Effects of Hurricane Hugo on Agricultural Structures

Jay D. Harmon, Clemson University
George F. Grandle, University of Tennessee - Knoxville
Clyde L. Barth, Clemson University

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J. D. Harmon, G. F. Grandle, C. L. Barth
MEMBER ASAE MEMBER ASAE MEMBER ASAE

ABSTRACT

A tour of damage to agricultural structures by hurricane Hugo was conducted. Empty grain bins which exhibited improper anchorage tended to fail. Post-frame buildings that were improperly anchored, braced or fastened failed, while others that were designed and constructed using sound engineering practices generally withstood hurricane winds. KEYWORDS. Structures, Grain storage, Hurricane damage, Wind.

INTRODUCTION

On 21 and 22 September 1989, the people of North and South Carolina experienced the wrath of Hurricane Hugo. Hurricane Hugo had peak wind gusts at Shaw Air Force Base near Sumter, South Carolina (approximately 130 km (80 miles) in-land from Hugo's landfall) of 48.7 m/s (109 mph). Initial estimates of damage to farm buildings in South Carolina were over $207 million. A fact-finding tour of damaged agricultural structures was conducted in a cooperative effort between Clemson University and the University of Tennessee. Information was gathered regarding the type of damage inflicted by the hurricane and types of buildings which appeared to be most susceptible to damage.

OBJECTIVE

The objective was to evaluate agricultural structure failures to determine what cost effective measures would reduce high wind damage.

SCOPE

A tour of hurricane damage was conducted during the week of 27 November 1989 and covered four counties with varying degrees of damage to agricultural structures. These counties (fig. 1) included Union County in North Carolina, and Clarendon, Lee, and Sumter Counties in South Carolina. Twenty-four sites were visited which included: turkey and broiler barns, equipment and hay sheds, grain bins, hopper-bottom bins, cotton and peanut storage facilities, free-stall dairy barns, concrete stave silos, tobacco drying barns, and swine production facilities. Approximately 50 agricultural buildings and 15 grain or hopper bins were observed.

METHODS AND PROCEDURES

The fact-finding tour was organized in cooperation with the County Cooperative Extension Service office in each of the four counties visited. The Extension Director from each county was asked to arrange visits to sites where undisturbed damage to agricultural facilities remained. Clarendon and Sumter Counties had large numbers of damaged agricultural production facilities so a full day was spent in each county. Only one half day each was spent in the counties of Union in North Carolina and Lee in South Carolina.

At each site visited, the details of the storm for that particular site were discussed with the County Extension person leading the tour or the owner of the site when available. Pictures and video footage were taken of the general surroundings and points of interest which influenced each building failure. An attempt was made to determine the progression of failure in each case. This included an estimate of the condition of the structure before the storm and which component(s) probably failed first.

Figure 1-Path of hurricane Hugo and relative damage in South Carolina along with locations of counties of site inspections.
THEORETICAL BACKGROUND

There are four basic loads for which buildings are designed to withstand: dead, live, snow, and wind loads (ASAE, 1991a; Walker and Woeste, 1991). Dead load is the weight of all permanent construction materials in the structure. Dead load is constant and acts vertically. Live loads result from the use of the structure. Typical examples include the weight and/or pressure of stored products, equipment, or livestock occupancy. Snow load is the weight of snow upon the roof and wind load results from the pressure wind places on the structure. All of these loads except wind load are somewhat static. Wind loads vary with the direction and speed of the wind and, therefore, create a unique problem which must be handled by proper design procedures.

When designing for wind loads, the effective velocity pressure is calculated (eq. 1) according to ASAE (1991a). This includes the effects of wind velocity (V), building height and exposure (Kz), and wind gusts (G):

\[ q = 0.00061 \times V^2 \times K_z \times G \times I \] (1)

- \( q \) = effective velocity pressure (kPa),
- \( V \) = wind velocity for extreme winds at 10 m (0.02 annual probability) (m/s),
- \( K_z \) = combined building height and exposure factor,
- \( G \) = gust factor,
- \( I \) = importance factor (0.9 for agricultural buildings that present a low risk to property or people).

The effective velocity pressure is multiplied by pressure coefficients to determine the pressure on individual building surfaces.

When wind encounters a building, many different pressures are created on building surfaces. If the wind blows toward the end of a gable roofed building, positive pressure exists on the windward endwall and a suction (negative pressure) exists on the leeward endwall and along the first portion of the roof ridge. A wind blowing toward the sidewall creates a positive pressure on the windward sidewall and, depending upon the roof slope, may also create positive pressure on the windward roof, but negative pressure is created on the leeward roof and leeward sidewall. A wind directed into an open front or unenclosed building experiences negative pressure on all surfaces. ASAE (1991a) defines an open structure as one with more than 20% of the windward surface open. The magnitude of these pressures increases with the square of the wind speed. Because of these negative pressures (or suction), components of the building which are designed to withstand a large weight from a snow load may not be adequate to withstand the uplifting force of a wind load. Pressure on building edges and corners are larger than wall and roof pressures.

The location of a structure relative to the “eye” of a hurricane affects the wind load on that structure. The counterclockwise wind pattern in a hurricane causes a complete reversal of wind direction from the leading to the trailing edge of the storm. This pattern also affects hurricane wind speeds. As one faces the direction of storm movement, the wind speeds on the “right” side of the eye will be greater than those on the “left” side by roughly twice the speed of the storm. In other words, damages should be greater on the right side of the storm. Winds with sustained speeds of 33 m/s (74 mph) or greater are considered hurricane force. Hurricane wind gusts are typically 120-150% of the sustained wind speeds. Most damaged structures were exposed to sustained wind speeds greater than 33 m/s (74 mph) but many were destroyed with tropical storm winds (less than 33 m/s or 74 mph).

OBSERVED DAMAGE AND DISCUSSION

On the fact-finding tour, structures were divided into two categories, post-frame buildings and holding bins or silos. Types of damage were categorized as being caused by different factors. These include: anchorage, bracing, enclosure or exposure, fasteners, and design strength. Many structures exhibited failure due to multiple causes.

HOLDING BINS AND SILOS

Several types of holding bins and silos were observed. These included hopper-bottom bins used primarily for temporary storage of grain or livestock feed, grain bins used for longer term grain storage, and silos constructed of concrete staves with metal hoops.

Four over-turned hopper-bottom bins were observed on the tour. Three bins were mounted to a concrete pad using 7.6 cm (3 in.) lag screws with lead anchors. The fourth bin had individual blocks of concrete attached to each of its four legs. The blocks remained attached but the bin was tipped over. In all cases the bins were empty at the time of the storm. One of the four bins caused additional damage to the grain handling facility when it fell on a guy wire and caused the grain leg system to topple over.

All hopper-bottom bin failures appeared to have been caused by improper anchorage. In one case, a welded plate detached from one leg. However, it may have been broken prior to the storm and did not seem to be the sole cause of the damage. One hopper-bottom was observed which did not fall while the rest of the farm sustained damage. Each of the four legs of this bin were bolted to a 10.2x15.2 cm (4x6 in.) rough sawn post buried 1.2 m (4 ft) in the ground. This may be an example of over-anchorage, but the other cases were certainly under-anchored.

Most grain bin failures were also due to inadequate anchorage. One group of 3.6 m (12 ft) diameter bins, perhaps 30 years old, were destroyed with the metal deposited a half mile or more from the site. These bins were merely set down over the outside of the concrete slab with little visible means of anchorage. At another site, a 9.1 m (30 ft) diameter bin, which was on the windward side of a group of bins, blew from its foundation. Anchorage consisted of four 8.9 cm (3.5 in.) lag screws with lead anchors. This bin impacted another bin, loosening it from its foundation. The last damaged grain bin observed was a 11 m (36 ft) diameter, 780 m³ (22,000 bu) bin containing 280 m³ (8000 bu) of corn at the time of hurricane Hugo. The anchors on this bin were extracted and the bin was bent at the grain level. The roof of the bin detached, with many fasteners pulling through the metal.
All of the grain bin damage, like that of the hopper-bottom bins, was related to insufficient anchorage. One of the most glaring inadequacies in bin construction was the placement of anchor bolts. Brock Manufacturing Company (1990) recommends as many as 20 anchors for a 9.1 m (30 ft) diameter bin. These anchors can be installed using one of several methods: 1) a 1.6 x 20.3 x 5.1 cm (5/8 in. x 8 in. x 2 in.) bolt with a depth of 16.5 cm (6.5 in.) (fig. 2); or 2) a 1.6 x 20.3 cm (5/8 in. x 8 in.) bolt with a 0.5 cm (3/16 in.) thick x 4.1 cm (1.625 in.) O.D. washer next to the bolt head and embedded to a depth of 16.5 cm (6.5 in.); or 3) a drill-in anchor bolt with a performance equal to a 1.6 x 21.6 cm (5/8 in. x 8.5 in.) glued bolt (HILTI Kwik-Bolt) with a minimum embedment of 17.8 cm (7 in.). Butler Manufacturing Company (1989) has similar recommendations. Clearly, none of the damaged bins were anchored according to these recommended specifications.

The last type of holding bins and silos observed were concrete stave silos. Two failed silos were observed. The first, a 3.6 m (12 ft) diameter silo, fell headlong with the wind. This silo had all of its metal hoops intact. Failure was apparently due to crushing of the staves on the leeward side. The second failure was a silo having a diameter of 9.1 m (30 ft) and height of approximately 18.3 m (60 ft). Staves on the windward side were broken in 45° angles upward in two directions to form a “V”. Most staves fell inside the remaining silo with hoops showing little damage.

Damage to concrete stave silos appeared to have been a material strength problem. The first silo exhibited aging of the staves and perhaps had a weak foundation which would cause a rocking motion. The second silo had staves in good condition but had a large enough radius of curvature that it withstood the wind pressure.

**POST-FRAME STRUCTURES**

The post-frame portion of the tour included many post-frame structures which were built for many uses. Rather than discuss each type of building examined, it is more practical to discuss the types of failures occurring in the buildings.

Anchorage of buildings in this study is defined as the bonding of poles or posts used for construction with the underlying soil. Two main anchorage failures were apparent: poles and posts either pulled out of the ground or pushed over. At some sites, particularly poultry houses, posts were embedded only 50.8 cm (20 in.) below grade. Tapered poles may offer more anchorage than dressed posts set at the same depth, but a depth of 50.8 cm (20 in.) is not adequate for either posts or poles. Standards for design of post embedment are specified in ASAE Standard EP486 (ASAE, 1991b). Actual design specifications vary with the building characteristics and soil bearing capacity.

The second category of failure involves bracing. Bracing for this study was limited mostly to knee braces. Knee braces are designed to give the building more stability. Knee braces may be nailed into the side of the pole or post extended to the top chord of the truss, and nailed to the bottom as well as the top chord.

There were two main problems with knee braces in buildings observed in this study; either they did not exist or they were substandard. In buildings which fell, knee braces were missing or had been toenailed into the poles or posts. Toenailing is perhaps sufficient for a compressive load but offers little resistance to tension, as would occur at high wind speeds. Few knee braces were fastened to the top chord of the truss being supported, most ended at the lower chord. Buildings with properly installed knee bracing generally sustained less damage than improperly knee braced structures.

The enclosure or exposure of the building was also a contributing factor in many failures. Several buildings were situated on hills with endwalls to the wind. These buildings appeared to collapse inward from the end with destruction continuing in a chain reaction. Exposed buildings were more susceptible to damage. However, exposed sites are often best for natural ventilation. Overall, the benefit of ventilation from an exposed site outweighs the increased chance of wind damage. Proper post-frame design and construction techniques will prevent most wind damage regardless of exposure. Exposure is a factor accounted for when determining effective wind pressure (ASAE, 1991a).

Several unenclosed buildings were observed with the open side oriented toward the wind. These sustained heavier losses due to the increased pressure created within the structure by the wind. Buildings with only two sides enclosed allowed wind to flow through without creating large increases in internal pressure and were observed to withstand the storm more often than three sided buildings.

Fasteners were an important part of many failures. The connection between the knee braces and the side poles or posts was often inadequate, as previously mentioned. The connection between the truss and the truss header was often weak and very questionable. One method for connection is to nail the truss or the rafter into the side of the poles or posts of the building with a truss header below this connection. This technique offers racking resistance as well as a solid connection between trusses and posts. Another method of fastening is accomplished by connection of the truss to the truss header using common nails or by using “hurricane clips” (rafter ties) to fasten the two components together. Many connections between the truss and truss header were only nailed. Canfield et al. (1991) concluded that hurricane clips offer greater uplift...
load capacity than do most toenailed connections. The number of cladding fasteners were also inadequate at building edges, roof edges, and the ridge where wind pressures are elevated.

The last category of failure is that of design strength. One of the most common strength of material problems occurred in the roofing. Many times nails had pulled through the roofing (particularly aluminum roofing) or the nails themselves were broken. Incidents involving broken posts were due to deterioration from prolonged exposure to animal manure and were not considered a design problem. Many building components were overdesigned for strength but the connection between these components were weak.

SUMMARY AND CONCLUSION

Hurricane Hugo had peak wind gusts at Shaw Air Force Base near Sumter, South Carolina (approximately 130 km (80 miles) inland from Hugo’s land-fall) of 48.7 m/s (109 mph). It is not economical to design agricultural buildings to withstand wind speeds of this magnitude. There are, however, some changes that should be made in building practices of the past. The following conclusions were indicated as a result of this study:

A large percentage of grain bins and hopper-bottom bins were inadequately anchored. No damaged bins were observed that met manufacturer’s anchoring recommendation.

Many damaged post-frame buildings were not properly anchored. This was particularly true of poultry houses.

Bracing of post-frame buildings was substandard in most cases. Toenailed knee braces detached during roof suction situations.

Buildings with an unenclosed side toward the wind often were destroyed. Two-sided buildings with open sides on the windward and leeward side had a higher survival rate.

Post-frame buildings were constructed with adequate members, but failed due to inadequate connections between members. Inadequate fastening of cladding at the edges of the roof and walls caused additional damage.

Post-frame buildings which were designed and constructed using sound engineering practices generally withstood hurricane Hugo while others failed. Sound engineering practice is a cost effective means of preventing complete building failure.

With more attention given to anchorage, bracing, and fastening, perhaps the new buildings which are being built will be safer, not only for hurricanes but for snow storms or high winds not necessarily connected with hurricanes. In Southern states, buildings are more likely to be destroyed by sleet and ice than by hurricanes.

ACKNOWLEDGMENT. Appreciation is extended to the University of Tennessee and Clemson University for providing the opportunity for this cooperative effort. Special thanks are due to the many producers who allowed us to visit their facilities and who agreed to be interviewed. Appreciation is also extended to the Cooperative Extension Service personnel in Union County, North Carolina, and Clarendon, Lee, and Sumter Counties in South Carolina, and to Alvin Etheredge of Duke Power Company for arranging site visits.

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