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Modeling a Grain Bin for Safe Entry Anchor Point Retrofit

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ABSTRACT. *American Society of Agricultural Engineer standard ANSI/ASABE S624 recommends all new grain bins produced after 2018 to have anchor points capable of handling a 2000 lb. loading for attachment of bin entry lifeline systems. However, many preexisting grain bins do not have these anchor points. This study aims to assess the feasibility of a safe entry anchor point retrofit by using finite element analysis.*

Finite element analysis (FEA) is useful to predict if the structure will withstand when subjected to stress. In this study, we used a grain bin owned by Penn State for 3D FEA modeling in Solidworks. Vertical roof deflection of the bin was measured using a precision phase-comparison laser while applying incremental static loads to the retrofitted rescue anchor points. The FEA model results were compared to the experimental measured results.

A 3D FEA model of a grain bin was created. The measured deflections compared well to defections predicted by finite element analysis. High amount of errors was observed in deflections between the measured and FEA modeling. The errors have resulted from the assumptions made during the model creation. However, the SolidWorks Simulation model still may be used to estimate loading scenarios in a safe and nondestructive way.

Based on the research findings, the project team recommends that the suitability of any bin to safely accommodate a lifeline and anchor point system must be verified on a case-by-case basis. Evaluation by a professional structural engineer and consulting with the manufacturer is recommended. This recommendation extends to all-grain bins, including those post-2018.

Keywords. *deflection, finite element analysis (FEA), grain bin, retrofit*

INTRODUCTION

As defined by OSHA 1910.146(b) standard, grain bins are a type of confined space that requires: limited/restricted means of entry or exit, large enough volume, and be so configured that an employee can enter and complete required work, and they are not designed for continuous human occupancy (OSHA, 1993). Hazards associated with grain bins include falls, exposure to dust, dust explosions, hazardous gases, entrapments, engulfment, electrical hazards, and entanglements (Field et al., 2014; Issa et al., 2017; OSHA, 2021). OSHA's Grain Handling Facilities Standard (1910.272) and Permit-Required

Confined Spaces Standard (1910.246) contain requirements for controlling hazards associated with grain storage structures. OSHA's standards were successful in reducing the number of fatalities and injuries at non-exempt grain facilities (O'Conner et al., 2012).

Farmers enter grain bins for various reasons but mostly to dislodge the material (Aherin et al., 2014; O'Connor et al., 2012). According to the Purdue Agricultural Confined Space Incident Database (PACSID), 1,731 grain storage and handling-related incidents were reported between 1962 and 2020, resulting in an injury, fatality, or required emergency extrication by first responders (Cheng et al., 2021). In 2020, there were 15 fatalities, and 20 non-fatal grain entrapment-related injuries reported.

Grain entrapments on grain structures occur due to flowing-grain, grain avalanche, bridging, or vacuum equipment (Issa et al., 2018). OSHA Standard 29 CFR 1910.272 issues safety guidelines regarding grain bin entry for workers. This standard highlights the use of harnesses and lifelines in grain storage facilities. Employers should provide body harnesses with a lifeline for employees whenever they need to enter a grain storage structure, or whenever they need to walk in or stand on stored grain. These lifeline systems must be engineered to support the forces imparted on them during an entrapment incident. 29 CFR 1910.272 standard also emphasizes issuing permit procedures for entering bins, silos, or tanks. However, farming operations that employ 10 or fewer employees and do not maintain temporary labor camps are exempt from OSHA enforcement even though, this standard does apply to small farm operations.

ASABE standard ANSI/ASABE S624 recommends that grain bins manufactured after 2018 be built to accommodate a bin entry lifeline system. The recommended system includes two anchor attachment points one located near the roof peak and one near the roof access. Anchor attachment points must support a minimum ultimate load of 2,000 pounds (ANSI/ASABE, 2018). Newer grain bins may be 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. The efficacy of a lifeline as a safety intervention for on-farm grain bins needs to be systemically evaluated.

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.

This study evaluates the characteristics of existing on-farm grain storage structures and the feasibility of a safe entry anchor point retrofit for a grain bin. A 3D modeling solution was created in Solidworks to assist engineers in safely assessing on-farm grain bin lifeline retrofit potential.

METHODS

To determine the feasibility of retrofits for safety anchor points, a 3D computer model of a grain bin is created based on the parameter from ANSI/ASABES624 standard (Figure 1). In order to validate the model, a physical vertical roof deflection of the bin was measured.

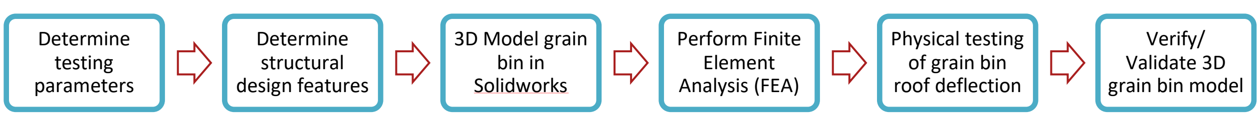


Figure 1. Flow diagram

Modeling of the Grain Bin

By using a grain bin owned by Penn State's Farm Operations and Services, a surface-based 3D grain bin model was created in Solidworks (Version 2022EDU). When modeling the grain bin, the following parameters were considered: bin sheet thicknesses, roof angle, roof thickness, diameter, fill hole diameter, and fill hole thickness with the following assumptions:

- 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
- The ladders on the grain bins offer no significant structural support in terms of dissipation of deflection

- Bin roof stiffening rings were left out due to possible additional complexity to the model
- Weather or temperature conditions were not considered 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 face instead of having hard corners.
- There is no grain in the bin.

Table 1. Bin specifications

Parameter	Values
Radius (mm)	3657.6
Roof angle (deg)	30
Fill collar radius (mm)	401.6
Fill collar thickness (mm)	3.8
Roof thickness (mm)	0.76
Fill collar lip height (mm)	50.8
Fill collar flange length (mm)	76.2

Rather than a solid body, surface modeling allowed for better interfacing between parts. The model began as a sketch of a single corrugation which can be seen below. This corrugation revolved 360° to make a ring, which was then patterned eleven 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 confidently assumed that the overlap between sheets was not going to be a point of failure during this testing.

Finite Element Analysis was used in Solidworks to perform static analysis for loadings. During the linear FEA process (elastic stage), the finite-element model (FEM) of the grain bin was constructed using 140,564 elements. Galvanized steel with elastic modulus = 28,007,547psi was used in the model.

Deflection measurements

Deflections also known as displacements can occur from external loads or from the weight of the structure itself. Vertical roof deflection of the bin was measured using a precision phase-comparison laser sensor while applying incremental dead loads to the retrofitted rescue anchor points. The laser sensor used was a Micro-Epsilon optoNCDR ILR1182-30 which has a resolution of 0.1 mm and repeatability of ≤0.5 mm from 0.1 to 50 m. The sensor was mounted on the sweep auger shield 83.8 cm from the grain bin center point as shown in Figure 2 and aimed at a spot on the roof directly above it. Since the sweep auger is supported by only the concrete center and circumferential footing structures and not the perforated metal floor, measurements were isolated from any floor deflections caused by the moving and loading of weights (Figure 3). A temporary loading cable was tied off at the sidewall rescue anchor point and was routed up over a pulley connected to the roof peak anchor point. The cable was loaded and unloaded incrementally by adding/removing ten tractor suitcase weights of approximately 29 kg one at a time. The loading ranged from 7.7 kg (the weight of the tackle without suitcase weights) to a maximum of 297.1 kg. The load was measured by a Bonvoisin Digital Crane Scale with an accuracy of 0.5 kg.

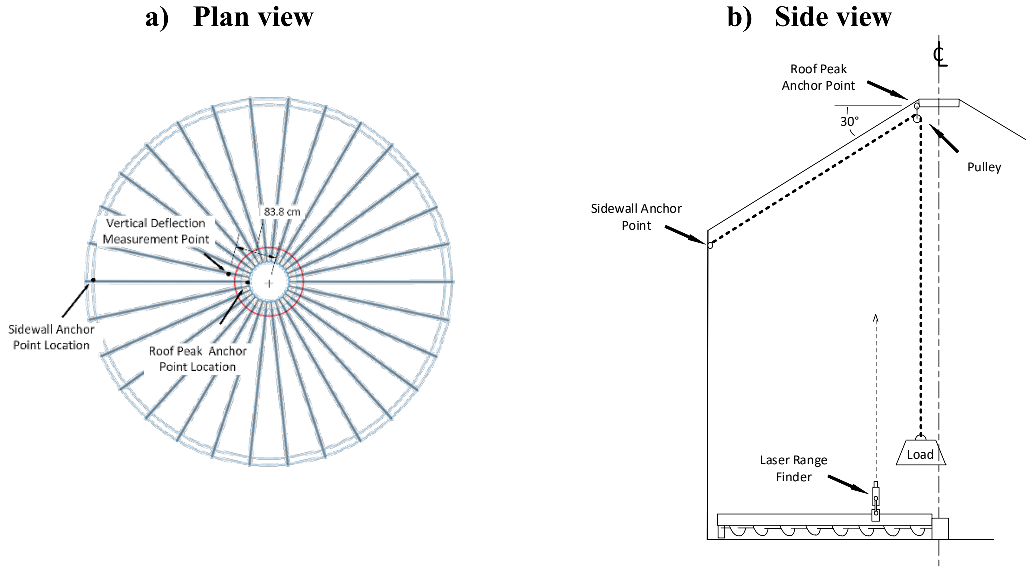


Figure 2. Location of deflection measurement a) plan view b) side view

Figure 3. Bin interior showing laser range finder and test weights

RESULTS AND DISCUSSION

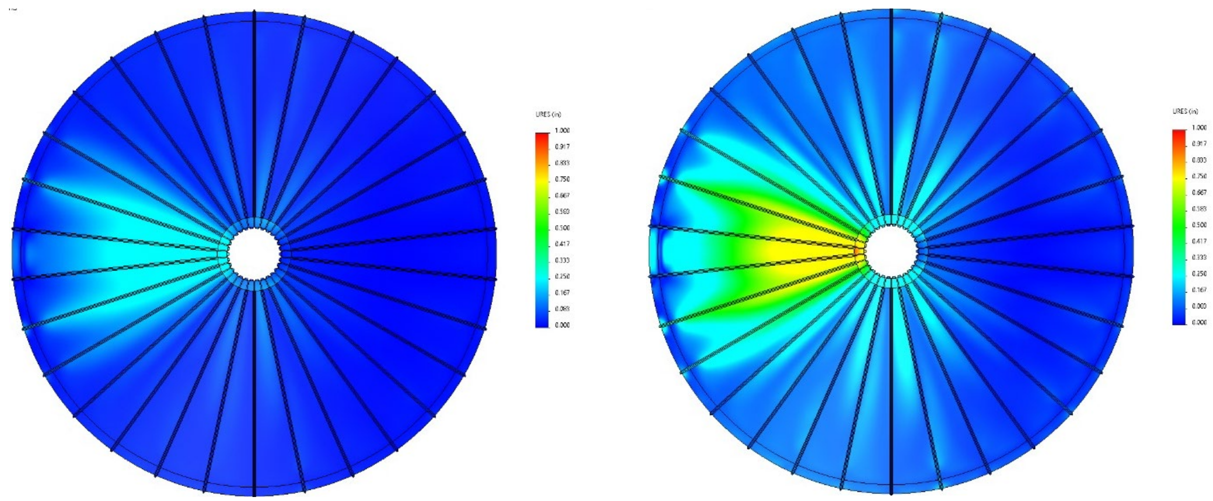
Experimental Results

The grain bin deflection measurements were taken after two complete loading/unloading cycles. During the two loading/unloading cycles, the bin structure settled as the panels shifted slightly against the fasteners and one another. The data collection was performed during the third loading/unloading cycle. The maximum load applied was 297.1 kg (655 lb). The deflection at the rooftop anchor point ranged between 0 and 2.4 mm. The deflections were slightly higher for unloading conditions than the ones measured during the loadings.

Finite Element Analysis (FEA) Results

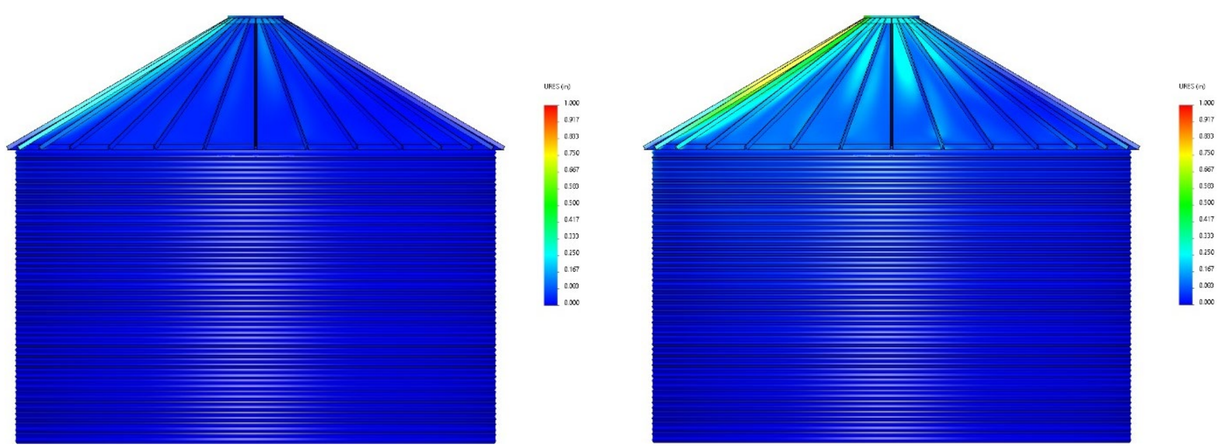
Displacement values under each loading were obtained from the FEA model. Maximum displacement (deflection) induced by the anchor loadings of 297.1 kg (655 lb.) and 907.2 kg (2,000 lb.) are shown in Figure 4 (top views) and Figure 5 (side views). FEA model for the 907.2 kg (2,000 lb.) was chosen to model for the minimum ultimate load supported by anchor attachment points stated in the ANSI/ASABE S624 Grain Bin Access Design Safety Standard. It sh

ould be noted that the anchor point is shown on the left side of the grain bin in the figures. Higher loadings resulted in bigger deflections in the FEA model. At the vertical defection measurement point shown in Figure 2a, the model gave -5.3 mm of vertical deflection for anchor loadings of 297.1 kg (655 lb.) while it was -16 mm for the maximum anchor loadings of 907.2 kg (2,000 lb.). As shown in Figure 5, the sides of the grain bin were not affected by the amount of loading.



(a) 297.1 kg (655 lb.) (b) 907.2 kg (2,000 lb.)

Figure 4. Maximum displacement on the bin rooftop in the FEA model as induced by the anchor loadings (top view)



(a) 297.1 kg (655 lb) (b) 907.2 kg (2,000 lb)

Figure 5. Maximum displacement on the bin in the FEA model as induced by the anchor loadings (side view)

Experimental and Model Results Comparisons

The measured and predicted deflections by the finite element analysis for various loading and unloading conditions are shown in Table 2. The deflection values during loading and unloading experiments were aligned with the FEA predicted deflections. Even though the measured and predicted values were very close in quantity, the percentage error ranged between 100% and 250%.

Table 2. Experimental and Model Results Comparisons

Loading - Deflection (mm)			Unloading - Deflection (mm)		
Load (kg)	Measured	FEA	Load (kg)	Measured	FEA
7.7	0.0	0.1	297.1	2.4	5.3

36.3	0.2	0.7	269.0	2.2	4.8
65.3	0.4	1.1	240.0	2.0	4.3
93.9	0.6	1.6	210.9	1.8	3.8
122.9	0.9	2.2	181.4	1.6	3.2
152.0	1.2	2.7	152.9	1.3	2.7
181.4	1.4	3.2	123.4	1.0	2.2
210.9	1.6	3.8	94.3	0.8	1.6
240.0	2.0	4.3	65.8	0.5	1.1
269.4	2.1	4.8	36.7	0.2	0.7
297.1	2.4	5.3	7.7	0.0	0.1

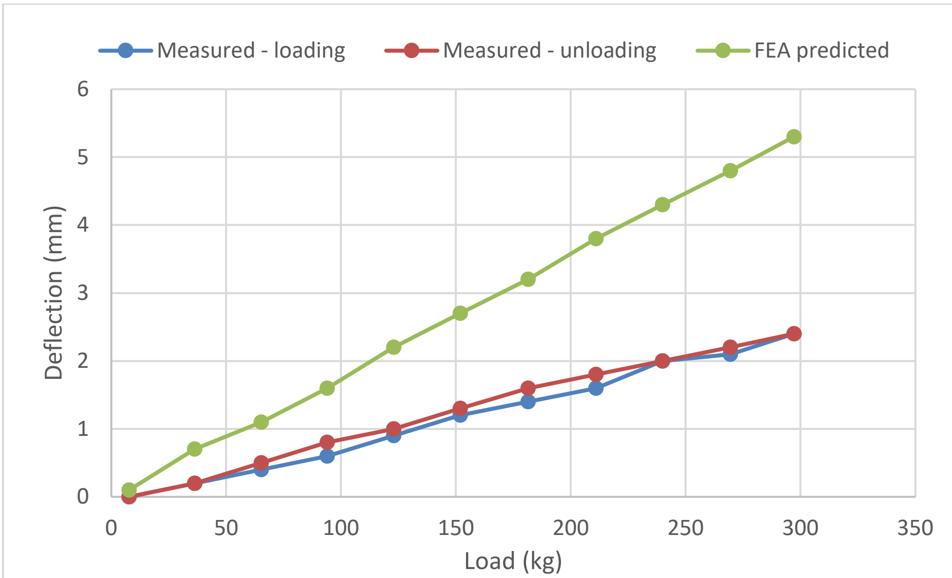


Figure 6. Comparison of deflections between FEA predicted and experimental values.

Conclusions and Recommendations

When entering a grain bin, all entrants should wear a suitable harness connected to a lifeline with anchor support, however not all grain bins have the anchor and lifeline system. In this study, a finite element analysis model was developed for a grain bin to simulate the loading and unloading conditions of an anchor point for safe entry to a grain bin. The experimental deflection results and FEA model results were aligned very well. Even though the amount of error was very high in percentage. It should be noted that the model does not account for weathering, degradation, modifications, and exact conditions of the grain bin.

The following conclusions were drawn from this study:

1. Because of the varying size, environmental and working conditions, and modifications, the suitability of any bin to safely accommodate a lifeline and anchor point system must be verified on a case-by-case basis.
2. Evaluation by a professional structural engineer and consulting with the manufacturer are recommended. This recommendation extends to all-grain bins, including those post-2018.
3. Engineering evaluation for safely accommodating a lifeline and anchor point system is essential for bins that are modified, damaged, or have other signs of degradation.
4. Educational efforts focusing on technologies and best practices can reduce the need for grain bin entry.

In conclusion, we concluded that finite element analysis can be vital to assess safety-critical structures such as grain bins. FEA can be used by all engineers to assess the structural properties of grain bins before installing an anchor point.

Through data collection and modeling, it was determined that there are too many variations among grain bins. Because of various types and modifications, grain bins must be assessed on a case-by-case basis whether a retrofit is feasible. Grain bin owners can check with their grain bin dealer or manufacturer, or they can work with a structural engineer to determine the feasibility of retrofitting. The suggested criteria were developed for structural engineers to assess grain bins and the feasibility of retrofitting safe entry points onto on-farm, non-stiffened grain bins. These criteria are a guideline, and the judgment of a structural engineer is highly recommended in ensuring the safety of grain bin modifications. Inspection criteria focus on the areas of foundation, hardware, oxidation, sidewalls, caulking, and roof inspection. The inspection criteria are intended to be a starting point to quantitatively assign values to the physical condition of a grain bin. These values are not a definitive answer nor do these values necessarily mean that your grain bin would be able to be successfully retrofitted with anchors points and a lifeline but should be used as a guide in the decision to retrofit the grain bin. This tool is to be utilized by structural engineers to assist in the decision-making process.

Author Contributions

Conceptualization, SG and LF; methodology, MD, RB, RT; validation, SG, RT; formal analysis, MD, RB, RT; writing—original draft preparation, SG; writing—review and editing, LF, MD, RB, RT; visualization, RB, RT, and SG. All authors have read and agreed to the published version of the manuscript.

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