

Case Study Evaluation of Farm and Commercial Grain Bins during the August 2020 Iowa Derecho Windstorm

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ABSTRACT

On August 10, 2020, a derecho windstorm occurred across several Midwestern states, including Nebraska, Iowa, Illinois, and Indiana, resulting in structural damage exceeding 750 miles in length. This event presented a unique opportunity to evaluate the performance of agricultural structures because of the unusually large area impacted in a predominantly agricultural region of the country. This study focuses on the response of steel grain bins, which are critical structures to support the agricultural industry and for which widespread damage was observed. While several factors impact the performance of steel grain bins under severe wind loads, the case study presented in this paper analyzes the performance of two common types of steel grain bins—namely, farm bins and commercial bins. The intended functions of these bins are the same, but they are marketed towards different scales of operation. In this paper, the performance of adjacent, geometrically similar farm and commercial bins is presented, which was documented through a combination of aerial imagery, structure-from-motion reconstructions, as well as manual measurements and photographs. While the farm and commercial bins were largely identical, the farm bins buckled and uplifted during the windstorm while the commercial bins were undamaged. Analysis of the bins concluded that the presence of exterior stiffeners, intended to permit larger storage sizes, provided additional resistance to wind loads.

Keywords: wind engineering, thin-walled steel structures, grain bin, structural engineering

INTRODUCTION

Rural communities, compared to their urban counterparts, are less disaster resilient and suffer greater losses each year due to natural hazards (UC Census Bureau, 2010; NOAA, 2018). While only 20 percent of the U.S. population resides in rural areas, rural areas are home to almost the entirety of the U.S. agricultural industry – an industry that contributed over \$500 billion to the U.S. economy in 2019 alone (USDA ERS, 2016; USDOC Bureau of Economic Analysis, 2019). Despite the criticality of agriculture to U.S. and global food production, the lack of economic diversity and prevalence of agriculture in most rural areas is theorized to be a major contributor to low disaster resilience (Cutter et al., 2016). While resilience is a function of many socioeconomic and organizational factors, the disaster response of the built environment is a critical aspect that cannot be ignored. In many rural areas, critical infrastructure includes vital agricultural support and production systems that support this economy, such as steel storage silos and farm bins.

Despite the criticality of the agricultural industry to the U.S. economy and global food production, agricultural storage silos and farm bins have received relatively little attention with respect to natural hazards research. It is estimated that there are over three-quarter of a million agricultural steel silos and farm bins in the United States alone (Bauer, 2014). Nearly all crops grown in the United States are stored following harvest in order to meet moisture content requirements or to align with seasonal and yearly market demands, which makes storage silos an essential component to the agricultural industry (Texas Farm Bureau, 2016; Brown, 2018). While storage silos and bins come in many forms, over 95 percent of all agricultural storage in the United States consists of thin-walled, cylindrical, corrugated steel structures (MacDonald and Hoppe, 2017), which form the primary focus of this study. These structures do not conform to typical standards and have been observed to perform poorly during severe windstorms (e.g., Ansal, 1999; Dogangun et al., 2009; ACI, 2016; Brito and Wittich, 2019). This paper aims to shed further light on the response of steel storage silos when subjected to straight-line wind loads. This is done through a case study investigation at a site with varying silo response following the August 2020 derecho event in Iowa.

SUMMARY OF AUGUST 2020 DERECHO

On August 10, 2020, a derecho windstorm developed in eastern Nebraska and swept eastward through several Midwestern states, including Iowa, Illinois, and Indiana. A derecho is a windstorm that is characterized by particularly long duration straight-line winds; however, tornadoes may also occur simultaneously as part of the larger storm system. Derechos, such as this event, tend to occur over relatively large areas of land. The August 2020 event left a path of damage exceeding 750 miles in length with the hardest hit areas along the Interstate 80 corridor in Iowa. This region includes several densely populated areas including the metropolitan areas of Des Moines, Ames, Cedar Rapids, and Davenport; however, the wide path of the derecho went through largely rural and agricultural counties. Figure 1 overlays the wind speeds of the derecho on satellite imagery of Iowa highlighting the nearly 50-mile-wide band of 80 mph wind, 20-mile-wide band of 100 mph wind, and 8-mile-wide band of wind speeds exceeding 120 mph (National Weather Service 2020).

The August 2020 storm caused more than \$11 billion in damage, which rivals the economic losses of major hurricanes that have struck densely populated coastal communities (e.g., Hurricane Laura in 2020 at \$14 billion) (NOAA, 2021). The derecho's damage included substantial damage to the agricultural economy and particularly to grain storage structures, such as silos and grain (or farm) bins. An estimated 57 million bushels of grain storage was lost during this storm, in addition to the loss of over 6 million acres of corn and soybeans (nearly 20% of Iowa's farmland) (Jibben, 2020). While crop insurance can cover the loss of planted crops and other policies can extend to structures such as grain bins, any grain stored in a damaged bin is not typically a covered commodity. Furthermore, the substantial number of grain bins damaged or collapsed during the storm exceeded the capacity for new construction resulting in a net loss of grain storage for the state.

OVERVIEW OF RECONNAISSANCE

In late August and early September 2020 following the derecho, structural reconnaissance was conducted by the first author and others as part of a coordinated effort by the Structural

Extreme Events Reconnaissance Network (StEER) and a grant for Rapid Response Research from the National Science Foundation to the first author. The coordinated effort sought to document the performance of various structures during the high wind event with particular attention to agricultural regions and steel grain bins/silos. The extensive reconnaissance effort surveyed properties across the range of estimated wind speeds (Figure 1), including the Iowa counties of Cedar, Jones, Linn, Benton, Tama, Marshall, Story, Boone, and Dallas. Within each county, regions were identified that included high wind (> 120 mph) and lower wind (< 80 mph) speed estimates to understand the range of structural performance. Within each region, a random sampling of properties was pre-selected to reduce bias in the data collection and ensure sufficient documentation of both damaged and undamaged structures. Property selection was conducted using satellite imagery of the area prior to the storm. Specifically, every other property was selected that included at least one steel grain bin that was accessible.

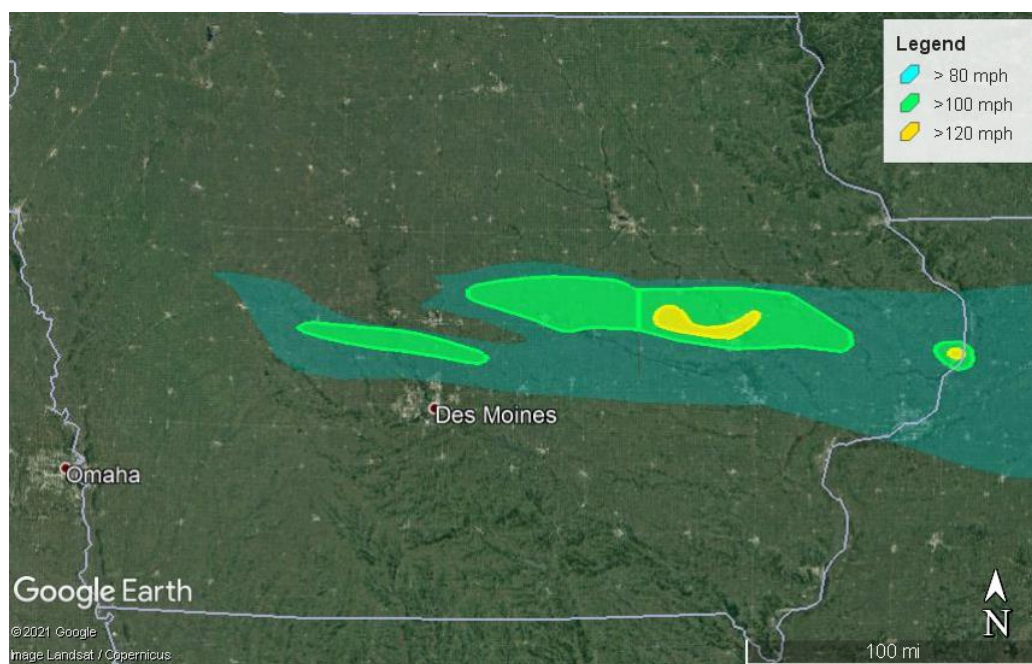


Figure 1. Map of wind speed estimations based on data from National Weather Service (NWS 2020). (Map data © 2021 Google).

Once at a selected property, collected data concerning the grain bin (or silo) included: manufacturer, estimated condition of the structure before the event, anchorage specifications, dimensions and thickness of the wall and base, material and condition of the foundation, as well as the specifications of any vertical stiffeners and horizontal wind rings. Documentation of the damage made use of the NHERI RAPID's RAPID App (Berman et al., 2020). Specific data included photographs of the damaged silo highlighting the failure mechanism(s), evidence of performance of the baseplate, foundation, and anchorage, and GPS coordinates of the structure. Aerial imagery was acquired using a small unmanned aerial system, which was also used in the generation of a three-dimensional point cloud of the site via Structure-from-Motion (SfM). Nearby and adjacent structures, such as barns and residential homes, were briefly documented in a door-to-door assessment approach (Kijewski-Correa et al. 2019) to aid in the estimation of the wind field (McDonald et al. 2006).

CASE STUDY: COMMERCIAL VS FARM BINS

While a much larger reconnaissance campaign was conducted as described in the previous section, a case study of an individual property is described herein due to its unique performance. This property contained 5 grain bins in an interconnected group (connected by lightweight truss structure/catwalk). Of the 5 bins, 4 were completely destroyed and 1 was undamaged. The 4 destroyed bins were acquired by the owner as ‘*farm bins*’ within the past 5 years, while the undamaged bin was acquired as a ‘*commercial bin*’ more recently. All 5 bins were geometrically similar and intended to meet the same purposes for the owner/farmer. Due to this unique performance, this site is explained in detail in the following sub-sections to further understand the causes of the differing performance.

Location and Estimated Wind Speed

The case study site is located in Benton County, IA, near the border with Tama County, as shown in Figure 2a. This area was within the 100 mph zone, as identified by the National Weather Service. The region surrounding the case study site is flat with little topographic variation to impact the wind speeds. The wind was primarily coming from the west-northwest in accordance with the storm. The layout of the site is shown in Figure 2b, where the 5 grain bins are located on the east side of the property. On the west side of the property, several low rise structures were present including a two-story residential home and a single-story lightweight barn/warehouse structure. The nearest structures from this site are approximately 1 mile to the west and 0.5 to the southeast. The surrounding land was dominantly mature corn crops with heights of several feet.

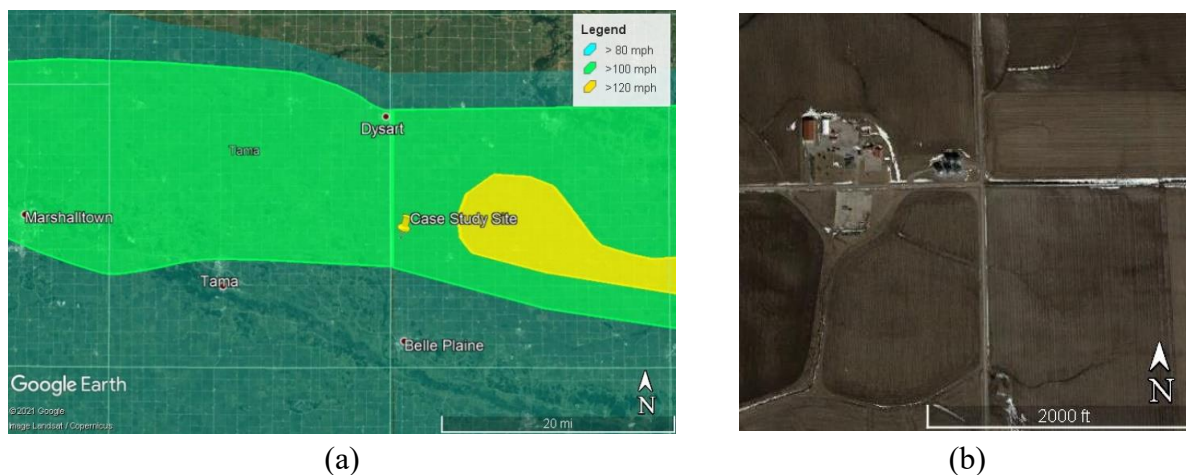


Figure 2. (a) Location of case study site in Benton County, IA, within the 100 mph wind zone. (Map data © 2021 Google) (b) Aerial imagery of the case study site prior to the August 2020 storm. (Map data © 2015 Google)

Structural Description

The grain bins at this site were located in a group, as shown in Figure 3a, and interconnected by a catwalk structure and filling/distribution system that was constructed of lightweight steel

truss. Bins 1 – 4 on the east side of the group were identical ‘*farm bins*’ purchased and installed at the same time (within the past 5 years). Bin 5, located on the southwest of the group, was more a more recently installed ‘*commercial bin*’. Regardless of whether the bin was ‘*commercial*’ or ‘*farm*’, each had a diameter of 48 ft, a sidewall height of 42 ft, a conical roof, and a concrete foundation. All bins were empty at the time of the storm in preparation for harvest.

Figure 3b is a photograph of Bin 5 from the west taken during reconnaissance. As can be seen, the sidewall of the bin includes vertical stiffeners along the wall height and a single wind ring. The wind ring is located 31 ft from the base of the bin and is connected to the vertical stiffeners. The vertical stiffeners, which consist of steel channels, are placed approximately every 5 ft along the circumference of the bin. The channels are continuous for 88 inches and are bolted to the corrugated panels every 4 inches. The vertical stiffener is connected to the anchorage at the base of the bin by a $\frac{3}{4}$ -inch embedded anchor. A close-up of the anchorage of this stiffener is shown in Figure 4a.

Bins 1 – 4 (farm bins) were by the same manufacturer and of identical overall geometry to Bin 5 (commercial bin). Similar to Bin 5, Bins 1 – 4 were characterized by a single wind ring that was located 31 ft from the base of the bin. In the absence of vertical stiffeners along the height of the sidewall, the wind ring was attached to short, steel channels that are similar to the vertical stiffeners of Bin 5. However, these short channels only span one corrugated wall panel (3.75 ft). These short channels are similarly attached to the corrugated wall panels by bolting every 4 inches. Bins 1 – 4 primarily differed from Bin 5 by the absence of vertical stiffeners. As a result, the anchorage of Bins 1 – 4 also differs from Bin 5. Figure 4 compares the different anchorage techniques. While Bin 5’s anchorage is directly connected to the vertical stiffeners, Bins 1 – 4 incorporate a short channel section of approximately 16 inches that is bolted to the corrugated panel every 4 inches. While Bins 1 – 4 have a similar anchorage spacing of 5 ft along the circumference of the bin, the embedded anchors are $\frac{1}{2}$ -inch in diameter compared to the $\frac{3}{4}$ -inch embedded anchors of Bin 5.

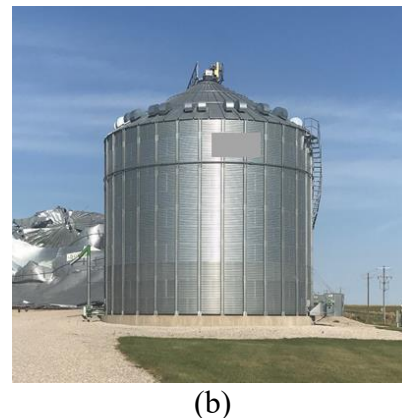
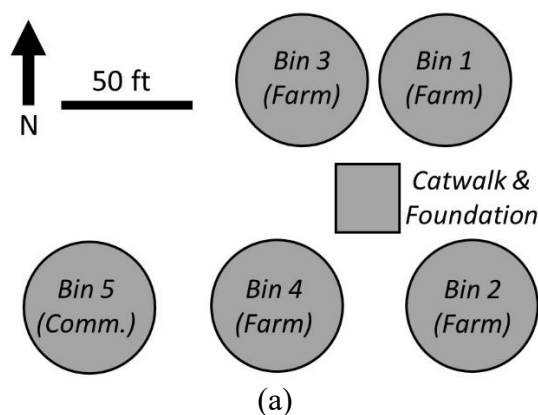


Figure 3. (a) Layout of the grain bins including identification of farm vs commercial styles and diameters. (b) Photograph of Bin 5 (commercial bin). Photograph by C.E. Wittich.

Aerial Imagery and Structure-from-Motion Reconstruction

In order to document the complex failure patterns and geometry of the site, aerial imagery was acquired using an unmanned aerial system (UAS). A DJI Inspire 2 with onboard Zenmuse

X5 camera and 15 mm lens was utilized on site to collect 110 low-altitude 20.8 megapixel images for point cloud reconstruction of the grain bin group and 36 images to document the surrounding area and topography. All UAS deployments were conducted in accordance with the Federal Aviation Administration regulations, specifically part 107.



Figure 4. (a) Vertical stiffener and anchorage for Bin 5 (commercial bin). (b) Typical anchorage clip for Bins 1 – 4 (farm bins).

The UAS was flown in a lawnmower-like pattern with approximately 70% overlap. Pix4D, a commercially available software, was utilized to process the collected aerial imagery to produce a high-resolution orthomosaic, digital surface model, and three-dimensional point cloud reconstruction. Pix4D identifies tie points between the images without user intervention and triangulates camera location and orientation to generate the sparse point cloud. A dense point cloud was subsequently generated using the image information in concert with the sparse point cloud. While structure-from-motion does not inherently provide scale, satellite imagery was used to lend an approximate scale to the resulting point cloud.

The resulting orthomosaic and isometric view of the three-dimensional point cloud are provided in Figures 5 and 6, respectively. Both of these are used in the following sub-section to interpret and quantify the damage at the site. The orthomosaic provides high-resolution aerial orthogonal image and map of the site, while the three-dimensional point cloud provides detailed geometry of the surface of the damaged bins.

Damage Observations

As shown in the orthomosaic of Figure 5 and the point cloud of Figure 6, Bins 1 – 4 were completely destroyed in the windstorm while Bin 5 survived undamaged. The wind direction was predominantly from the west-northwest causing Bins 3 and 5 to be on the windward side of the bin group. Bin 3 evidenced roof tearoff and sidewall buckling, which was followed by anchorage tearout from the concrete foundation (see Figure 7a). A centrally-located truss structure associated with filling of the bins also collapsed. The truss was found to be bent over Bin 2 with the short concrete foundation completely uplifted off the ground. Failure of this truss resulted in the crushing of Bin 2, rather than a wind failure of Bin 2 (see Figure 7b).



Figure 5. Orthomosaic of case study site following August 2020 derecho.



Figure 6. Isometric view of the three-dimensional point cloud of the grain bin site.

Bin 4, which was exposed on its northwest side, similarly collapsed due to wind pressure (see Figure 7c). The conical roof structure failed and collapsed inwards with several roof-sidewall attachments failing during this process. The sidewall on the northwest (windward) side similarly buckled and the embedded anchors tore out of the concrete foundation on the windward side. Bulging of the sidewall panels on the leeward side was also observed. The buckling failures

observed for Bins 3 and 4 compared with the undamaged state of Bin 5 highlight key differences in the design and construction. While geometrically similar and rated for the same grain capacity, Bin 5 was classified as a ‘commercial bin’ compared to Bins 1 – 4 which were ‘farm bins’. The primary design difference is the presence of vertical stiffeners (steel channels) along the height of the sidewall that connect the roof structure to the foundation through embedded anchors. The vertical stiffeners are well connected to the sidewall through bolts approximately every 4 inches. The stiffeners are placed circumferentially at approximately 5 ft on center. While the design of commercial bins targets large-scale farm operations, these additional design considerations result in a substantial gain in wind resistance for bins of smaller size that are typically comparable with ‘farm bins’.

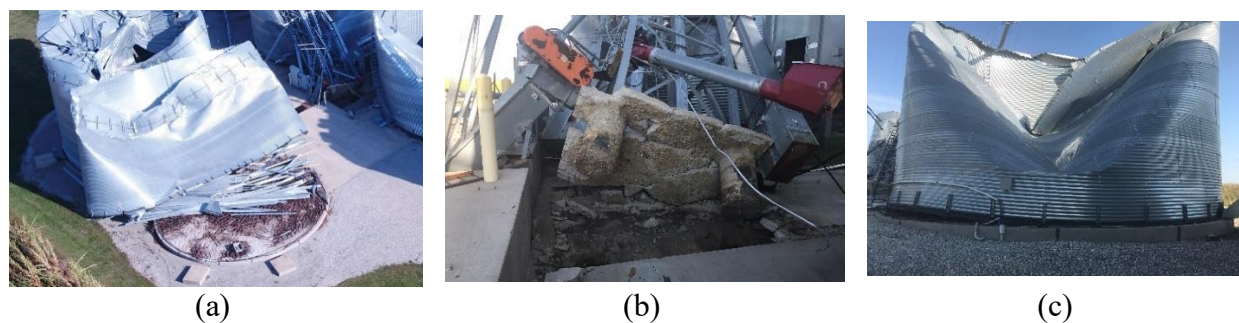


Figure 7. (a) Bin 3 with roof tearoff, sidewall buckling, and anchorage tearout. (b) Foundation uplift of central truss structure. (c) Bin 4 with roof collapse, sidewall buckling, and anchorage tearout.

CONCLUSIONS

A case study investigation of the performance of a group of grain bins was presented following the August 2020 derecho that swept across Iowa. The case study site was on the western border of Benton County with Tama County, near Elberon, NE. Wind speeds were estimated to be in excess of 100 mph for a significant duration of time, per the National Weather Service. At this site, five grain bins were surveyed – four of which were completely destroyed and one of which was undamaged. All five bins were empty at the time of the wind storm and were geometrically similar bins. The primary difference between the bins involved the use of vertical stiffeners along the height of the sidewall that are intended to transmit the load from the roof to the foundation. The failed bins evidenced failure of the roof structure, sidewall buckling, and subsequently anchorage failure. The bin that survived was classified as a ‘*commercial bin*’ meant to handle repeated fills outside the typical uses of an individual producer, while the failed bins were classified as ‘*farm bins*’. Commercial bins are typically of much larger sizes, while farm bins are typically smaller. This particular site, uniquely, had commercial and farm bins of the same dimensions and capacity. It is concluded that the design of commercial bins, involving the use of vertical stiffeners and more robust anchorage, yields a more wind resistant design.

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