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STRAIN ANALYSIS OF PREEXISTING GRAIN BIN STRUCTURES FOR RETROFITTING SAFE ENTRY TECHNOLOGY

A Thesis in

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Abstract:

Grain bins are regarded as one of the most hazardous working environments in the agricultural sector. While OSHA federal regulations mandate entrants wear a harness and lifeline while in a bin, farms with less than 10 employees are exempt from all OSHA requirements. Most entrapment and engulfment incidents occur at these ~260,000 OSHA exempt grain storage facilities. If these facilities possessed and properly implemented safety technology, many of these incidents could be prevented. In August 2018, ASABE standard ANSI/ASABE S624 was approved, recommending that all new grain bins produced have anchor points capable of handling a 2000lbf loading for attachment of bin entry lifeline systems. However, many preexisting grain bins do not have these anchor points. A 3D finite element model of a grain bin was created and used to model the structural performance of a pre-existing grain bin that is subjected to simulated loadings consistent with the loads seen during an entrapment incident. Verification of this 3D model was attempted via experimental testing on two on-farm grain bins using strain gauges. The experimental strain was recorded and an error comparison was conducted to determine the error seen between the simulated testing and the experimental testing. The error analysis resulted in a range from -1108.59% error to 1782.04% error. Assumptions in both the modeling and experimentation processes were the cause of most of this error and unfortunately time did not permit continued testing to isolate the error from each assumption. This has spurred the need for further testing and the use of different testing methods. Continued strain gauge testing is needed, as well as bin deflection testing, to ensure more consistent results before this model can be used to generate recommendations regarding the retrofit of bin entry lifeline systems.

Contents

List of Figures

List of Tables

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1.0 Introduction

Grain bin entrapments and engulfments are potential hazards associated with grain storage facilities across America. Entrapment is defined as an incident where a person is submerged in grain, but their head is still above the level of the grain and self-extrication is impossible. Engulfment implies that a victim is entirely submerged in grain (Issa et al., 2017). Entrapments can occur when caught in flowing grain, falling through bridged grain, or when a grain wall avalanches or collapses. As of 2019, there have been 1,496 reported incidents involving grain storage and handling. In 2019, there were 38 grain entrapment cases, 23 of which were fatal. This number is 26.7% higher than that reported in 2018 and was the highest it has been in the preceding four years (Cheng et al., 2020). Numerous studies have been conducted in order to document these facilities, determine factors contributing to entrapments, understand how to mitigate incidents, and determine ways to perform safe extrication of entrapped persons (Freeman et al., 1998, Issa et al., 2017, Moore and Jones, 2017). The OSHA definition of a confined space requires that a space have: limited/restricted means of entry/egress, large enough volume and be so configured that an employee can enter and complete required work, and not been designed for continuous human occupancy. Grain bins fall under the Occupational Safety and Health Administration (OSHA) definition of a confined space.

One prevention strategy that is being used in commercial grain storage facilities is the use of a lifeline system to keep workers from being entrapped in grain. OSHA Standard CFR 29 1910.272 issues safety guidelines regarding grain bin entry for workers but provides exemptions for farms. Highlighted in this standard is the use of harnesses and lifelines in grain storage facilities (OSHA, 2002), and safe entry permitting procedures to protect workers from grain bin entrapments and engulfments. However, this standard is not enforced on farms that have 10 or fewer workers. These lifeline systems must be engineered to support the forces imparted on them during an entrapment incident. According to ASABE standard ANSI/ASABE S624, anchor points must be able to support a minimum ultimate load of 2000lbf(8900N)(ANSI/ASABE, 2018). Newer grain bins are beginning to come equipped with anchor points rated to support these forces, but it is unknown if preexisting grain bins possess the structural integrity to handle these forces when retrofitted with anchor points. The Grain Safe Handling Coalition (GHSC) has published a recommendation for grain bin retrofit lifeline installation which will be followed for this research. The efficacy of a lifeline as a safety intervention for pre-existing on-farm grain bins needs to be systemically evaluated.

2.0 Literature Review

Hazards of working in and around grain bins have been well documented in the research literature. The main goal of these studies has been the implementation of standards and safety mechanisms to make agricultural work, specifically grain storage, safer for farmers, their families, and their employees. OSHA standards provide an exemption clause to small farms which limits inspection and enforcement of these safety standards. Thus, many on-farm grain bins lack a lifeline and harness system. However, the prevalence of entrapment and engulfment incidents has been documented since the mid-1960s and continues to be documented to track the magnitude of the problem on exempt farms. Recent collaborative industry efforts have yielded ASABE standard S624 which establishes that new on-farm grain bins should be manufactured with anchor points capable of supporting a minimum ultimate load of 2000lbf(8900N)(ASABE/ANSI, 2018). It is unknown if preexisting grain bins possess the structural integrity to handle these forces. Retrofitting existing grain bins with lifeline anchor points is a viable next step in improving grain bin safety, and by being able to retrofit older grain bins with these technologies, it allows for safer entry to those grain bins.

2.1 Grain Entrapment Methods

The most common type of flow exhibited by flowing grain in a bin is termed “funnel flow”. Because most grain bins unload (remove grain from the bin) through a hole in the bottom center of the bin, the flowing grain forms a column directly over it and is fed from the top of the pile of grain. This funnel is a contributor to entrapments. The grain is being sucked out from under the feet of the entrant, which causes the entrant to sink and the grain flowing from the top of the pile covers the entrant. This causes the entrapment and can submerge an individual up to their shoulders in the grain in as little as thirty seconds (Schwab et al., 1985). There are many ways that grain can collapse and entrap or engulf a person. Field et al. (2014) identifies seven different categories of grain entrapment:

Free Flowing-Grain Entrapment: an entrapment that usually occurs during unloading while the grain is flowing through an open hole beneath the column. The center of the column flows straight down over the hole and draws the victim down with it where usually they come to rest directly over the hole in the floor.

Bridging/Crusted Horizontal Surface Entrapment: an entrapment in which the victim breaks through a crust of grain concealing a void. Once the crust is broken, the victim falls in, grain avalanches into the hole and covers the victim.

Vertically Crusted Grain/Avalanche Entrapment: an entrapment where spoiled grain is clinging to walls of the bin. When this is disturbed by the victim, the grain held up above the crust falls like an avalanche and crushes and/or entraps the victim.

Free Standing Pile Entrapment: an entrapment where walking on grain creates an avalanche from above and due to the volume of grain moving, it is enough to cover the victim.

Grain Transport Vehicle Entrapment: similar to Free Flowing-Grain Entrapment. Entrapment comes from being drawn under due to flowing grain. These entrapments occur in Grain Transport Vehicles.

Unintended Release/ Structural Failure Entrapment: entrapment where due to unexpected release of grain through an access point or structural failure of a bin, grain is released and swallows the victim.

Grain Vacuum Entrapment: entrapment due to removing grain from beneath the feet of the victim with a vacuum. Due to the high volume of flow these vacuums have, they can draw the victims down into the grain very quickly.

Farm safety specialists at Purdue University have been documenting agricultural confined space incidents since the early 1970s with the purpose of aiding in the reduction of their frequency and severity. Each year researchers sort through these incidents and compile a report that includes comparisons to previous years, and records trends and overall numbers of incidents (Issa et al., 2018) In 2017 no fewer than 54 incidents occurred in confined spaces, 23 of which were related to grain entrapments. This number is down 26% from 2016, as is the 5-year running average which is 29.4 cases. These statistics are based solely on the incidents reported to the Purdue Agricultural Confined Space Incident Database (PACSID), so it does not contain every incident across the country. PACSID shows the distribution of these reported incidents across the country and tracks them from year to year. Most of these incidents take place in the Corn Belt (Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, Ohio, South Dakota, Wisconsin) but that does not make this problem any less of a nationwide issue. As of 2019, it appears that Maine, Rhode Island, Vermont, Wyoming, Hawaii, Alaska, and Nevada are the only states without reported incidents in PACSID, but that is not necessarily the case due to the fact that many reports each year do not have a specified location attached to them.

2.2 OSHA Regulations

OSHA has promulgated standards for fall protection equipment that is required to be used at all commercial grain handling facilities when conducting certain work. Of the four different classes for fall-safety equipment, only Class 3 and 4 equipment may be used in grain bin operations. OSHA Standard 29 CFR 1910.272 states that any worker entering a non-exempt grain storage facility is required to wear a full body harness and to be attached to a lifeline. This standard also requires another person to be present as an observer and to manage slack in the lifeline (OSHA, 2002). Unfortunately, there is little evidence that the harness and lifeline help to prevent entrapments, perhaps to negligence and improper use of safety equipment (Issa et al., 2018). OSHA Directive CPL 2-.051J states that farms with 10 or fewer employees will not be inspected. This is one of the reasons that incidents occur at these facilities. With no OSHA inspection to warrant enforcement of standards, there is little incentive to purchase safety equipment or follow proper safety procedures. It is hard to know if a lifeline would have successfully prevented any of the incidents at these exempt facilities (Issa et al., 2018).

2.3 Current Grain Extrication Methods

Currently, grain rescue tubes or coffer dams are the most heavily utilized method used for extraction from a grain entrapment. This method involves the assembling of a tube, usually of constructed of a lightweight metal or polymer, to act as a retaining wall around the victim. This tube is used to prevent grain from rushing back into the cavity that is made from the grain as it is removed from around the entrapped individual. This method allows for the safe extrication of a victim who is entrapped, however it is not feasible for an individual who has been engulfed because it is unknown where they are located under the surface of the grain. This method is the current best practice for rescuing victims entrapped in grain because it minimizes damage to both the bin and the grain stored inside. Another method of extrication is to cut holes in the sidewall of the bin and allow the grain level to decrease and uncover the victim. This is usually only used in extreme circumstances where the victim is engulfed because it causes significant damage to the bin and the grain that is spilled onto the ground. The third method of extrication is using a lifeline to pull the victim straight out of the grain. This is very dangerous due to the extreme forces imparted on the human body, usually along a very small surface area such as from a rope. A full body harness is designed to distribute these forces more evenly across the body and allows for more intense loadings to be put on the body without inducing bodily injury. The harness in a grain bin, used correctly in conjunction with an outside observer and a lifeline, will prevent someone from sinking more than two feet into grain in the event of an entrapment incident (Issa et al., 2018) The forces imparted on someone during an extrication can be incredibly hazardous to a person with multiple reported cases of serious injury or death due to trying to vertically pull someone out of the grain without first clearing grain away from around the body before the extrication attempt (Issa and Field, 2017, Moore and Jones, 2017, Roberts et al., 2015, Schwab, 2017).

Personal safety is a pinnacle of human thought, and when someone is put in a situation by a person with higher authority to complete a task that they themselves deem unsafe, people have a tendency to reject these directives in lieu of self-preservation. When an employee feels that their employer prioritizes their safety and health, quality of work increases (Das et al., 2007). This idea is directly applicable to this project. By providing safety measures and improvements that make the tasks safer to complete, farmers will be able to do their jobs with more confidence and security.

Most of the ~750,000 steel grain bins in the United States are found at OSHA exempt facilities. As per OSHA 29 CFR 1910.272, grain bins are required to have anchor points onto which a lifeline is to be connected for grain bin entrants so that it is not possible for the entrant to sink further than waist deep. The problem is that without the use of an overhead pulley, it is very difficult to satisfy this requirement. One difficulty with ensuring that all bins, including preexisting bins, have anchor points is that it is unknown which preexisting bins if any will accept a lifeline retrofit. Many of these older bins, while designed for snow loads, were not specifically designed for the loadings inherent to a grain bin entrapment (Bauer, 2014).

2.4 Grain Bin Design

Grain storage structures have been around since the late 1800s, beginning as upright wooden structures used to store grain, but it wasn't until the early 1920s that they began to resemble the current default configuration of an upright cylindrical structure. Much of grain bin design throughout the years has been a product of trial and error (Halmos and Koen, 1982). The bins were designed and constructed based on previous failures. When a component of a grain bin failed, it was replaced with a heavier gauge component. This was non-standardized and produced variations from manufacturer to manufacturer as each company found a design that worked for them.

Today's grain bins are large cylindrical storage tanks made of corrugated, galvanized steel sheets that are formed into rings, stacked on top of each other with some overlap, and then bolted together. This allows for grain to be held inside, taking advantage of steel's high tensile strength to contain the load. At the bottom of the bin at ground level, the corrugated steel sheets are the thickest. This is because they have to contain higher outward pressures from the column of grain inside the bin, whereas the higher sections of the bin can utilize thinner sheets. These sheets can range in thickness from 13 gauge to 20 gauge for a 30-foot diameter, 6 sheet tall bin. Despite being thin, these bins are able to hold the pressures of grain pushing outward. There have been studies that examine the friction forces from different grains on the sidewalls and the forces required to remove a person from grain (Issa and Field, 2018, Moore and Jones, 2017, Roberts et al., 2015, Schwab, 2017), but it does not appear that any research has been done on roof loadings or how grain bins react to different external point loads. Structural failure of a grain bin most often manifests as buckling of the sidewall.

2.5 Review Conclusion

Recently manufactured grain bins have engineered safe entry anchor points, but it is unclear whether their load rating is consistent among manufacturers and whether the load rating complies with the newest standards. Performing an engineering assessment of these on-farm bins will help determine retrofit options for safe anchor points. Existing on-farm bins may withstand the forces imparted on them during an impact event from someone falling, or from an event where someone is being drawn down by flowing grain. The development of an engineering modeling tool will help ensure anchor point design and modifications that will not present additional safety hazards. This will give design engineers an innovative tool that will aid in giving many farms across the U.S. the option of safer bin entry. Retrofitting a bin with anchor points can be a very cost-effective option in the range of a few hundred dollars, compared to purchasing a new bin with the technology already built into them.

3.0 Goal, Objectives, and Hypotheses

3.1 Goal

The goal of this research project is to develop an engineering modeling tool that can be used to assess the safety of the retrofit lifeline anchor points for on-farm grain bins. In order to create this tool, a working, parametrically driven 3D model of a grain bin will be created so that shock loads seen in a short fall or an entrapment incident can be simulated with this model. This model will simulate the structural performance and response of grain bins loaded from a lifeline anchor point system. Once this model is created, physical testing will commence on test grain bins in order to verify simulated results with the model. The intent is not to test each individual bin, but to be able use the model to ensure the bins' structural integrity, saving time and money for the end user interested in these systems.

3.2 Objectives

Three objectives were selected for this study:

1) First off, a working parametrically driven 3D model of a grain bin needs to be created. This model will take into account diameter, height, roof angle, roof collar thickness, and bin sheet thickness. These parameters are the most frequently varied parameters in grain bin construction.

2) Once this model is created, test simulations will be conducted while changing the simulated values of the test parameters to ensure the model is stable enough to handle variation.

3) Finally, physical testing will occur in order to verify the output of the model.

Once these objectives are met and it is confirmed that the grain bin model is a reliable indicator of how a real grain bin will react to different loadings, this model can be used to simulate end users’ bins and test them to determine whether or not a lifeline anchor retrofit kit will be acceptable for safe use in that grain bin.

3.3 Hypotheses

It is hypothesized that the model created for this study will be able to yield simulated strain data within 53.7% of that which is recorded during physical testing. This error value is found and justified below in section 4.3 (Determination of Testing Parameters). Many preexisting bins were not designed to hold live loads. They are however designed to hold snow and wind loads, so because of this, it is hypothesized that the loadings seen during an entrapment incident will fall within the allowable load range that the dead load accounts for, assuming that the bin is not loaded by snow and/or wind during the rescue operation.

The hypotheses predicted for this thesis are as follows:

H_0: The percent error seen when comparing the 3D simulation and the experimental data will be less than or equal to 53.7% ($\%\ \text{Error} \leq 53.7\%$)

H_1: The percent error seen when comparing the 3D simulation and the experimental data will be greater than 53.7% ($\%\ \text{Error} > 53.7\%$)

4.0 Methodology

4.1 Methodology Introduction

Due to the high cost and large time period needed to perform strain analysis on every grain bin in order to determine whether it is able to handle the loads imparted during an entrapment incident, a 3D computer model will be developed to test preexisting grain bin designs. This will allow for testing to be done in both a more time-efficient and cost-efficient manner. Once a grain bin is designed within the 3D model, it should be able to accurately display how the grain bin will react to different loadings. In order to be confident in the ability of the 3D model to provide accurate simulated results, a physical test involving grain bins was necessary. By validating the 3D model with real world data, it allows for credibility and confidence in the model to determine whether or not potentially lifesaving equipment can be installed into grain bins.

4.2 Overall Project Process

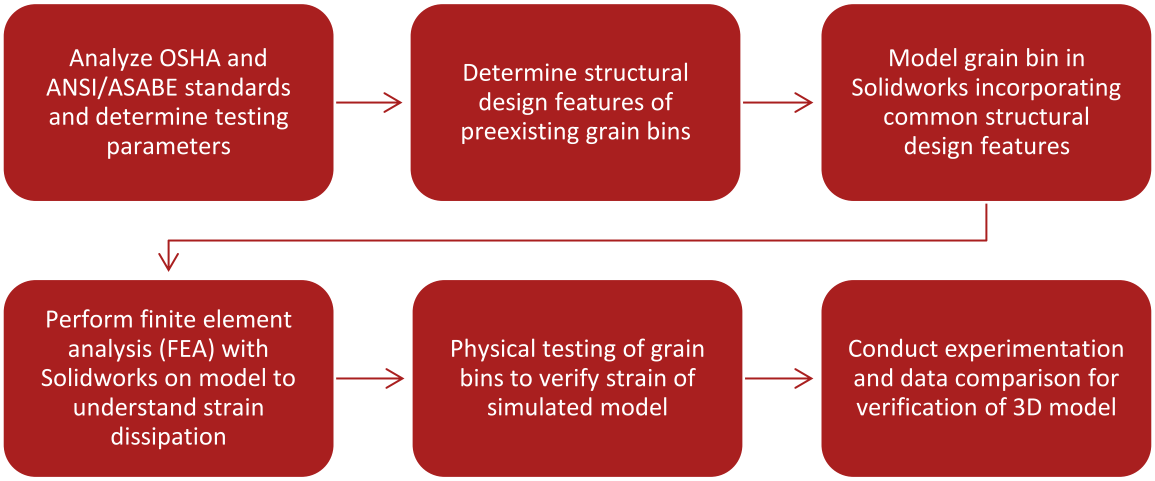


Figure 1: Methodology Flowchart

4.3 Determination of Testing Parameters

In order to determine testing parameters, the current recognized standards and regulations needed to be analyzed. OSHA 29 CFR 1910.272 and ANSI/ASABE S624 both contain criteria that need to be met in order for grain bins and grain bin entry to be compliant. OSHA standards are mandated for commercial and industrial use, but there is an on-farm exemption clause. Although this project focuses on systems that are exempt from OSHA inspection, the standard will still be used as a normative reference. The same is true for ANSI/ASABE S624, which is an industry standard, but is not required to be followed. Regarding initial safe entry, before entry takes place, OSHA mandates an entry permit, Lock Out Tag Out procedures, and atmospheric testing. OSHA also requires a safe way to tie off workers, either with a boatswain's chair or a lifeline and full body harness. ANSI/ASABE S624 was passed in August 2018 and it recommends that all grain bins produced thereafter should be equipped with two lifeline safety anchor attachment points. One point should be attached to the top side of the wall, within arm's reach of the roof entry hatch, and the other should be attached on the roof fill collar. Standard S624 states that grain bin safe entry anchor points must have an ultimate capacity of 2000lbf(900kg). This number is

53.69% factor of safety, meaning that of the 2000lbs(900kg), 1073.8lbs(487.1kg) are included in the calculation to account for error and safety. This system allows for an outside observer/attendant to stand watch and maintain slack in the lifeline while the entrant completes their job walking inside of the bin. The safety precautions laid out by both standards were followed during the installation and data collection discussed in this section. The diagram of loadings and components can be seen below in Figure 2.

4.4 Determination of Structural Features

Most grain bins have the same basic cylindrical shape and are made from thin sheets of galvanized corrugated steel sheeting which are bolted together to form rings. These rings are stacked and bolted together in order to enclose the volume that contains the grain. The roof is made of galvanized steel sheets which are constructed in a way that when stacked, they make a round roof. The roof has a hole at the peak for loading the grain bin with grain, and an entry hatch at the bottom of the roof at a minimum, as well as an entry door at the ground level of the bin, and two ladders (one ladder on the inside of the bin and one ladder on the outside of the bin. Occasionally, depending on the size of the bins, the exterior ladder may be replaced with a staircase that winds around the diameter of the bin, but for this project, only bins with ladders were tested. Despite these similarities, there are many slight differences between bins in terms of how they are constructed. Bin sheet thickness varies as bin height increases. This is because the outward pressures from the grain are a function of height. At the bottom of the bin the bin sheet thickness is at its maximum to contain the grain. As the pressure lessens higher up the bin, sheet thickness can decrease. These bin sheet thicknesses are not standardized and therefore vary between manufacturers.

4.5 3D Modeling and FE Analysis of Grain Bin

A 3D grain bin model was created in Solidworks.

The model geometry was based on the dimensions and design features of two grain bins. These grain bins are owned by Penn State University’s Farm Operations and Services, and measurements of all structural components were taken. These measurements were compared to each other and a base design was determined. This base design was subjected to structural analysis. Because the purpose of this model is to be used as a tool to model multiple different bins and provide data for how feasible a grain bin safety anchor point retrofit would be, each individual bin was not modeled. This allowed for some assumptions to be made about these bins in the hopes that the error incurred from the assumptions would still be within the tolerances of 53.69% error as specified by the ANSI/ASABE S624 standard. There are too many factors to be considered when modeling grain bins, especially if the model is to represent multiple different kinds of bins, so the most significant factors such as the bin sheet thicknesses, roof angle, roof thickness, diameter, fill hole diameter, and fill hole thickness were taken into account. This is not to say that modeling is not worth while. It shows that there are many factors and when conducting a preliminary analysis such as this one, certain assumptions were made. The assumptions that follow were made in an attempt to streamline the modeling process:

- The grain bins are in excellent condition and do not have any oxidation or structural deficiencies
- The grain bin roof entry hatch is not a structurally significant piece to model because of the large amount of variation in entry hatch designs and sizes, as well as the fact that the strain data that is being focused on is localized in locations not connected to the entry hatch
- The ladders on the grain bins offer no significant structural support in terms of dissipation of strain
- Bin roof stiffening rings were not taken into account due to the complexity they would have added into the model
- There are no weather or temperature conditions being taken into account in the model
- There are no aftermarket or user manufactured changes or equipment added to the grain bins
- The grain bin 3D model is a model without seams. The thicknesses are applied to each surface after construction of the model.

These assumptions allowed for the grain bin model to remain as structurally significant as possible, while eliminating many of the manufacturer’s variations in non-significant structural components. The simplified model was able to run simulations and make changes to the model to accommodate different designs. Below are the structural parameters that were taken into account for each bin and their dimensions in Tables 1 and 2. Note the locations of the different parts of the grain bin in Figures 2 and 3.

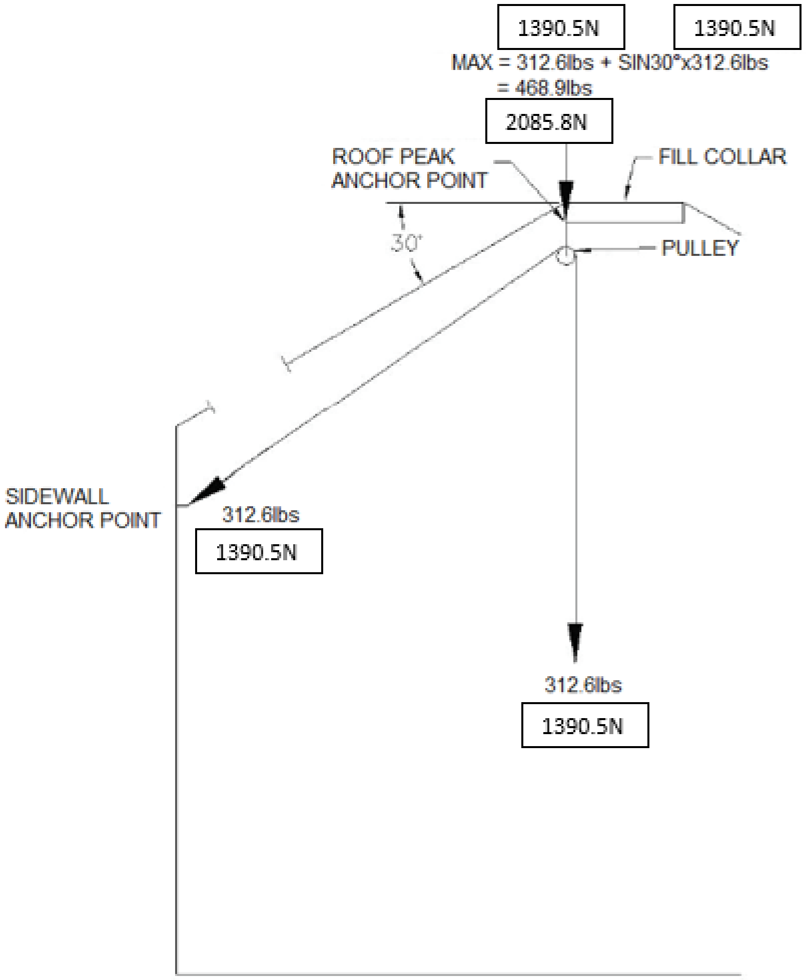


Figure 2: Diagram of Loadings from ASABE/ANSI Standard S624

Table 1: Bin 1 Specifications

Bin 1
GSI

Sheet	Gauge	Thickness (in)(mm)	Radius (ft)(m)	Roof Angle (deg)	Fill Collar Radius (in)(mm)	Fill Collar Thickness (in)(mm)	Roof Thickness (in)(m)	Fill Collar Lip Height (in)(mm)	Fill Collar Flange Length (in)(mm)
1*	13	0.093750 (2.38125)	15(4.572)	30	19.5(.495)	0.175(4.45)	0.03(.762)	1.75(44.5)	8.5(215.9)
2	13	0.093750 (2.38125)							
3	14	0.078125 (1.984375)							
4	16	0.062500 (1.5875)							
5	17	0.056250 (1.42875)							
6	18	0.050000 (1.27)							

* denotes bottom sheet

Table 2: Bin 2 Specifications

Bin 2
GSI

Sheet	Gauge	Thickness (in)(m)	Radius (ft)(m)	Roof Angle (deg)	Fill Collar Radius (in)(mm)	Fill Collar Thickness (in)(mm)	Roof Thickness (in)(mm)	Fill Collar Lip Height (in)(mm)	Fill Collar Flange Length (in)(mm)
1*	14	0.078125 (1.984375)	12(3.658)	30	15.8125(401.7)	0.15(3.81)	0.03(.762)	2(50.8)	3.75(95.25)
2	15	0.0703125 (1.78594)							
3	17	0.056250 (1.42875)							
4	18	0.050000 (1.27)							
5	20	0.037500 (0.9525)							

* denotes bottom sheet

Figure 3 shows a rendering of the 3D model of the grain bin that was created, the testing locations, and the sheet numbers.

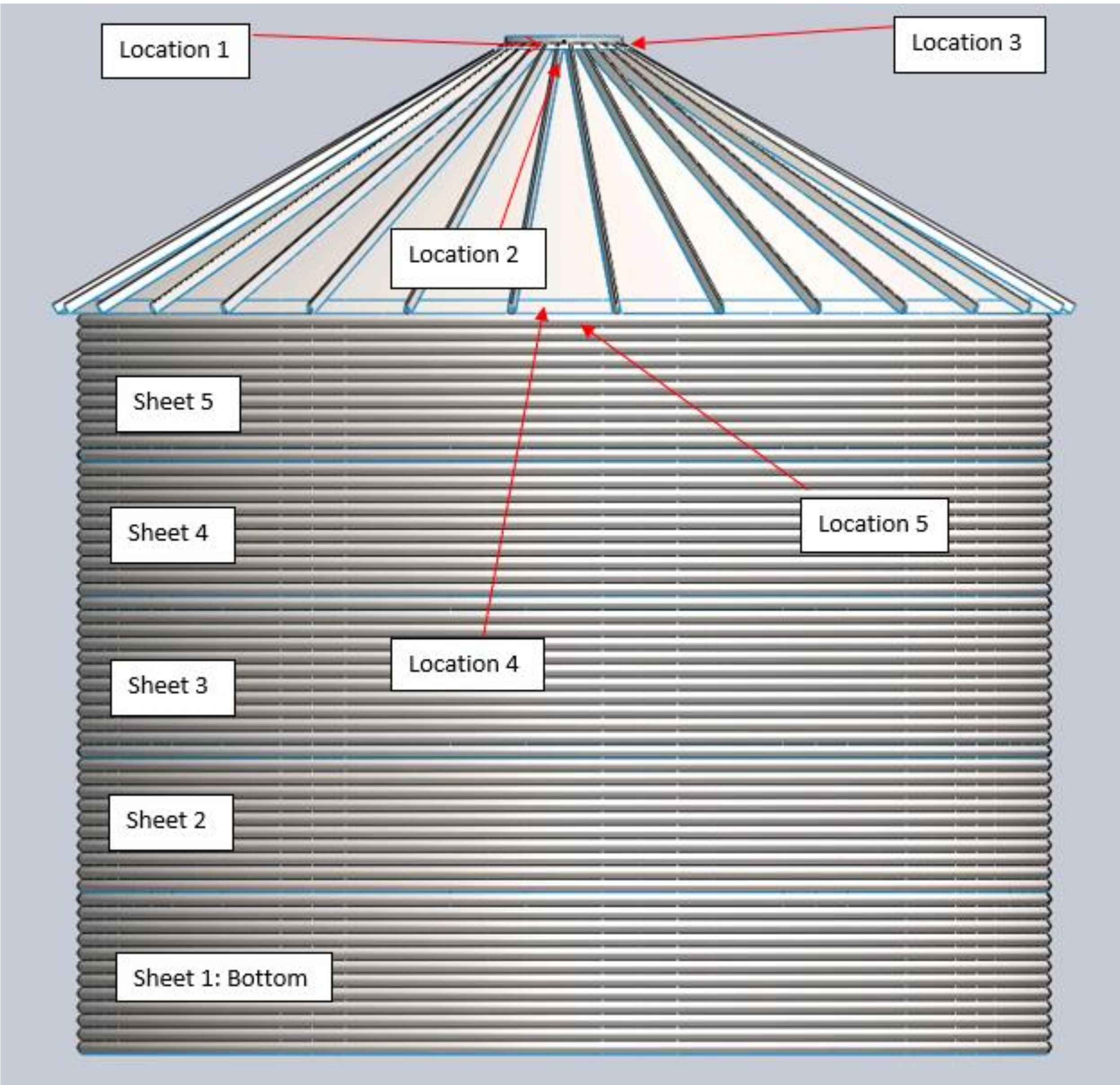


Figure 3: Map of Sheets and Testing Locations

The 3D model is a surface-based model. By creating a model with surfaces rather than solid bodies, it allowed for better interfacing between parts. This is not to say that the model does not take into account individual part thicknesses, but it does so in a different way. Because the geometries are so thin compared to the size of the bin of the grain bins in reality, issues regarding how the model solved during simulation and how the interfaces interacted between parts of the model occurred. The model began as a sketch of a single corrugation which can be seen below. This corrugation was revolved 360° to make a ring, which was then patterned 11 times upon itself to make one full bin sheet ring. Instead of making sheets and bonding them together, it was assumed that the rings were solid without seams. This was assumed due to the rings overlapping (where one ring ends and the next begins, the first corrugation of the new ring and the old ring are overlapped). Because it is known that these grain bins are structurally sound and can hold grain when filled, it was assumed that the overlap between sheets would not be a point of failure during this testing.

The roof is modeled similarly to the rings of the grain bin. First a base surface revolve was made as a solid, smooth, seamless roof, and then the ribs of the metal roof, where the sheets overlap to form each panel were added into the model. Finally, the peak collar was revolved on top to finish the bin. The bin models do not contain ladders or roof entry manholes as explained above, but they also do not have bin roof stiffening rings on the roof for the same reason. Introducing more non-standardized variables into the model reduces the time efficiency of the model and allows for greater probability of incompatibility of features, leading to failed simulations and model failure. Many different versions of this model were created in the pursuit of the final, parametrically driven grain bin 3D model.

4.6 Experiments for Model Verification

In addition to the grain bin 3D model, measurements were taken of strains on the two grain bins when subjected to a simulated entrapment incident. First, safe entry anchor points were retrofitted to the grain bins. A 10k zinc plated steel swivel anchor (Guardian Fall Protection MEGA Swivel) was installed on the peak collar on both bins and a sidewall anchor (FrenchCreek Production #1550 D-Bolt) was installed directly under the manhole entrance at the bottom of the roof on both bins. The specific locations for these installations were influenced by obstructions due to other objects that were already installed in the bins. For this project, non-destructive load testing was approved, but because there were already fixtures present in the bins (Stir-ator tracks, grain distributors, electrical motors, etc.) the number of locational possibilities for mounting was limited. The sidewall d-ring anchors were mounted to the sidewall inside of the top three full corrugations, and the peak swivel anchors were mounted inside the peak collar in line with the manhole (or as close as possible to avoid already existing machinery and wiring inside the bin). See Figures 4 and 5 for anchor point installation photos.

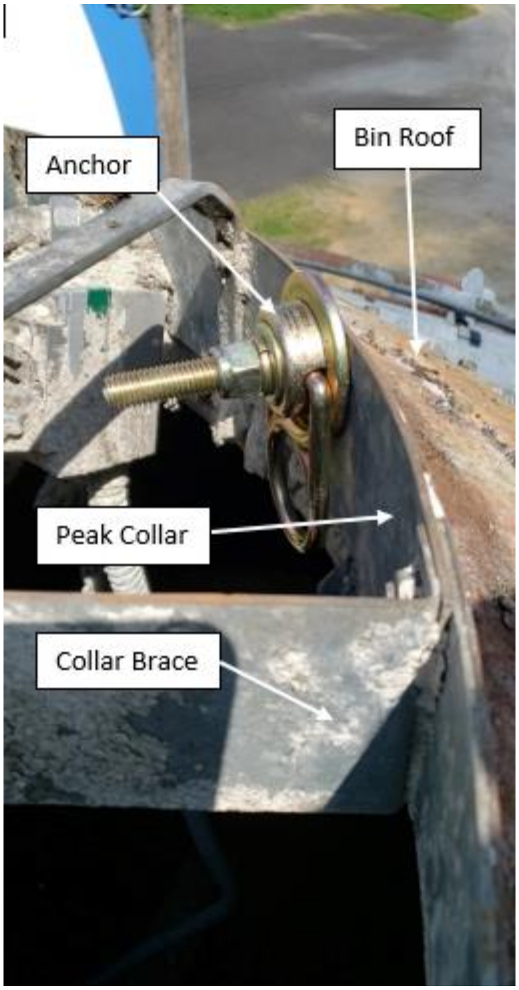


Figure 4: Peak Collar Swivel Anchor Point

Figure 5: Sidewall Anchor Point

The two physical grain bins were instrumented with strain gauges (Micro-Measurements C2A-06-250LW-350). The strain gauge specifications can be seen below in Tables 3 and 4:

Table 3: Strain Gauge Specifications

Grid resistance - Ω	350.0±0.6%	
TC of Gage Factor, %/100°C	(+1.5±0.2)	
Gage Factor @ 24°C	2.120±0.5%	
Transverse Sensitivity	(+0.5±0.2)%	
Thermal Output Coefficients for 1018 Steel @ GF of 2.00		
Order	°F	°C
0	-2.49E+02	-9.90E+01
1	5.91E+00	6.44E+00
2	-4.07E-02	-1.05E-01
3	9.15E-05	4.91E-04
4	-5.69E-08	-5.98E-07
5		

Table 4: Strain Gauge Dimensions

	Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
Inches	.250	.363	.100	.100	.440	.160
Millimeter	6.35	9.22	2.54	2.54	11.18	4.06

The 350Ω gauges were chosen due to their pre-soldered and sealed joints for uncertainty in weather conditions when data collection was going to commence, and because of the interest in maintaining signal integrity for small strain measurements. The 350Ω gauges also will aid in compensation of the long leadwires. The strain gauges are made of a C2A material. The strain gauge area is .025in^2(16.129mm^2).

The strain gauges were mounted to the bin following Micro-Measurements instructions for proper strain gauge bonding and adhesion. They were then covered with weatherproofing (Micro-Measurements M-Coat FB-2 Butyl Rubber Sealant). The strain gauges wires were routed down the side of the grain bin to the ground where the data collection equipment (Vishay Precision Group SB-10 Switch and Balance Unit and P3 Strain Indicator) was placed. This was so that there were no strains imparted by anyone sitting on the bin recording data. Because of the small loads that were being applied, the model showed that the strain was dissipated rather quickly over the sheet metal around the anchor points, within the range of a few feet. Because of this, it was not necessary to cover the grain bins in strain gauges, but to focus on a few points and determine whether or not the model could accurately portray the physical findings in these areas. The gauges were oriented perpendicular to each other as seen below:

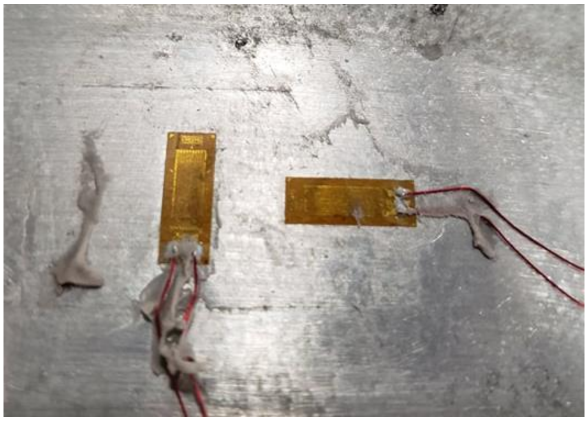


Figure 6: Perpendicular Arrangement of Strain Gauges

The orientation of the strain gauges was such that both axial and transverse strains could be recorded at each location. Since these grain bins were in use and had caps covering the fill holes, the gauges needed to be placed as proximal to the anchor point location as possible without being on the vertical ring of the collar. Because of this, the collar gauges were placed on the angled flange that parallels the roof just below the anchor attachment point. The sidewall gauges were placed proximal to the anchor point. The strain gauges were labeled and oriented such that each data collection site was consistent with one another, allowing for consistent readings across collection points and easy mounting.

The strain gauges were mounted in 5 location on the grain bin to record data from points of interest on each bin. At each of the 5 locations, two strain gauges were placed as stated above, one horizontally and one vertically. These locations were determined by looking where areas of high strain relative to the loadings imparted on the bin would be. Each location can be seen in the figures below, and both bins had strain gauges mounted in relatively the same location. Due to the mesh sizing of the simulation and the constraints inherent to these bins being in use at the time of data collection, the locations varied minorly. Although the locations may not have been exactly the same, they were still within the area of high strain and allowed for a reading of that strain to be recorded and analyzed. These locations and sheet numbers of the bin scan be seen in Figure 3 above:

Location 1 is located below and to the left of the peak anchor within 6 inches. Location 2 is directly below the peak anchor on the peak collar within 6 inches. Location 3 is located 90° counterclockwise on the top of the bin on the peak collar from the peak anchor. Location 4 is located to the left of the sidewall anchor point within 6 inches (0.15m) of the anchor. Location 5 is located below the sidewall anchor point. Locations 1, 2, 4, and 5 were chosen to capture measurements of anticipated high strain that were expected in these locations during a rescue event. Location 3 was chosen to assess how the strain gauges were reading areas of anticipated low strain.

When installing the strain gauges on the grain bins, the grain bin surface was prepared following the manufacturer's instructions (Micro-Measurements' Corp, 2021), utilizing Micro-Measurements' Silicon Carbide Paper, CSM-3 Degreaser, M-Prep Conditioner A, and M-Prep Neutralizer 5A. For mounting the gauges and adhering them to the prepared surface, Micro-Measurements' M-Bond 200 catalyst and adhesive were used following the following the manufacturer's instructions (Micro-Measurements' Corp, 2021). This standardized the gauge installation process and ensured a good bond between the strain gauges and the grain bin surfaces. After the strain gauges were bonded to the exterior of the bins they were weatherproofed. This was done by Butyl Rubber sheets (Micro-Measurements M-Coat FB-2). The butyl rubber was cut and placed over each two-gauge collection area and firmly pressed onto the area, ensuring a complete seal that isolated the strain gauges from the elements. Once the gauges were mounted, the sensor wires were color coded with different color tape, denoting the strain gauge that it was attached to for easy identification on the ground at the data collection equipment.

When connecting the strain gauges to the collection equipment, a three-wire quarter bridge circuit was used. The three-wire quarter bridge circuit consisted of a strain gauge (C2A-06-250LW-350), a resistor (Riedon 101-350RB 350Ω 1/4W 0.1% Axial), and a Vishay Precision Group SB-10 switch and balance unit. This unit is a switch box with 10 channels, each with its own potentiometer for the zeroing of strain gauges before testing commenced. Calibration was done solely with the switch and balance unit. A shunt resistor was not used. Transverse sensitivity was also not able to accounted for. The SB-10 was connected to a Vishay Precision Group P3 Strain Indicator and Recorder. This allowed for the strain readings to be easily read on the LCD display. Strain data were recorded in a notebook and later input into an Excel document for analysis.

Before the test, a rope system consisting of a knot passing pulley (Petzl Kootenay Knot Passing Pulley), two carabiners (Omega Pacific Screw Locking Carabiners), two sewn loop prusik cords, a prusik minding pulley (PL-OB15-1-Rock Exotica Omni-Block), and a 150 foot (45.72m) length of rope (RRS004-150-RNR Poseidon Series Lifeline ½”) was installed inside each bin. This rope system is similar to that described by the GHSC. This is a variant of the same system that can be installed into a pre-existing grain bin for lifeline purposes. This system was left in place when zeroing the strain gauges because of the infeasibility of installing and uninstalling it each time a test was done.

Each test attached 312.6lbs(1390.5N) of weight to the lifelines system. The weights used were five International Harvester ballast weights, weighing a total of 312.6 lbs(1390.5N). These weights were measured using a scale (Salter Brecknell PS500lb ± 0.2lb). These weights were selected because they were so easily transportable and able to be carried and suspended safely from a lifeline. In addition, the testing was to be non-destructive, so it was not permitted to endanger the bins. The weight selected was enough to observe and record strain from the strain gauges. Originally three weights were chosen; 1lb(.4536kg), 10lb(4.536kg), and 100lb(45.36kg), but these weights were not significant enough to make recordable strains on the grain bin. ASABE/ANSI S624 states that the grain bins must be able to withstand 2000lbs(900kg) of weight on a lifeline, but because this was to experimentally verify the simulation model results, an arbitrary weight of 312.6lbs(1390.5N) was selected. This amount of weight in the configuration that it was in made it easy to connect and disconnect the weight from the lifeline system. The weights were tied to the end of the rope, whereas in the model two separate loads were used to simulate the tension from the rope, one at each anchor point. The loadings can be seen above in Figure 2. Three identical tests were performed on each grain bin with each test taking approximately 60 minutes. The weather for each day of data collection can be seen below in Table 3:

Table 5: Weather Data for Test Dates

Bin 1 Test		Bin 2 Test	
Date	5/12/2020	Date	5/7/2020
Time	13:53	Time	15:53
Temperature	50°F	Temperature	59 °F
Humidity	35%	Humidity	31%
Barometer	30.11 "Hg	Barometer	29.76 "Hg
Wind	15mph WNW	Wind	16 mph W
Visibility	10 miles	Visibility	10 miles

One difference was identified during the grain bin testing. One of the bins (bin #2) was empty and it was possible to enter the bin from the bottom and connect and disconnect the weights, whereas the other bin was about two thirds of the way filled with grain. The bin with grain in it required a confined space entry permit so that the weights could be brought in through the top access hatch and attached to the lifeline. The permit was completed and approved prior to bin entry. In addition, the use of the Lock Out Tag Out process, a safety harness, and lifelines were required. All safety procedures were followed during this testing, including the use of an observer prior to and during entry for testing.

To test the hypotheses set out in this project, a one sample, one sided t-test will be conducted.

5.0 Results and Discussion

5.1 Simulated Results

The grain bins were meshed in Solidworks FEA. The mesh information can be seen in Table 6 below:

Table 6: Bin 1 and Bin 2 FEA Mesh Data

Study name	Bin 1 FEA	Bin 2 FEA
Mesh type	Shell Mesh Using Surfaces	Shell Mesh Using Surfaces
Mesher Used	Standard mesh	Standard mesh
Automatic Transition	Off	Off
Include Mesh Auto Loops	Off	Off
Jacobian check for shell	On	On
Mesh Control	Defined	Defined
Element size	23.919 in	23.919 in
Tolerance	0.3 in	0.3 in
Mesh quality	High	High
Total nodes	136323	108501
Total elements	67650	53933
Time to complete mesh(hh:mm:ss)	00:01:52	00:01:14

The mesh sizing was chosen to keep as much detail in the model to accurately display the strain at certain points, while keeping the model easily solvable. At Locations 1, 2, 3, 4, and 5, mesh controls were put in to further refine the mesh, but throughout the majority of the model, the mesh was left alone. The mesh control can be seen below in Figure 7. At both loading points, which can be seen at the top edge of the grain bin and the top end of the corrugated bin sheets.

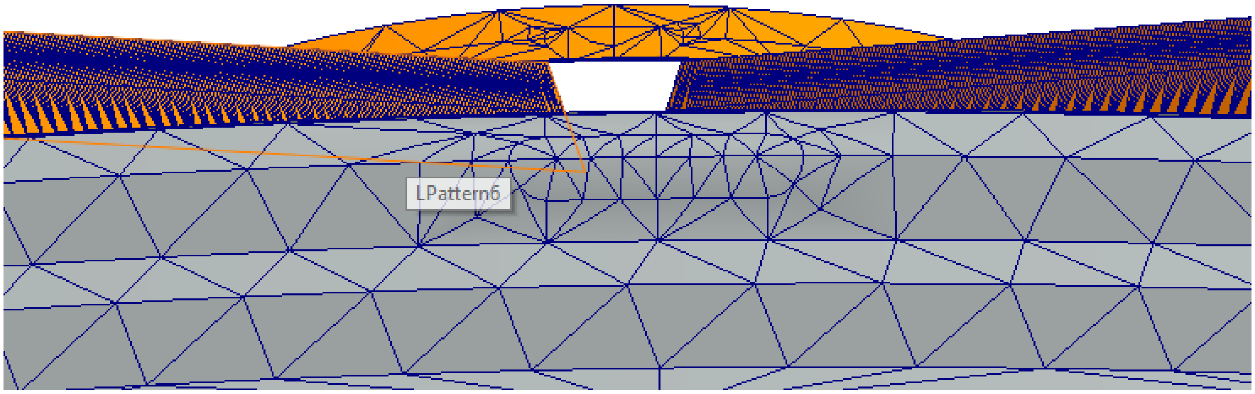
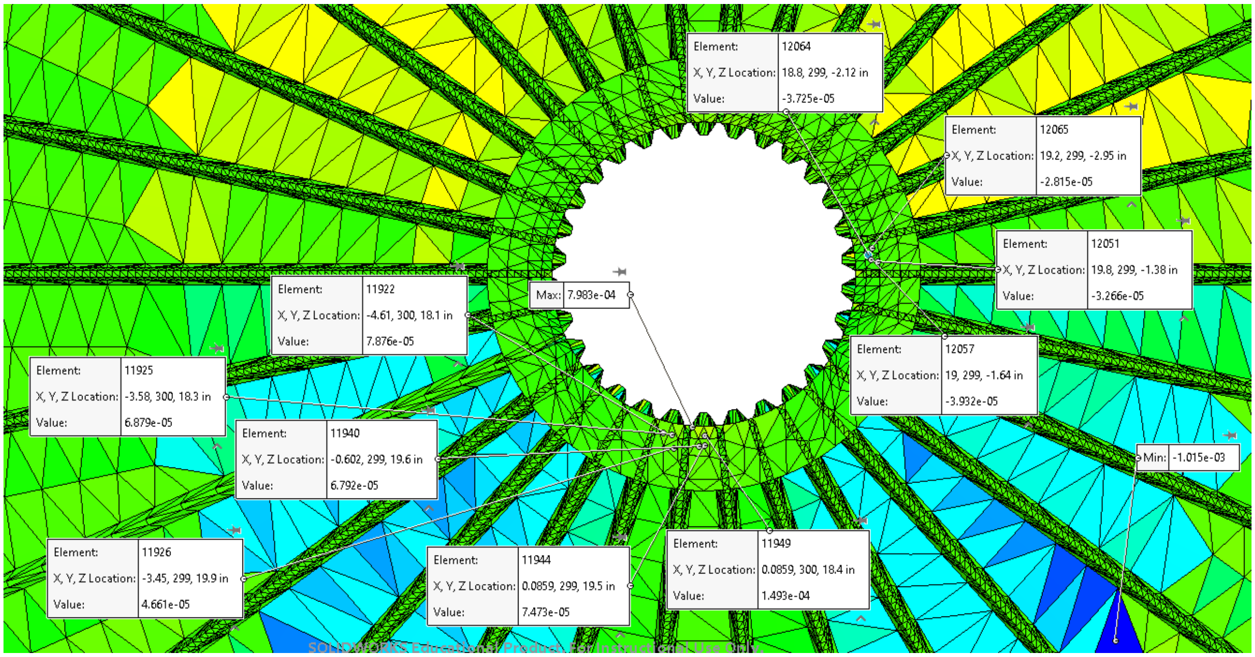


Figure 7: Visualization of Mesh Control

Solidworks FEA reports strain normal to both the X and Y direction. Below, the FEA elements used to analyze the data are be shown. The pictures used came from the Bin 2 model and can be seen below in Figures 8, 9, and 10. The locations sampled were the same for the Bin 1 model, the only difference between them is the number of the FEA elements, due to the difference in the sizes of the bins.


Element: 12064
X, Y, Z Location: 18.8, 299, -2.12 in
Value: -3.725e-05

Element: 12065
X, Y, Z Location: 19.2, 299, -2.95 in
Value: -2.815e-05

Element: 12051
X, Y, Z Location: 19.8, 299, -1.38 in
Value: -3.266e-05

Element: 11922
X, Y, Z Location: -4.61, 300, 18.1 in
Value: 7.876e-05

Max: 7.983e-04

Element: 12057
X, Y, Z Location: 19, 299, -1.64 in
Value: -3.932e-05

Element: 11925
X, Y, Z Location: -3.58, 300, 18.3 in
Value: 6.879e-05

Element: 11940
X, Y, Z Location: -0.602, 299, 19.6 in
Value: 6.792e-05

Min: -1.015e-03

Element: 11926
X, Y, Z Location: -3.45, 299, 19.9 in
Value: 4.661e-05

Element: 11944
X, Y, Z Location: 0.0859, 299, 19.5 in
Value: 7.473e-05

Element: 11949
X, Y, Z Location: 0.0859, 300, 18.4 in
Value: 1.493e-04

Figure 8: Bin 2 FEA Elements at Data Collection Points 1, 2, and 3

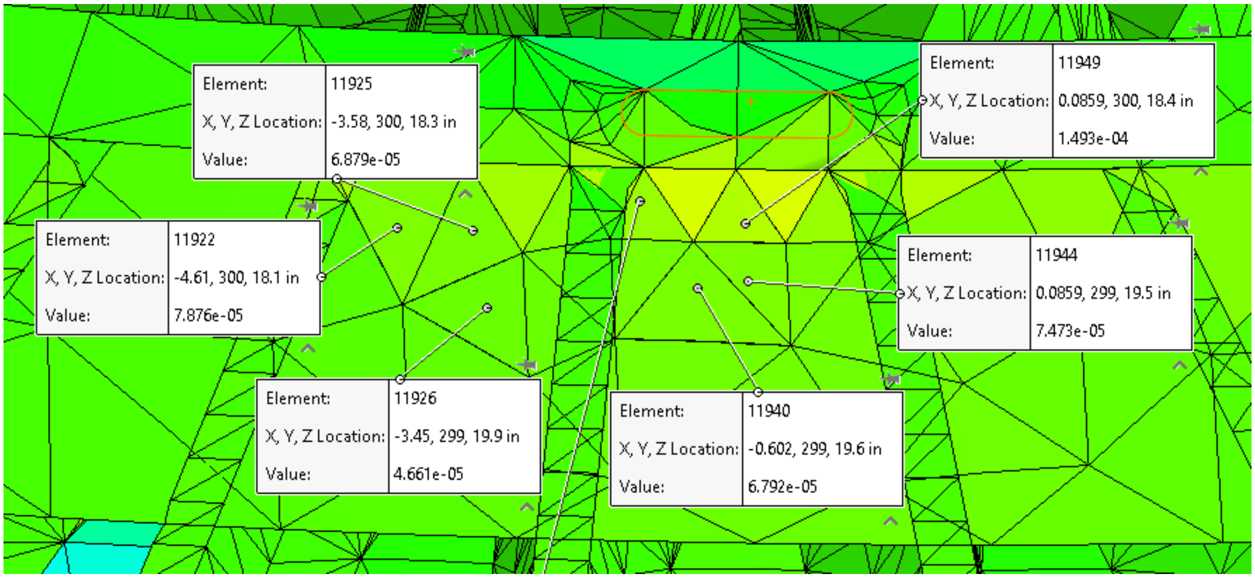


Figure 9: Bin 2 FEA Elements at Data Collection Points 1 and 2

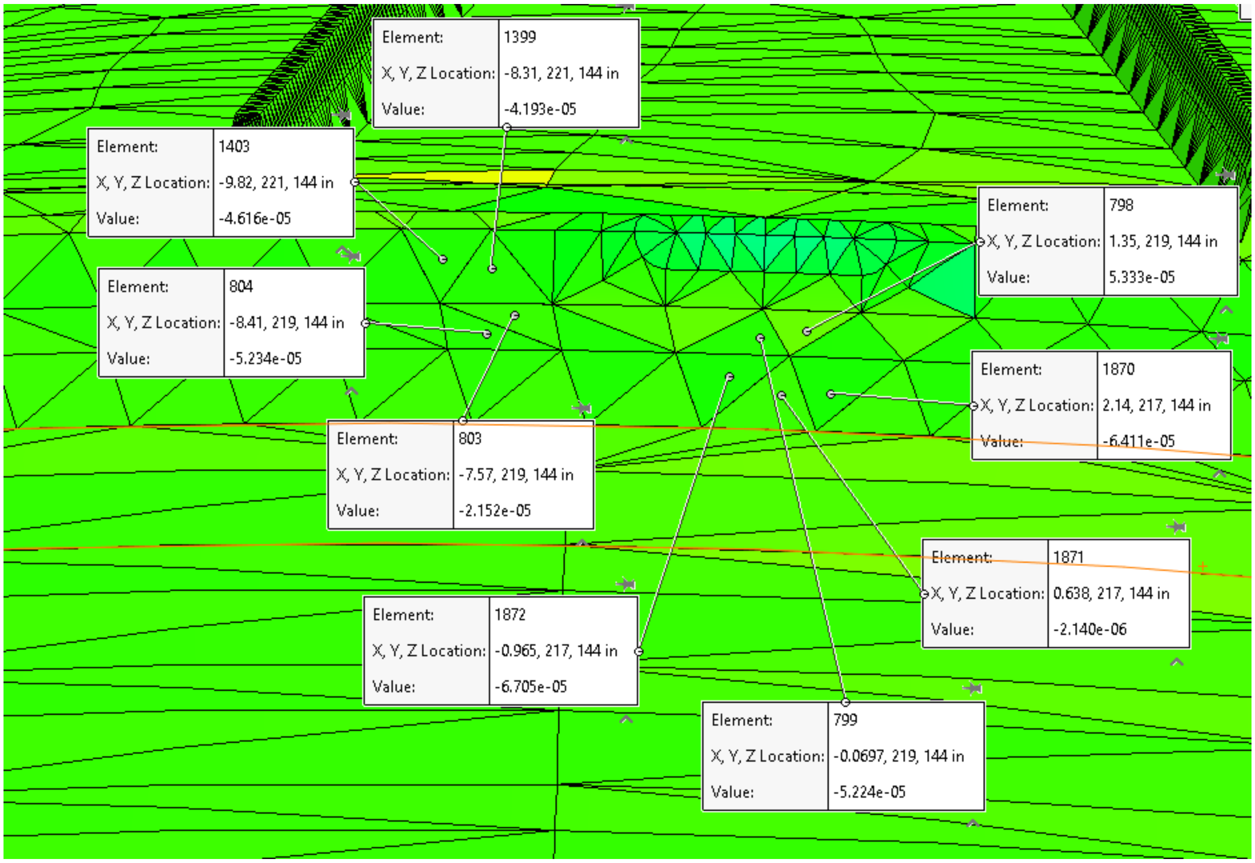


Figure 10: Bin 2 FEA Elements at Data Collection Points 4 and 5

The coordinate system and origin of the 3D model can be seen below in Figure 11. The positive X direction extends out to the right of the model and the positive Y direction is in the direction of the height of the grain bin.

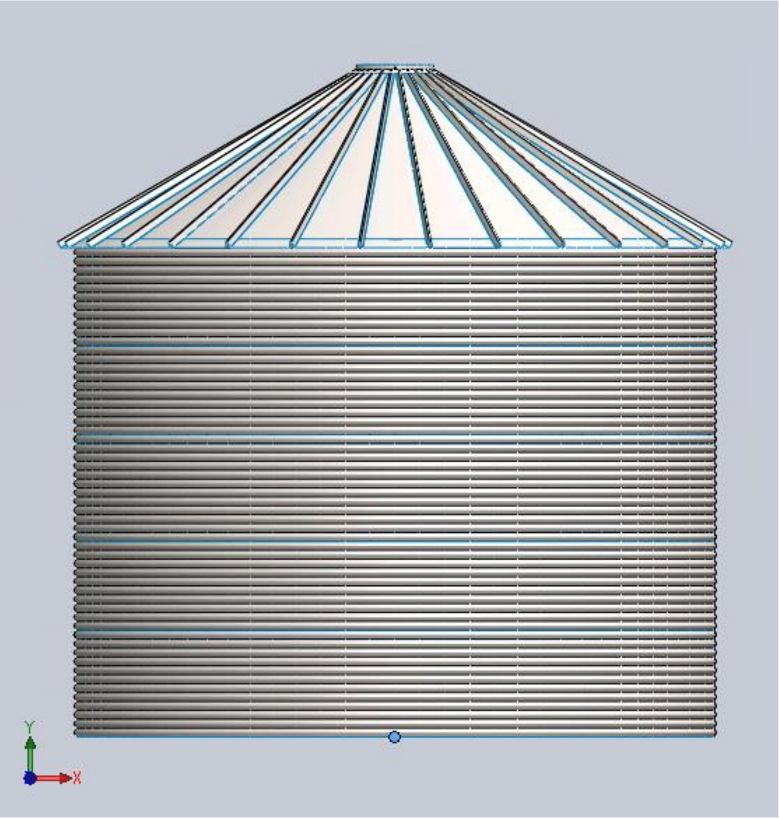


Figure 11: Bin 2 3D Model with Coordinate System and Origin

Below the raw FEA simulation data that was collected can be seen. This data includes the element number that the data was collected at, the X, Y, and Z coordinates in inches, and Epsilon X (EPSX), Epsilon Y (EPSY), and ESTRN (Equivalent strain) all in microstrain. The FEA Element Number refers to the number assigned to the individual FEA element during simulation. The strains are reported in microstrain and the elements physical location in the model are denoted by the X,Y, and Z coordinates.

Table 7: Bin 1 FEA Simulation Data

FEA Element #	EPSX (µƐ)	EPSY (µƐ)	ESTRN (µƐ)	X (in)	Y (in)	Z (in)	Corresponding Measurement Location
987	-6.02E-05	1.92E-05	6.00E-05	0.5777	218.6667	180.1724	5
988	5.34E-05	-4.43E-05	7.00E-05	-1.2864	219.3333	179.8156	5
1265	1.89E-05	-2.14E-04	1.26E-03	-7.7491	223.1037	179.7546	4
1268	1.56E-05	-3.51E-05	4.00E-05	-9.8133	222.6667	179.9075	4
1728	-3.79E-05	-1.32E-04	9.00E-05	-8.2770	220.6667	179.6288	4
1732	-5.19E-05	-7.84E-05	1.10E-04	-9.8133	221.3334	179.9075	4
1734	-5.00E-05	-1.01E-04	7.00E-05	-11.5198	220.6667	179.4498	4
2319	-7.98E-05	4.99E-05	1.20E-04	0.5777	217.3333	180.1724	5
2320	-4.39E-06	4.21E-05	4.00E-05	-1.4496	216.6667	179.8133	5
14914	5.36E-05	4.71E-05	1.00E-04	-6.3787	318.2524	21.2510	1
14916	6.06E-05	2.81E-05	9.00E-05	-4.8114	317.5469	22.9172	1
14923	2.18E-04	7.09E-05	1.70E-04	-0.6254	318.5401	21.7076	2
14926	2.27E-04	7.41E-05	1.70E-04	0.2083	318.5414	21.7068	2
14927	1.09E-04	3.17E-05	1.00E-04	1.3052	317.8396	22.8640	2
15036	-8.01E-05	-2.68E-05	6.00E-05	21.7922	318.4921	0.5763	3
15041	-7.55E-05	-2.48E-05	7.00E-05	21.3947	318.7249	0.2881	3
15042	-7.71E-05	-2.60E-05	6.00E-05	21.7961	318.4920	-0.4228	3

Table 8: Bin 2 FEA Simulation Data

FEA Element #	EPSX (μƐ)	EPSY (μƐ)	ESTRN (μƐ)	X (in)	Y (in)	Z (in)	Corresponding Measurement Location
798	5.33E-05	-1.14E-04	8.00E-05	1.3455	219.0663	143.9567	5
799	-5.22E-05	-6.84E-05	6.00E-05	-0.0697	218.7068	144.1542	5
803	-2.15E-05	-6.95E-05	7.00E-05	-7.5714	219.4618	143.5527	4
804	-5.23E-05	-3.14E-05	6.00E-05	-8.4065	218.6947	143.9146	4
1399	-4.19E-05	-3.91E-07	8.00E-05	-8.3106	220.9562	143.7342	4
1403	-4.62E-05	-2.07E-04	1.10E-04	-9.8223	221.1625	143.7498	4
1870	-6.41E-05	-2.57E-05	1.10E-04	2.1393	217.0311	143.9981	5
1871	-2.14E-06	-2.57E-05	4.00E-05	0.6383	216.9107	143.9488	5
1872	-6.71E-05	-2.55E-05	1.10E-04	-0.9651	217.3693	144.1915	5
11922	7.88E-05	4.18E-08	9.00E-05	-4.6085	299.5278	18.0661	1
11925	6.88E-05	-8.41E-08	7.00E-05	-3.5840	299.5278	18.3009	1
11926	4.66E-05	-1.61E-07	3.00E-05	-3.4464	298.6562	19.8590	1
11940	6.79E-05	1.44E-06	4.00E-05	-0.6022	298.9467	19.6397	2
11944	7.47E-05	1.19E-06	6.00E-05	0.0859	299.0232	19.5234	2
11948	2.08E-04	1.60E-06	1.50E-04	-0.6942	299.9969	17.8229	2
11949	1.49E-04	2.38E-06	1.20E-04	0.0859	299.6807	18.3846	2
12051	-3.27E-05	2.14E-06	3.00E-05	19.7638	298.8566	-1.3752	3
12057	-3.93E-05	1.72E-06	3.00E-05	19.0498	299.2550	-1.6429	3
12064	-3.73E-05	1.69E-06	3.00E-05	18.7524	299.3998	-2.1189	3
12065	-2.82E-05	1.70E-06	2.00E-05	19.1688	299.0952	-2.9518	3

Between the two different bins, because they are different sizes, there is a difference in the number of elements that were used to analyze data. These points were chosen to represent the area at which experimental data was collected, so even though there were different numbers of elements inspected, the collection areas were well represented.

5.2 Experimental Results

Data collection was conducted using the aforementioned methods and recorded by hand into a notebook. That data was then transferred into Microsoft Excel for processing. The three individual test results for each bin were averaged together. The experimental data can be seen below in Tables 8 and 9. To visualize the physical locations for 1_y, 1_x, 2_x, etc., see Figure 3 above.

Table 9: Bin 1 Average Strain

Bin 1	Average				
	Strain0	Strain1	Diff	Min	Max
L	ε	ε	Δε	ε	ε
1_y	-2.00E-06	-8.43E-05	-8.23E-05	-8.50E-05	-7.90E-05
1_x	0.00E+00	-2.10E-05	-2.10E-05	-2.40E-05	-1.80E-05
2_y	0.00E+00	-1.67E-05	-1.67E-05	-1.80E-05	-1.40E-05
2_x	-2.00E-06	1.35E-04	1.37E-04	1.27E-04	1.49E-04
3_y	-2.00E-06	-3.67E-05	-3.47E-05	-3.50E-05	-3.40E-05
3_x	-1.67E-06	-1.47E-05	-1.30E-05	-2.10E-05	-4.00E-06
4_y	-3.33E-07	6.33E-06	6.67E-06	5.00E-06	8.00E-06
4_x	2.33E-06	1.06E-04	1.04E-04	9.90E-05	1.10E-04
5_y	-4.33E-06	1.02E-04	1.07E-04	1.00E-04	1.13E-04
5_x	-3.33E-07	1.73E-05	1.77E-05	1.10E-05	2.50E-05

Table 10: Bin 2 Experimental Strain

Bin 2	Average				
	Strain0	Strain1	Diff	Min	Max
Location	ε	ε	Δε	ε	ε
1_y	-1.00E-06	-1.47E-05	-1.37E-05	-2.00E-05	-8.00E-06
1_x	2.33E-06	-1.60E-05	-1.83E-05	-2.00E-05	-1.50E-05
2_y	-6.67E-07	5.63E-05	5.70E-05	4.20E-05	7.10E-05
2_x	0.00E+00	1.03E-05	1.03E-05	6.00E-06	1.50E-05
3_y	0.00E+00	-2.37E-05	-2.37E-05	-3.30E-05	-1.40E-05
3_x	2.00E-06	-8.33E-06	-1.03E-05	-1.20E-05	-8.00E-06
4_y	6.67E-07	-5.26E-04	-5.27E-04	-5.33E-04	-5.20E-04
4_x	1.00E-06	6.50E-05	6.40E-05	5.70E-05	7.40E-05
5_y	3.33E-07	9.90E-05	9.87E-05	9.70E-05	1.01E-04
5_x	-6.67E-07	1.50E-04	1.50E-04	1.48E-04	1.53E-04

The data above in Tables 8 and 9 were the result of averaging three tests where weight was loaded onto the lifeline and then the strain measurement was recorded. The Strain0 refers to the average initial strain measurement after “zeroing” the test equipment and that is in units of microstrain. The SB-10 that was used is an old piece of equipment, which contributed some error to the data that was collected. The zero was done as best as possible. Prior to the experiment all contacts and electrical switches were cleaned. Strain1 refers to the average strain measured after the load was added and the test was underway and is also in units of microstrain. Diff refers to the difference of the Strain0 and Strain1 measurements and was used as the metric that the simulation data was analyzed against. The “Min” and the “Max” measurements were the minimum and maximum strains seen during each of the three tests.

5.3 Data Comparison

Both the 3D model and the experimental data were in units of strain, and it when conducting the comparison, it was originally hypothesized that the data, when broken into the normal X and Y components in the 3D model would match with some semblance of reasonability with the experimentally collected data. This turned out to not necessarily be the case. The data was put into Microsoft Excel and an error analysis was conducted on it. Due to there being such a small sample size of bins that were able to be studied, it was infeasible to conduct a true statistical analysis. The error analysis averaged the strains seen at each FEA simulation element and then used the following equation to report the error:

$$\frac{experimental - simulated}{experimental}\, x\ 100 = \%\ \text{error}$$

It was anticipated that the error seen between the 3D simulation and the experimental data would fall between the 53.7% error. When comparing the data however that was not the case. Below in Figures 12 and 13 a graphical representation of the error analysis can be found.

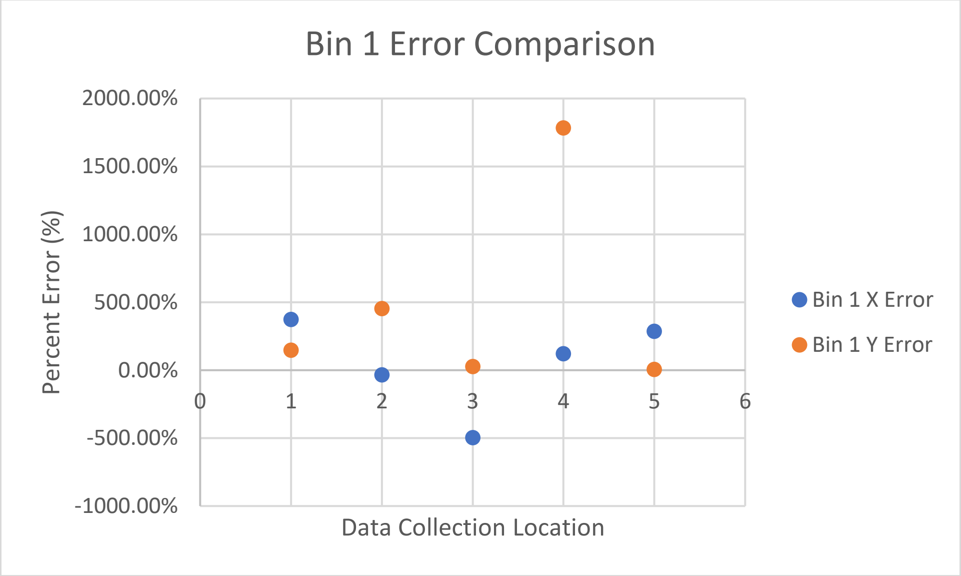


Figure 12: Bin 1 Error Comparison

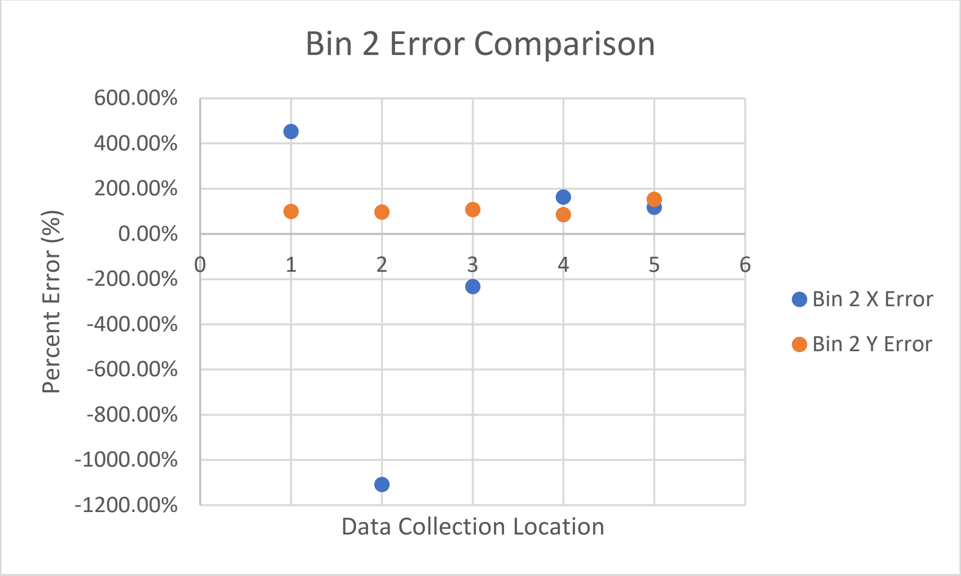


Figure 13: Bin 2 Error Comparison

A one-sample, one-sided t test was conducted to test the hypotheses formulated in this thesis. This test would determine if the percent error seen in this project was statistically significant enough to reject or retain the null hypothesis. The one-sided t-test that was conducted yielded the following results:

$t_{calculated} = 0.653$ $t_{95\%} = 1.729$

Where $t_{calculated}$ is the calculated t value and $t_{95\%}$ is the t-table value for a 95% confidence test with 19 degrees of freedom. The $t_{calculated}$ value was calculated using the 20 percent error values we found, and can be found in the appendix below.

5.4 Discussion

The goal of this research was to create an engineering tool to aid in the structural analysis of grain bins to determine whether or not they could be safely retrofitted with safe entry anchor points. To determine if this research was successful, three objectives were set out to be accomplished: the creation of a parametrically driven 3D model capable of being changed to represent different size and shape grain bins, the testing of that 3D model to ensure that the model is stable enough to handle changing the size and shape of it, and then finally to verify the 3D modeling simulation results with physical experimentation.

To test if this goal and the objectives were achieved, two hypotheses were posed for this project. The null hypothesis stated that the percent error shown between the 3D simulated results and the experimental results would be less than or equal to 53.7%. The alternate hypothesis stated that the percent error would be greater than 53.7%.

The first two objectives were accomplished in this research. A 3D model was created that could be parametrically driven and represent a wide variety of grain bins that responded well to changing parameters. This is a great step forward for grain bin safety in and of itself, because up to this point, there have been no grain bin 3D simulation models available to be found online or for those not employed by grain bin manufacturers. Creating the model from scratch was incredibly difficult. Solidworks is a great tool that can be used to model and simulate with ease, but when it came to modeling a thin-walled steel grain bin structure, there were a few different methods that could be used. This research project went with the creation of surface revolutions which were then assigned thicknesses, as opposed to making extrusions with very small thicknesses. Even though there was an incredible amount of troubleshooting during the initial creation of this model, it was able to be successfully created with great responsiveness to the changes in parameters, as well as a great simulation of strain when it is subjected to loadings. With this step, the door has been opened for continuing clarification and research into grain bin safety regarding structural analysis and modeling.

The third objective in this research, the verification of the 3D model using physical experimentation did not give the results that were anticipated. In order to verify the model, the strains observed needed to fall within the 53.7% percent error of the simulated value, and that was not the case at the time of the completion of this thesis. When conducting the experimentation portion of this research, it was known that there is no guarantee that the data will be perfect when conducting field research. It was learned that in a controlled testing environment more assumptions can be made because the test environment can be exactly as simulated, but in the field it becomes increasingly more difficult to manage. From shifting wind conditions to varying temperatures to the constant loading and unloading of the bins being tested, there were many variables that could not be accurately modeled in the simulation. For example, when the strain gauges were placed and affixed to the bin, each bin produced a signal on the SB-10 switch and balance unit, which led to the assumption that each gauge was properly mounted and adhered. If a strain gauge did not fully adhere or stick to the bin, it was not possible to test due to the time constraints put on this research by the COVID-19 pandemic, the Pennsylvania lockdown restrictions, and the stress that came along with them. With more time, more data could have been collected, and any inconsistencies found between the simulation data and the physical verification data could have been addressed. Unfortunately, that was not the case.

With the first two objectives were completed, it is important to take a look at why the third objective will take more time and experimentation. Using what we have learned throughout the course of this research to keep moving the needle in the positive direction, we must ascertain the causes of error and mitigate them. That way when this research is continued and finished, further researchers will be that much further ahead from where this research concluded.

Taking a look at Figures 12 and 13, an inconsistent and erratic distribution of error can be seen. In both the X and the Y directions, the percent error found between the experimental data and the simulated data ranged from -1108.59% error to 1782.04% error. The model was supposed to be used as a tool to be able to represent a large number of grain bins in different configurations and report strain data within the acceptable amount of error, but at this time that was not the case.

After testing the hypotheses in this study, the H_0 was retained. The $t_{calculated}$ value was less than the $t_{95\%}$ value which means that, statistically speaking, the average error that was found between the 20 percent errors found (129.66%) was not significantly that much different than the acceptable amount of error (53.7%) for this project. Although we are not able to reject the null hypothesis at this time, there is still more work to be done. Because the error values are so high both positively and negatively, the average value became non-statistically significant. With more data to be collected, it will allow for further examination of this hypothesis. Although the null hypothesis was able to be retained, it is necessary to look into why the error values were so high.

Many assumptions were made during the creation of the model which led to some of the error seen between the 3D model and the physical tests done on the bin. One assumption was that the weather and wind would be negligible. Because of the weather and the temperature, the bonding from the strain gauges to the grain bin may have been compromised and allowed for much of this error. Another source of error was the assumptions made in the 3D model of the bins. The roofs were simplified and did not consider many of the aftermarket features that the grain bins tested on had such as internal StirAtors or distributors, nor did it take into account the roof stiffening ring that the bins had. These assumptions were made in order to allow the model to be representative of multiple different grain bins from multiple different manufacturers, but as of now the model is unable to accurately represent one grain bin let alone many.

This study had a lot of lessons to learn from it. This is the first time that this type of study has been conducted for the purpose of learning more about the structural integrity of grain bins in regards to retrofitting non-standard, load bearing equipment onto them. As of now there is no publicly available research to support the above hypothesis, and considerable amounts of work was conducted to try to change that.

During the course of this research, it was found that it is possible to model a grain bin to a great deal of detail. Solidworks was able to capture the shape and function of the bins and emulate the strain response to a load imparted upon it. Solidworks was chosen because it was a program well known to the graduate researcher in charge of modeling this project, and because of the ease of use during simulation. There are many simulation options in Solidworks that could have helped refine the simulation such as adding in temperature constraints, modeling wind loads, and structural deformities and rust, but due to the inability to record that type of data accurately to inject into the model, it was not focused on. The assumption was made that even though it was known that these would be sources of error, they would be acceptable and still allow the model to fall within the acceptable 53.7% of error. Had this research been conducted in a controlled environment, that very well have been the case, with more time to conduct multiple experiments and obtain greater amounts of data. As of now, that research is continuing past the time of writing this thesis.

Because of the time constraints put onto this research by the COVID 19 pandemic, further data was impossible to collect. If it were, changes would have been made to the 3D model, as well as the experimental equipment used. When the experimentation was conducted, due to budget constraints and the fact that this was a proof of concept study, archaic equipment was used and that potentially contributed to the extreme amount of error found.

Loading conditions of the grain bins were not considered for this research. The bins that were available to be tested on for this research were currently in use and were unable to be reserved and emptied for the duration of this project. This resulted in different amounts of grain being in each bin throughout the tests. One of the bins was empty through the duration of the project, but that was out of good fortune. The other bin was over half full at any given time and during the two different data collection days, grain had been drawn down from the bins in between. This lack of control over the test subjects is something that should be noted and fixed during continued research by others.

Continuing research is necessary to determine whether this research can be considered a valid tool for determining the structural integrity of grain bins. This continued research includes further experimental testing on grain bins to gather more data and be able to conduct more in-depth analyses of the strains seen in a grain bin. Also, instead of focusing solely on the strain seen in bins, displacement measurements will also be taken. If continuing research is to be conducted using strain measuring methods, the use of shunt resistors for calibration and transverse sensitivity correction should be considered.

It was discovered that in trying to match the strains from the experimental data to the simulated data, there were some obstacles that hindered the analysis that require further troubleshooting. When comparing the simulated and experimental strains, it was assumed that the X and Y directional measurements would directly correspond to each other, but upon further inspection due to the strain gauges not being infinitely small, they collected the strain over an area that was not entirely co-planar with the X and Y directions. This led to difficulties in comparing the data and led to error seen in the comparison.

6.0 Conclusions

In this research, three goals were set out to objectively evaluate the success of this project. These three goals were accomplished and the null hypothesis was retained. The average strain dataThe ability to 3D model a grain bin for use to evaluate retrofit capabilities of grain bins still requires continuing research. This research has been a steppingstone into furthering the innovations of grain bin safety. Starting with the initial hypothesis that the 3D model of the grain bin would satisfy the need for a robust model that could aid in the analysis of many different bins from many different manufacturers, it was found that when too many assumptions are made, the model does not have the required detail to accurately represent real life. It was learned in this research project that even though most grain bins have the same basic shape and structural design, they are all far different. By trying to make a one size fits most 3D model, the ability to concretely model the forces on a particular bin was made impossible. By not having a test bin that was constructed for the sole purpose of completing this research, collecting data and minimizing all sources of error became very difficult. If further research is conducted on this topic, it would be recommended to not use a bin that is currently in use for farm related duties, but to construct a bin in which researchers may manage and negate sources of error themselves.

Among further research methods being discussed, making a change from strain-based measurements to deflection-based measurements may aid in simplifying analysis. Due to the nature of the corrugations of grain bins and the size of the strain gauges that were used, it was not possible to mount the strain gauges perfectly on an XY plane. By switching to a deflection-based measurement, the hope is that by being able to match deflection results between experimental and simulated data it will be easier and more expeditious to provide recommendations for grain bin retrofits.

An incredible amount of time and energy went into the careful consideration of how to conduct grain bin retrofits safely and cost effectively. By taking the first steps into this research topic, it opens the door for others to continue the discussion of grain bin safety as it relates to engineering interventions. Allowing for these research findings to be disseminated throughout the agricultural and engineering communities will hopefully continue moving the needle towards reducing the amount of grain bin engulfment fatalities both nationwide and around the world.

7.0 Appendix

Below are the two full data sets collected with the percent errors from comparison as discussed above.

Bin 1x

Location 1	Sim	Exp	Location2	Sim	Exp	Location 3	Sim	Exp	Location 4	Sim	Exp	Location 5	Sim	Exp
14914	5.385E-05	-2.10E-05	14923	2.181E-04	1.37E-04	15036	-8.010E-05	-1.30E-05	1265	1.892E-05	1.04E-04	987	-6.02E-05	1.77E-05
14916	6.058E-05	-2.10E-05	14926	2.266E-04	1.37E-04	15041	-7.553E-05	-1.30E-05	1268	1.556E-05	1.04E-04	988	5.34E-05	1.77E-05
			14927	1.088E-04	1.37E-04	15042	-7.709E-05	-1.30E-05	1728	-3.790E-05	1.04E-04	2319	-7.98E-05	1.77E-05
									1732	-5.186E-05	1.04E-04	2320	-4.39E-05	1.77E-05
									1734	-4.995E-05	1.04E-04			
avg	5.722E-05			1.845E-04			-7.757E-05			-2.105E-05			-3.263E-05	
error		372.45%			-34.34%			-496.72%			120.24%			284.71%

Bin 1y

Location 1	Sim	Exp	Location2	Sim	Exp	Location 3	Sim	Exp	Location 4	Sim	Exp	Location 5	Sim	Exp
14914	4.71E-05	-8.23E-05	14923	7.09E-05	-1.67E-05	15036	-2.68E-05	-3.47E-05	1265	-2.14E-04	6.67E-06	987	1.92E-05	1.77E-05
14916	2.81E-05	-8.23E-05	14926	7.41E-05	-1.67E-05	15041	-2.48E-05	-3.47E-05	1268	-3.51E-05	6.67E-06	988	-4.43E-05	1.77E-05
			14927	3.17E-05	-1.67E-05	15042	-2.60E-05	-3.47E-05	1728	-1.32E-04	6.67E-06	2319	4.99E-05	1.77E-05
									1732	-7.84E-05	6.67E-06	2320	4.21E-05	1.77E-05
									1734	-1.01E-04	6.67E-06			
avg	3.758E-05			5.888E-05			-2.585E-05			-1.121E-04			1.670E-05	
error		145.64%			453.26%			25.42%			1782.04%			5.50%

Bin 2x

Location 1	Sim	Exp	Location2	Sim	Exp	Location 3	Sim	Exp	Location 4	Sim	Exp	Location 5	Sim	Exp
11922	7.88E-05	-1.83E-05	11940	6.79E-05	1.03E-05	12051	-3.27E-05	-1.03E-05	803	-2.15E-05	6.40E-05	798	5.33E-05	1.50E-04
11925	6.88E-05	-1.83E-05	11944	7.47E-05	1.03E-05	12057	-3.93E-05	-1.03E-05	804	-5.23E-05	6.40E-05	799	-5.22E-05	1.50E-04
11926	4.66E-05	-1.83E-05	11948	2.08E-04	1.03E-05	12064	-3.73E-05	-1.03E-05	1399	-4.19E-05	6.40E-05	1870	-6.41E-05	1.50E-04
			11949	1.49E-04	1.03E-05	12065	-2.82E-05	-1.03E-05	1403	-4.62E-05	6.40E-05	1871	-2.14E-06	1.50E-04
												1872	-6.71E-05	1.50E-04
avg	6.472E-05			1.249E-04			-3.435E-05			-4.049E-05			-2.644E-05	
error		453.02%			-1108.59%			-232.37%			163.26%			117.59%

Bin 2y

Location 1	Sim	Exp	Location2	Sim	Exp	Location 3	Sim	Exp	Location 4	Sim	Exp	Location 5	Sim	Exp
11922	4.18E-08	-1.37E-05	11940	1.44E-06	5.70E-05	12051	2.14E-06	-2.37E-05	803	-6.95E-05	-5.27E-04	798	-1.14E-04	9.87E-05
11925	-8.41E-08	-1.37E-05	11944	1.19E-06	5.70E-05	12057	1.72E-06	-2.37E-05	804	-3.14E-05	-5.27E-04	799	-6.84E-05	9.87E-05
11926	-1.61E-07	-1.37E-05	11948	1.60E-06	5.70E-05	12064	1.69E-06	-2.37E-05	1399	-3.91E-07	-5.27E-04	1870	-2.57E-05	9.87E-05
			11949	2.38E-06	5.70E-05	12065	1.70E-06	-2.37E-05	1403	-2.07E-04	-5.27E-04	1871	-2.57E-05	9.87E-05
												1872	-2.55E-05	9.87E-05
avg	-6.783E-08			1.652E-06			1.812E-06			-7.715E-05			-5.178E-05	
error		99.50%			97.10%			107.66%			85.35%			152.48%

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