galvanised sheet

	Lower	Upper		
Phiw	15	23	D1	Tables 3.1, 6.1, 6.3
Phiw_h	15	23	D1	D1 - Galvanised hopper

x2	0.36	m
y1	0.035	m
u2	0.088608	
u3	0.911392	
mui	0.424475	0.57735
muw	0.267949	0.424475
mueff	16	23.65442

$$\mu_{eff} = u_2\ \mu_i + u_3\ \mu_w$$

	Lower	Upper	
Phiw	15.7	23.7	degrees
Phii	23	30	degrees
Phiw_h	15	23	degrees

TABLE 2.1

DESIGNATION OF SURFACE ROUGHNESS

Type	Description of surface	Mean centreline roughness, μm	Typical materials
D1	Polished	0.01 to 1	Polished stainless steel, extruded high density polyvinyl ethylene, galvanized carbon steel, aluminium
D2	Smooth	1 to 10	Pickled stainless steel, cast high-density polyvinyl ethylene, painted carbon steel, carbon steel with light surface rust, smooth ceramic tiles, steel-finished concrete, profiled sheeting with vertical ribs—mobile bulk solid
D3	Rough	10 to 1000	Off-form concrete, pitted carbon steel, coarse ceramic tiles, profiled sheeting with vertical ribs—immobile bulk solid
D4	Corrugated	>1000	Profiled sheeting with horizontal ribs