ABSTRACT

LONG, JOHN MICHAEL. Research on a Post-Frame Burley Tobacco Curing Structure for Wire-Frame Racks. (Under the direction of Michael Boyette.)

The purpose of this research is to develop a post-frame structure to utilize wire-frame racks in the curing of burley tobacco in non-traditional growing areas. The Piedmont and Coastal Plain regions of North Carolina have little existing burley curing infrastructure. The current trend for mechanically harvested burley tobacco utilizes the cut-notch method. Wire-frame racks are used by many growers as part of an in-field curing structure for cut-notch harvested plants. Incorporating wire-frame racks into a post-frame structure provides greater protection from adverse weather than a typical in-field wire-frame rack curing structure. All of the in-field advantages and mechanisms of wire-frame racks are retained with this design. A two-tier test building was designed and constructed to handle modified wire-frame racks. Individual rack weight data were collected during the curing season to observe the effect of plant weight loss on structural load duration. Individual rack weight change was recorded for the entire curing process. The most significant changes in weight and color occurred during the first twenty-eight days. The tobacco underwent three different color stages during the curing process: green, yellow and brown. When examining these stages on an individual basis, weight loss rates doubled between curing stages. The overall data set followed a simple decay differential equation. The rate at which the plant lost weight can be attributed directly to water loss and the plant’s rate of water loss was directly proportional to the amount of water remaining.
Research on a Post-Frame Burley Tobacco Curing Structure
for Wire-Frame Racks

by
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DEDICATION

I’d like to dedicate this thesis to my family. I’m the luckiest person to have been born into a family like ya’ll. You’ve supported me the whole way. I couldn’t have done it without you.

The right word may be effective, but no word was ever as effective as a rightly timed pause.

-Mark Twain, *US humorist, novelist, short story author, & wit*
BIOGRAPHY

John Long was born in High Point, North Carolina on January 25th, 1983. He is the son of Michael and Patricia Long of Winston-Salem, North Carolina and the oldest of two children. John grew up on a small family tobacco and cattle farm in the community of Midway in Davidson County, North Carolina. John graduated from North Davidson Senior High School in 2001. John was very active in both the National FFA and the Boy Scouts of America. John obtained both organizations’ highest ranks of American Farmer Degree and Eagle Scout, respectively. John enrolled at North Carolina State University in the fall of 2001 majoring in biological engineering with agricultural and environmental concentrations. John became involved with the North Carolina State University’s Student Branch of the American Society of Agricultural and Biological Engineers as an undergraduate, where he held offices at both the local and regional level. John was also a charter member of the chapter’s quarter-scale tractor design team, Pack Pullers, and remained actively involved with this endeavor throughout his time at NC State. Upon graduation in 2005, John enrolled in a Master’s program in the department of Biological and Agricultural Engineering where he was actively involved in burley tobacco research.
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1. INTRODUCTION

Burley tobacco production can be found today in almost every part of the temperate and tropical world. It is grown in a variety of climates, topographies and economic conditions but there is one commonality between all of these. Burley is generally grown, harvested, and cured in the same manner no matter how backward or technologically advanced the country. There has been very little mechanization or change in the labor practices in the past century. The tobacco plants are still largely hand cut and air cured in much the same fashion one would find if they were in colonial Virginia (the site of the first commercial tobacco production) in the late seventeenth century (Herndon 1957). With the advent of mechanization from field to market preparation in other difficult to harvest crops such as flue-cured tobacco, fresh produce, and other specialty crops, one could logically assume that burley tobacco could be mechanized in a similar manner. By applying mechanization techniques to the harvest and curing of burley tobacco one should be able to significantly reduce the labor required and time invested on a per acre basis.

In addition to labor savings, time, always an issue in harvesting, is especially exacerbated in burley production as acreages increase. In the traditional burley growing regions of the US, such as Kentucky and Tennessee, allotments have averaged around one acre per grower. This modest amount was easily harvested by a grower and their family within a perfectly acceptable period of time. However, the producers who have needed the most labor relief were those that held five acre and larger allotments (Duncan et al. 1996). For
maximum quality at harvest, burley tobacco is cut and readied for curing three to four weeks after topping (Smith et al. 2005). This need requires that the burley be harvested within a one to two week window to achieve optimum harvest quality. With small acreages, the required harvest window is adequate with conventional methods and more than adequate with mechanized methods.

Burley grown during the 2005 season followed a different set of rules. The Tobacco Quota Buyout of 2004 abolished the federally regulated quota system for all types of tobacco. This deregulation allowed some growers the option to cease raising burley tobacco. On the other hand, it also allowed growers, who remained in the tobacco industry, the opportunity to expand their production. With increases in individual grower acreages, more burley tobacco per grower must be harvested during the short optimum harvest time after topping. If the burley tobacco is harvested after the one to two week window, significant reduction in yield or complete crop failure can occur.

The Tobacco Quota Buyout of 2004 also allowed new tobacco growers to enter the marketplace in new ‘nontraditional’ regions such as the Piedmont and Coastal plain of North Carolina. The large influx of new producers provides a unique opportunity; since as new producers of burley tobacco, they have little or no existing infrastructure. Further, they also have no background nor preconceived notions about the crop production practices and look to university research and extension efforts for information about the proper way to successfully grow and harvest the crop. This attitude has provided new growers
the opportunity to utilize some of the various mechanized system without having to discard their investments in a previous conventional system.

1.1 NORTH CAROLINA BURLEY INFRASTRUCTURE

Since there is a lack of on-farm infrastructure to house and cure burley tobacco in non-traditional areas such as the Piedmont and Coastal Plain of North Carolina, a system must be developed and adopted by each grower. It is obvious that there is always a tendency for growers to emulate or develop systems that are used by current growers of burley tobacco in the more traditional areas.

1.1.1 CONVENTIONAL SPLIT-STALK

The split-stalk method is the traditional and most widely used method of hanging burley tobacco for curing and, consequently, many first-time growers chose to harvest and cure their burley tobacco utilizing this method. Workers pass through the fields, cutting the stalks at their base. The whole tobacco plant is then forced down a four-foot long wooden stick which splits the stalk as it is forced down the stick. Usually six plants are evenly-spaced on a single stick in this manner. The sticks are then hung across two horizontal boards, poles, wires, or ledges in some type of barn or covered structure. This method of harvest and curing is the most labor intensive, but the most widely used in traditional areas as well as non-traditional areas of North Carolina. This system, proven over generations, requires the least capital costs, but the most labor. Since small-acreage growers often lack resources but often have sufficient farm labor, it is
logical this method would be most favored by these growers. In addition to issues of labor and capital, many new North Carolina growers chose this method for several other reasons.

Since the split stalk method is the conventional curing method, it is a time proven system and is viewed by growers as less risky than newer methods. First, risk reduction is important to new growers wishing to reduce the number of variables that could go wrong when attempting to bring a new crop to market. Second, many growers chose this method because they had older flue-cured stick barns, empty equipment sheds and excess available labor from other crops. Many growers who did not have existing infrastructure that could be retrofitted for burley curing barns, created relatively low-cost temporary in-field curing structures. These structures varied in construction, but all consisted of a single tier with lengths of smooth fence wire across multiple posts. Figure 1-1 presents one example of an outdoor curing structure. Similar in structure to clotheslines, they provided long parallel lines of wire spaced to allow split-stalk sticks to hang just above the ground. These structures were then covered by long sheets of black plastic. Informal data collected from growers has indicated these structures could be built for less than $1000 per acre of capacity.

1.1.2 WIRE-FRAME RACKS

In addition to the split-stalk harvest method mentioned above, the “cut-notch” harvest method was developed as an alternative. This method provided a
mechanism to affix stalks to a single strand wire. This was accomplished by cutting an angled notch in the stalk approximately one inch from the base. An example of a stalk harvested with this method can be found in figure 1-2. This notch is typically tapered to be wider at its opening. This allows for easier placement on the wire while still allowing a press fit. Plants harvested with this method can be placed on a variety of wire-strung structures. One such structure utilized by growers is the wire-frame rack.

One of the most common non-conventional systems chosen is the in-field curing structure using a wire-frame rack. An example of such a system can be found in figure 1-3. This system has several advantages. Wire-frame racks can be carried on trailers or harvesting machines that use the cut-notch method of mechanically harvesting. This method speeds up the harvesting process and allows the tobacco to be removed from the ground immediately. This procedure reduces the amount of foreign matter found on the cured leaf and prevents some contamination by soil-born matter. Typically these racks, consisting of either two or four legs, are placed next to one another in a linear fashion. This placement is typically done near the edge of the recently harvested field. Figure 1-4 is an example of a row of empty four-legged racks along a field border. Upon filling with freshly cut tobacco, these structures are covered by plastic sheeting to prevent rapid moisture loss and rain damage and facilitate the curing process. This type of system tends to be a cost effective method for curing burley tobacco considering the amount of materials required to cure an acre of tobacco consists of the racks, legs, plastic sheeting, and material to secure the sheeting. There are
no permanent structures to be built by the grower. Even though the in-field curing structure has many advantages, there are several drawbacks to this type of system.

The first problem with in-field curing structures is that they have little protection from the weather. The only protection for the curing tobacco is a thin sheet of plastic. This lack of protection is less of a problem in traditional tobacco curing areas, but especially in areas like North Carolina there is always the threat of severe weather such as hurricanes and the like during the curing season. One of the biggest threats to in-field curing tobacco is wind. Wind, especially the speeds associated with hurricanes, can cause the tobacco to fall onto the ground from the curing structure. If not replaced immediately onto the frame, the wetted tobacco will rot. This is true more so with cut-notch harvested burley tobacco since the stalks are held on the wires by gravity only. Currently, notching tends to be less consistent, leaving differing sized notches based on stalk size, shape, and height. These different notches will all hold the burley tobacco onto the wire with enough force to overcome the initial weight of the plant and some side to side movement but on windy days, the unprotected plants may swing on the wire, loosening the press-fit notch between the wire and the plant. This loose fit eventually leads, overtime, to the plant falling. Conventional split stalk methods that have several plants affixed to a wooden stick tend to withstand wind loading by rotating at the interface between the stick and the barn structure, thus these plants are less negatively affected by wind.
The applicability of in-field curing structures tends to vary based on grower acreage. As the total acreage of an individual grower increases, the likelihood that all of their burley tobacco crop will be grown in a single field, or in fields near each other, decreases considerably. This increase in acreage means that instead of managing or overseeing a single in-field curing structure, a grower would need to visit multiple sites to manage the curing process for his entire crop. This increase in management becomes more important in areas where field sizes are smaller and growers rent land from multiple landowners, such as in the Piedmont of North Carolina. As a result, larger growers decide to transport their entire crop to a centralized location to help reduce the amount of travel required during the curing season. Since most all current in-field curing structures are of a single tier, a significant amount of area is required to properly cure a crop at a centralized location. For example, a typical wire-frame system will require 1500 square feet of open area per acre of harvested crop (assuming only a 5500 plant population per acre). For a 20 acre crop, the required space would be close to 7 tenths of an acre. Nevertheless, the amount of land area required would be cut in half just by employing a double tier system. This feat could be accomplished by stacking an additional row of wire-frame racks on top of another row. However, this could be highly unstable, or require specially designed and more expensive racks and loading machinery. Also, placing plastic sheeting on these racks would become an ordeal since the height necessary to reach over the racks would also double and require additional labor. Since there are clear labor advantages to the wire-notch system, overcoming the disadvantages of single tier in-field curing
structure by the development of a multi-tiered structure for wire-frame racks should have positive benefits.

1.2 STATEMENT OF OBJECTIVES

The goal of this research was to develop a research structure to effectively handle burley tobacco for a successful curing process. This research curing structure should include the following aspects:

- The structure should utilize wire-frame racks to hang cut-notch harvested burley tobacco.
- The structure should provide facilities to cure tobacco at a centralized location.
- The structure should allow individual wire-frame racks to be isolated for research.
- The structure should implement a multiple tier system.
- The structure should be designed to allow the use of inexpensive rough-cut lumber.
- The structure should be safe, labor efficient and easy to maintain.

The research project will produce a workable prototype that will apply these concepts during field testing.
Figure 1-1  Outdoor curing structure for split-stalk sticks

Figure 1-2  A cut-notch method harvested burley tobacco plant
Figure 1-3  A typical wire-frame rack in-field curing system

Figure 1-4  Row of wire-frame racks along a field border
2. LITERATURE REVIEW

Burley tobacco has been harvested using what is known as the conventional or split-stalk method for decades. This method is very labor intensive. Workers pass through the fields, cutting the stalks at their base. The whole tobacco plant is then forced down a four-foot long wooden stick which splits the stalk as it is forced down the stick. Usually six plants are evenly-spaced on a single stick in this manner. These sticks are then gathered by workers and placed on trailers or wagons for transport. The sticks are then moved from these transports to multi-tier barns where workers lift these sticks into place. The amount of labor required for harvest and preparation for curing is only exacerbated by the shear monotony.

There have been many notable efforts to alleviate some of the labor and time involved in preparing stalk-cut burley tobacco. Walton et al. (1985) developed a portable frame system beginning in the 1982 season that cantilevers the burley tobacco on conventional tobacco sticks within the curing frame. Each frame held 50 sticks, (each stick consists of 5 stalks) requiring 28 frames per acre. The average fill time per frame for a pair of workers was 4.5 min. resulting in 4.21 man-hours per acre. A tractor mounted front-end loader then loaded these frames in a barn for the duration of the cure. The total system reduced the labor required to move the burley tobacco from the field to the barn by 68% over conventional systems. As a result of this research, the idea of portable curing frames was utilized by each of the three major paths that burley tobacco mechanization took thereafter in research.
2.1 CONVENTIONAL INFRASTRUCTURE MODIFICATION

One of the first directions towards mechanization involved the modification of conventional curing facilities to reduce the labor involved and the number of workers required to hang stalk-cut burley tobacco. Duncan et al. (1982) introduced a cable hoist system that would allow a worker to lift and position 1,200 to 1,500 pounds of stick harvested tobacco in a conventional curing barn with the push of a button. Duncan et al. (1996) further developed this system (known in Kentucky as the cable hoist system) and evaluated it in several modified conventional air-cured barns. The hoist system was able to utilize one or two workers to fill an entire conventional barn of burley tobacco. This system reduced the labor by up to 45% compared to conventional methods of housing stick harvested burley tobacco. The labor savings were found to show a break-even potential over a five to seven year period for a 5 acre allotment.

2.2 IN-FIELD CURING SYSTEMS

A second mechanization path developed based on in-field loading of portable curing frames. A semi-mounted harvest system was developed by Casada et al. (1987) that cut and simultaneously notched a 45 degree cut in the stalk for hanging on wire. This system utilized a grasping chain that carried the cut burley tobacco to a trailing wagon that held a wire strung portable frame. Workers collected the tobacco off the grasping chain and placed it on the wagon mounted portable frame. This was one of the first systems that integrated harvesting, handling and housing of stalk-cut burley tobacco. The cutter system
could harvest at a rate of 40.5 plants per min. The portable curing frames were stacked in barns in a similar fashion to those developed by Walton et al. (1985). This system was expanded upon by the system developed by Bader et al. (1990). Bader developed and tested a trail-type harvester that utilized the same cutting head and grasping chain. The harvester trailed behind the tractor cutting and notching the burley tobacco. The grasping chain laid the burley tobacco on a conveyor belt that carried the plants to three workers standing on the harvester. These workers hung the plants on a wire-strung portable curing frame. The frame was removed by a front-end loader once it was filled. This trail-type design utilized similar portable frames to Walton et al. (1985), but required 10 man-hours per hectare to move frames from the field to a stacked position in the barn. The biggest improvement upon previous systems was a reduction in field losses. The total labor savings over conventional methods was approximately 63%. Most of this labor reduction occurred during the harvest phase rather than the housing phase. The housing of the burley was similar to that of earlier portable curing structures. Walton et al. (1991b) evaluated this system even further and determined that the trail-type system could harvest 0.7 hectares per day and save the producer up to 45% in labor over the conventional system. Less skill was required with the notched burley tobacco system compared to conventional stalk split method, but it was noted that ‘houseburn’ was more of a problem in this system due to the high density of the stalk-cut burley tobacco.
2.3 AUTOMATED HARVEST/CURING SYSTEMS

A third mechanization pathway utilized a fully automated system to minimize labor inputs. Wells et al. (1990a, b) developed a complete mechanical system to cut, notch, invert, and index each plant on a portable curing frame with essentially no manual labor. The machine system offloaded filled frames and begin indexing plants on a new frame with little intervention or supervision. This system decreased 80-85% of the labor required to harvest and house stalk-cut burley tobacco as compared to the conventional manual method. At the completion of harvest, the filled frames were lined up at the field borders, covered in plastic, and left there throughout the curing process. Figure 2-1 shows this harvesting system in action. This system had an approximate capacity of 1.4 to 2.0 hectares per day (Wells et al. 1990a). Walton et al. (1991a) evaluated the new curing structures developed for this automated system. Data were collected and evaluated over a three year period based on: plant varieties, densities, position in the curing frame, and stalk position. One set of curing frames were placed in the field over sod and under plastic covers, while another set was placed in a barn for curing. The remaining burley tobacco was cured in a conventional barn on sticks. During normal curing seasons, the tobacco cured in the conventional and field cured frames were found to be of equal quality and both were superior to the frames cured in the barn. During curing seasons that had lower than normal ambient relative humidities, the field cured frames had a higher grade index than the other two methods. During wetter than normal curing seasons, the conventionally cured burley tobacco had a higher grade index
than the other two methods. Walton et al. (1991a) determined this was due to relative humidity in the field frames reaching saturation each night. Walton also determined that variety had no effect on grade index in the curing frames.

Camenisch et al. (2002) utilized components of the system proposed by Wells et al. (1990a, b). Their system utilized a similar notching method that allowed plants to be placed on slotted steel rails. A tractor-towed trailer mechanism was developed to move ten slotted steel rails per load. These rails were placed on parallel wooden beams located at a location for curing where they will be covered in plastic similar to the lined up portable curing frames used by the harvester utilized previously by Wells. The system was determined to be comparable to the rate of the Bader et al. (1990) harvester, but only required two workers to operate the system therefore reducing the overall labor required.
Figure 2-3  Wells et al. (1990) mechanical harvesting system
3. DESIGN

Several objectives were addressed during the design process. The authors primarily wanted to utilize the wire-frame racks incorporated into the in-field curing structures by many growers, to arrange these wire-frame racks into multiple tiers at a centralized location, and to isolate individual wire-frame racks for study. These objectives were incorporated into the final design of the prototype structure.

3.1 WIRE-FRAME RACK

The first objective of this study was to design wire-frame racks to secure the harvested burley tobacco in the prototype structure. The most prominent design used by growers incorporated a five foot wide piece of 9 gage welded wire reinforcing mesh used primarily in concrete construction. The mesh was secured along the top of a rectangular wooden frame. Other designs (described above) utilize smooth wire strung across the length of the rectangular frame. The concrete reinforcing wire style rack offered several advantages over the wire-strung frames. The concrete reinforcing wire utilizes a six inch square grid of wires. Tobacco could be placed on the wires running the length of the rack and be evenly spaced with little effort since each stalk fits neatly in a single square of the grid and a six-inch spacing is considered ideal. This eliminated any effort by a worker to maintain even spacing. Also, this grid prevented the tobacco from bunching along the wire due to movement due to wind or transport of the frames. The legs of these wire-frame racks usually consist of 1 ½ diameter, schedule 40
black steel pipes. A common example of a wire-frame rack loaded with burley tobacco can be seen in figure 3-1. The frame consisted of 2 by 6 dimension lumber with 2 by 4 cross-members and two or four vertical legs elevating the frame off the ground. This type of wire-frame rack was the basis for the wire-frame racks utilized in the prototype design.

Several changes were made to this simple wire-frame rack design to improve its ease of use. Figure 3-2 presents a drawing of the new wire-frame rack design. There were two noticeable improvements between the original wire-frame rack design, currently used by some growers, and the new modified wire-frame rack design, used in the prototype structure. The most obvious improvement was the lack of metal legs to hold the rack off the ground. These legs, usually made of steel, were costly and were replaced by short extensions of the wooden frame to allow the rack to rest on a ledge at four points. These short extensions are referred to as legs or ears. The second change was the use of 2 by 8 inch dimension lumber on the shorter ends of the wire-frame rack. These end pieces were notched to provide a better interface for lifting the wire-frame racks from the two shorter ends. This difference in height provided a gap when stacked. This 1.75 inch gap is identified in the stack of modified wire-frame racks found in figure 3-3. This gap improved a worker’s ability to separate individual wire-frame racks and also provided a spot to lift entire stacks of wire-frame racks with equipment such as forklifts and tractor-mounted front-end loaders.

The resulting wire-frame rack spans a total length of 11 feet -7 inches including the legs and a width of 6 feet- 1 ½ inches. The total tobacco hanging
area without the legs was 10 feet- 1 ½ inches. Using 5 foot wide concrete reinforcing wire or re-mesh, a total of 220 plants can be cured per rack. If one assumed that a single plant’s maximum weight is 8 pounds, then the entire rack would weigh 1860 lbs including the 100 lb empty rack weight. Note that for further calculations, a maximum loaded wire-frame rack weight of 2,000 pounds was assumed, unless noted otherwise.

3.2 CENTRALIZED CURING STRUCTURE

The second objective of this design was to provide a means of curing a crop of burley tobacco on wire-frame racks at a centralized location. This system was designed to arrange the wire-frame racks into multiple tiers and multiple rooms. A small structure divided into two rooms containing two tiers each was designed to hang twenty of the modified wire-frame racks. Figure 3-4 presents an isometric overview of the building. The building, constructed at the Central Crops Research Station near Clayton, N.C., utilized a post-frame construction design. A standard twenty-four foot width was selected to allow for the two rooms to be approximately twelve feet on-center. This width allowed for prefabricated twenty-four foot trusses to be used; this idea was quickly discarded for the post-frame rafters to provide an unobstructed attic space for a future hoist or rack lifting apparatus and to reduce the amount (and associated extra costs) of prefabricated wood products in the design.

One of the secondary goals of this structure was to be able to utilize a similar design and building method in a production situation because this
structure was primarily designed for use in the study of burley tobacco curing. More specifically, the idea was to study curing in non-traditional growing areas of North Carolina. The aim for this design was that it would be simple enough that it could be easily constructed by a grower with a minimal amount of previous carpentry skills and that most of the components could be produced from locally produced lumber. Most of the lumber used in the design of this facility was southern yellow pine. This is an industry term for the wood that comes from four main pine species: shortleaf, longleaf, loblolly, and slash. It is difficult to find a county in North Carolina that does not have a ready supply of yellow pine tree species suitable for lumber.

3.2.1 Floor Plan

The structure was designed to cover a 24 by 44 foot area and include a 14 foot driveway at one end. Figure 3-5 provides an overhead view of the structure, noting the driveway on the right-hand side. This driveway provided shelter and access to trailers loaded with burley tobacco during the process of transferring the harvested tobacco into the curing structure. The driveway was designed perpendicular to the two rooms containing ten wire-frame racks each. The two 12 by 30 foot rooms contain six posts or columns placed six feet on-center. This permitted each of the wire-frame rack’s legs to sit on a different column. No rails or horizontal boards were used to connect these posts beyond the header that runs the length of the structure. Instead, rack legs rested on a ‘rackmount’ consisting of 2 by 6 boards doubled and affixed to each column using four 5/16
inch lag screws as seen in figure 3-6. This ‘rackmount’ design allowed individual wire-frame racks to be moved down the length of the structure then lifted vertically above the desired mounting location with the legs passing through the space between columns. The wire-frame racks can then be moved again horizontally to line up with the mounting locations and lowered to rest on these locations. This method of mounting the wire-frame racks to the structure permits an overhead lifting apparatus to easily position the wire-frame racks. Although the lifting apparatus was not included in the facility as built, it would have the ability to translate the wire-frame racks while they are close to the ground to limit the amount of time a person would be underneath. Worker safety was an important aspect of the design.

3.2.2 Roof

The structure was designed to be covered by a gable style roof. This style roof is common on agricultural structures and provides an attic space in the center of the building. This attic space provides ample air flow space for a good cure. A 4/12 pitch was chosen for the roof slope. The roofing material chosen was a 26 gauge painted, raised-rib roofing. The metal roofing was purchase in three foot sections and was custom cut to cover the full slope length of 15 feet. Several variables were taken into prudent consideration when designing the roofing system. The design load value summarizes these considerations including: the snow load, wind load, live load, and dead load of the roofing system.
3.2.2.1 Wind Load

The wind load was calculated as a gable roofed structure built at Clayton, NC. The structure was assumed to be located in open terrain with scattered obstructions less than 53 ft high. This allowed standardized loading charts and tables to be used to determine the wind load (Midwest Plan Service 1983).

The first step was to calculate the effective velocity pressure, $q$, in pounds per square foot (psf) as shown in figure 3-7. Calculating this pressure value requires the extreme wind velocity for the location, the combined exposure and gust ($K_zG$) factor, and the structural importance factor. The extreme wind velocity at 33 ft elevation for a 50-year recurrence interval was determined to be 80 mph for Clayton, NC. The combined exposure and gust ($K_zG$) factor was determined to be 1.14 for a 20 ft mid-roof height structure. An importance factor of 1.0 was used for agricultural structures. This resulted in a $q$ value of 18.678 psf. This effective velocity pressure is then converted to a design pressure normal to the roofing surface by multiplying by an appropriate pressure coefficient, $C_p$. The pressure coefficient is based on wind direction and roof configuration.

Two roofing configurations were analyzed to determine the worse case scenario: gable roof (Case I, II, and III) and umbrella gable roof (Case I and II). The gable roof scenarios represent how the structure will react to wind when the curtains are completely down. After calculating the gable roof loading data, ‘Case I’ had the highest downward pressure normal to the roof surface as shown in figure 3-8a. The resulting downward wind load for this situation was 3.74
pounds per square foot (psf). In all three gable roof cases, the roof uplift was of more concern because the maximum uplift was 13.1 psf. The umbrella gable roof scenarios represent how the structure will react to wind when the curtains are completely up or when the structure is unloaded. The highest overall downward and upward roof forces were calculated for this scenario. These scenarios are illustrated in figure 3-8b. When the structure is unloaded, the highest downward force of 11.2 psf was calculated. When the structure is loaded with burley tobacco, the highest upward force of 20.5 psf was calculated. All uplift forces aside, the highest downward force occurs when the structure is empty; therefore, the design wind load for the structure was 11.2 psf.

3.2.2.2 Snow Load

The snow load was calculated using a balanced roof loading on an unobstructed roof. A maximum ground snow load for Clayton, NC with a 50-year recurrence interval was assumed. According to the tabular values, Clayton, NC will see a maximum ground snow load of 10 psf. The roof snow load was calculated using several factors including: the relationship between roof snow and ground snow pack (roof snow factor), the structure’s exposure (exposure factor), the slope of the roof (slope factor), and the structural importance factor. The ground snow load was multiplied by all of these factors to convert it to a roof snow load as presented in figure 3-9. The roof snow factor was determined to be 1.0 since the ground snow pack was less than 15 psf. The exposure factor was determined to be 1.0 to cover cases where trees and other structures may prevent
the wind from blowing snow off the roof, thus reducing the snow load. The slope factor was determined to be 0.94 for a 4/12 slope roof. The structural importance factor was determined to be 1.0 for agricultural buildings that must be more reliable to protect crop loss due to collapse. Overall, the calculated snow load that was used in the design was 9.38 psf.

3.2.2.3 Dead Load

The roof dead load is simply the load placed on the structure by the weight of all the components that make up the roof system. This was determined by summing the weight of each component and dividing this weight over the horizontal projection area of the roofing system. The pressure value, psf, for each roof system component can be found in table 3-1. The total dead load for the roof system was 3.6 psf.

The rafter weight of 1.9 psf was based around a 2 by 8 inch, no. 2 southern yellow pine on two foot spacing. Fifty rafters were used with the end rafters consisting of two boards each. Every rafter was notched and attached to the headers with two toe-nailed 16 penny common wire nails and two engineered metal hurricane fasteners on each end. These hurricane fasteners help prevent failure in the case of excessive uplift wind loads. Rafters were reinforced with 2 by 4 inch dimensioned lumber nailed diagonally across the bottom of all the rafters as shown in figure 3-10. Collar beams consisting of 2 by 4 inch dimensioned lumber were nailed across every other rafter pair to provide further stiffing.
Two by four inch dimension lumber laid flat spaced 2 feet on-center was used for the purlins. Boards were cut so that purlin joints were staggered and four 10d ring-shank nails were used at each joint. In addition, two 10d ring-shank nails were used to hold purlins to each rafter. The 26 gauge roofing material was attached with 1-1/2 inch roofing screws in accordance with the manufacturer’s instructions.

3.2.2.4 Design Load

Upon determining the four general loading types that affect agricultural structures, the task was shifted to determining what the overall design load should be for the roofing system. This was best determined by comparing three different possible combinations of loads: dead load + snow load, dead load + wind load, and dead load + live load. Table 3-2 outlines these three loading combinations. A minimum live load of 13 psf is suggested, but a 20 psf live load is more common in many structures as well as many building codes. For most of North Carolina, this means that the live load takes design precedence over snow and wind loads; therefore, a design load of 24 psf was chosen. This was an iterative process because dead load is part of the design load. The design load affected the choice of roofing materials which in turn affected the dead load.

3.2.3 Columns

A total of 21 columns were used in the construction and design of the prototype structure. The center columns in a post-frame structure always see the
highest loading potential. The center columns in the prototype structure received loading from both the roof and the hanging burley tobacco crop. The column with the highest loading potential was difficult to determine. The center column located closest to the driveway and the interior center columns have the two highest loading potentials of all the columns. The center column closest to the driveway receives a roof tributary area of 120 sq ft and the equivalent weight of one wire-frame rack (four legs rest on this column). If one analyzes the loading on one of the interior center columns, any of these columns receive a roof tributary area of 72 sq ft and the equivalent weight of two wire-frame racks (eight legs rest on this column). The two types of columns were compared based on their differences. The center column closest to the driveway had a difference of 48 sq ft of roof tributary area and the interior center columns had a difference of a single wire-frame rack's weight. Assuming the maximum wire-frame rack weight of 2,000 lbs and a total design roof loading of 24 lbs/sq ft (dead load + live load for this case), the interior columns were determined to have a higher loading by approximately 850 lbs. These calculations account only for vertical loading and do not take into account any variations in rack weights resulting in off-center loading. The biggest dilemma in these calculations is that load duration is not taken into account. The roof loading tends to have a much longer load duration overall and the rack weight duration is no longer than the length of the crop curing season. This is one factor that the authors hope to investigate further utilizing this prototype structure.
3.2.3.1 Design Calculations

Once the two columns with the highest loading potential were identified, further calculations were used to size the columns necessary to support the structure. The 2001 edition of the National Design Specification for Wood Construction was used to size the columns. For simplicity, all of the columns in the structure were designed based upon the two columns identified earlier. Two steps were involved in the overall design verification process.

The first approach was to design based on a building with no crop loading. Pressure treated 6 by 6 no. 2 southern pine timbers were selected for the calculations. These timbers have a modulus of elasticity of 1,200,000 psi and a design stress in compression parallel to the grain of 525 psi. The center column located closest to the driveway had the highest amount of tributary roof area, so this column was chosen to verify the unloaded structure’s design. Using the roof design loading and the tributary roof area, a column load of 2880 pounds was calculated. The next step was determining the actual column stress parallel to the grain, $f_c$. This was calculated by simply dividing the column loading by the cross-sectional area of the column. For a 6 by 6 timber, the cross-sectional area is 5-1/2 inches squared or 30.25 square inches. The resulting actual column stress is 95.2 psi. For the design to be adequate, the calculated actual stress must not exceed the design stress. The design stress was simply the tabulated design stress for the 6 by 6 timber, 525 psi, multiplied by several design factors. These design factors included: load duration, wet service, temperature, size, incising, and column stability. For this particular case, temperature and wet service...
factors were equal to one because the columns were not exposed to harsh weather conditions. The incising factor was also one since the type of lumber used did not require incising. The size factor was already incorporated into the design value of 525 psi. The load duration factor was selected based on the design load which consisted of a dead load and a live load. According to the design specifications per the *National Design Specification for Wood Construction*, the shortest load duration is the ruling load duration; therefore, the load duration factor of one was chosen based on the live load. The column stability factor required further calculations.

The column stability factor takes into account both the critical buckling design values for compression members and the Euler buckling coefficient. The equation for the column stability factor ($C_p$) is:

$$C_p = \frac{1 + \left(\frac{F_{cE}}{F_c^*}\right)}{1.6} - \left[\frac{1 + \left(\frac{F_{cE}}{F_c^*}\right)}{1.6}\right]^2 - \left(\frac{F_{cE}}{F_c^*}\right)$$  \hspace{1cm} \text{Equation 3-1}

- $F_c^*$ adjusted tabular design stress parallel to the grain using other design factors, psi
- $F_{cE}$ critical buckling design value for compression members, psi

Equation 3-1 required that the critical buckling design value for compression members be calculated. This design value accounts for the tendency for long slender columns to fail due to buckling along the length of the column rather than simply exceeding stress values. The equation for the critical buckling design value used was

$$F_{cE} = \frac{K_{cE}^* E'}{(l_c / d)^2}$$  \hspace{1cm} \text{Equation 3-2}
As shown in equation 3-2, the critical buckling design value required the tabular design value for the modulus of elasticity. In this case, 6 by 6 inch timbers have a design modulus of elasticity of 1,200,000 psi and a square cross-section dimension of 5.5 inches. A Euler buckling coefficient of 0.3 was used because all the timbers were visually graded lumber. The effective length was calculated assuming an original length of 240 inches. The column interface with the header was assumed to be a pinned connection, while the interface with the ground was assumed to be a fixed connection (the columns were anchored in concrete in a 4 foot deep hole). These assumptions reduced the effective length to 168 inches. The resulting critical buckling design value was 386 psi. Substituting this into equation 3-1, the column stability factor was then calculated to be approximately 0.549. This reduces the overall design column stress parallel to the grain to 288 psi. Thus, the design column was oversized roughly by a factor of 3 when examining the building with no crop load.

If the ground-column interface was assumed to be a pinned connection, instead, there would be no difference between the actual length and the effective length. This alternative would have a critical buckling design value of only 189 psi and a column stability factor of roughly 0.327. The resulting column stress parallel to the grain would be a mere 172 psi. This worst-case scenario was still
oversized by a factor of 1.8. One can quickly see that the fixed connection is a critical piece in the design of post-frame structures. Much of the structure’s stability is based upon a proper column-ground interface.

With the first design approach satisfied, a second approach was taken to design the columns with a maximum crop load placed on the structure. The entire weight of the crop was placed directly on the columns through the “rackmounts” that were attached with lag screws. This load was estimated with a maximum load of 2,000 pounds per rack. An even loading within each rack was assumed with 500 pounds exerted on each of the rack’s legs. The center column closest to the driveway was selected as the column with the highest potential loading when a zero crop load was assumed, so this was the logical starting point for this approach. This particular column supported a total of four rack legs, one from each of four racks. This brings the total crop load for this column to 2,000 pounds or a single rack’s worth of weight. This weight was added to the design load calculated previously from the roof tributary area. The total column loading was now equal to 4,880 pounds. From this new loading, the new actual column stress parallel to the grain for this column was now 161 psi. This increase alone causes no reason for concern. If we assume the same design factors from the previous approach, a design column stress parallel to the grain of 288 psi would still be oversized by a factor of approximately 1.8. This assumption is very conservative because the load duration would change by incorporating the crop load. This change would in turn increase the design column stress parallel to the grain.
Even though the center column closest to the driveway was still able to handle the combined load of the crop and roof tributary area, this did not immediately mean that all of the columns were still over designed. The rest of the center columns supported a much smaller tributary area, but provided support for twice the number of wire-frame rack legs. Eight legs total were supported by each of the four interior columns in the center of the structure. This was equivalent to two full racks’ worth of weight or 4,000 pounds supported by each column. If we add the tributary roof loading to the crop weight, a grand total of 5,728 pounds were supported by each of these columns. The actual column stress parallel to the grain for one of these columns was equivalent to 189 psi. Even at this higher loading the design column stress parallel to the grain exceeds the actual column stress by a factor of 1.5.

Since the crop load was only present to stress the building for such a short time when compared to other loadings, the load duration design factor could be adjusted in this instance. The load duration factor is affected by the shortest load duration of any load combination. Using only a two-month load duration, the design loading can be multiplied by a factor of 1.15. With a seven-day load duration, the design loading can be multiplied by a factor of 1.25. The load duration factor then increases the overall design column stress. The problem with this line of thought is lack of information to determine the best load duration to use. A two-month load duration means that the full green leaf load of 2,000 pounds will remain on the building during the entire length of this time. Assuming such is impractical and at times very economically detrimental, but
necessary to assume worst-case design scenarios. One goal of this research was to provide insight into this area.

3.2.3.2 Construction

Two different sized posts were purchased for the construction phase of this research project: twenty foot long, 6 by 6 inch dimensioned, pressure treated posts for the outside columns and 24 foot long, 6 by 6 inch dimensioned, pressure treated posts for the center columns. These posts were buried four foot in the ground and placed on a one foot diameter by 1.5 inch thick footing. Holes were drilled perpendicular to the length of the post and re-bar was inserted in these holes at the bottom of each post before placing the posts on the concrete footing. Three cubic feet of concrete was poured around the post into a one foot diameter hole and the rest of the hole was back-filled with packed soil. Later, the 20 ft and 24 ft posts were notched and leveled to 15 feet and 19 feet above grade, respectively.

3.2.4 Headers

Headers were designed using no. 2, southern yellow pine. Each column was notched to allow the headers to rest on top as seen in figure 3-11. Each header was then bolted to the columns using four one-half inch carriage bolts at each column. Headers were sized in accordance with the 2001 edition of the National Design Specification for Wood Construction using the roof design load, individual tributary roof area, and column spacing.
3.2.4.1 Design Calculations

All of the headers were designed around two column spacings of six and fourteen feet. The majority of the designed crop holding area was designed around columns six foot on center. The three headers that span the driveway area were designed around a fourteen foot spacing. Each outer line of columns supported a quarter of the total roof tributary area, while the center line of columns supported half of the total roof tributary area. Using this information, four different size headers were designed to support the roof loading. These four header sizes included: 6-foot outer, 6-foot inner, 14-foot outer and 14-foot inner. Since the crop loading was placed completely on the columns, crop loading had no effect on header design.

The six foot column spacing headers were designed using the roof design load of 24 psf. The outer headers had a 6 by 6 foot roof tributary area. This resulted in 6 square feet of roof tributary area per linear foot of header. Multiplying this by the roof design load of 24 psf resulted in a distributed header loading of 144 pounds per linear foot or 12 pounds per linear inch. From this distributed load, the maximum moment can be found. The equation for the maximum moment \( M_{\text{max}} \) of a simply supported beam was

\[
M_{\text{max}} = \frac{\omega \cdot L^2}{8} \quad \text{Equation 3-3}
\]

\( \omega \) total distributed load, pounds/inch

\( L \) span length, inches
The maximum moment for the outer headers was 7,776 inch-pounds. A 2 by 10 inch, (nominal size) no. 2 southern pine board was chosen to begin the design calculations. This dimensioned lumber board has a modulus of elasticity of 1,600,00 psi and a design stress in bending of 1,050 psi. The next step required determining the actual header bending stress, $F_b$, for a 2 by 10 inch board. The actual header bending stress, $f_b$, was determined using the following equation

$$f_b = \frac{6 \times M_{\text{max}}}{b \times d^2}$$  \hspace{1cm} \text{Equation 3-4}

- $M_{\text{max}}$ maximum beam moment due to loading, inch-pounds
- $b$ beam breadth, inches
- $d$ beam depth, inches

The actual header bending stress was determined to be 364 psi. This number represents the amount of bending stress encountered by the beam due to roof design loading. The idea behind this calculation was to have a reference point to compare the theoretical bending stress to this value. This ensures that the actual bending stress does not exceed the theoretical bending stress.

The theoretical or design header bending stress, $F_b'$, was calculated by multiplying the design bending stress for the header, in this case 1,050 psi for a 2 by 10 inch board, by several design factors. These design factors included: wet service, temperature, size, load duration, incising, flat use, repetitive member, form, and beam stability. Both the wet service and temperature factors were equivalent to one since the headers will not be exposed to adverse weather conditions. The incising factor used was one because the headers were not
treated. The size factor was already incorporated into the tabular design values for dimensioned lumber narrower in width than a nominal twelve inches. The load duration factor in this design was easier to determine because, as was mentioned above, the crop load had no effect on the header design. The shortest load duration for the roof design load was a live load. This resulted in a load duration factor of one. The remaining four factors are all unique to bending design calculations. The flat use factor is required when load values are not placed parallel to the narrow face of the dimensioned lumber. This was not the case for this design, so a flat use factor of one was used. The repetitive member factor applies to members that are composed of at least three 2 to 4 inch thick pieces of dimensioned lumber. These members have to be in contact or spaced no further than 24 inches on centers and must be adjoined by a roof, floor, or some other load distributing element. This design factor did not apply since only a single board was used so a repetitive member factor of one was used. The form factor applies to round beams or square beams that are loaded in the plane of the diagonal forming a diamond cross-section. Since the load was applied along the narrow face, a form factor of one was used. The beam stability factor required further calculations.

The beam stability factor, \( C_L \), much like the column stability factor, takes into account the critical buckling design value for bending members and the tabulated design value for bending stress. The equation used for the beam stability factor is
\[
C_L = \frac{1 + \left( \frac{F_{bE}}{F_b^*} \right)}{1.9} \sqrt{\left[ 1 + \left( \frac{F_{bE}}{F_b^*} \right) \right]^2 - \left( \frac{F_{bE}}{F_b^*} \right) - 0.95} \quad \text{Equation 3-5}
\]

- \(F_b^*\) adjusted tabular design stress in bending using the other design factors, psi
- \(F_{bE}\) critical buckling design stress for bending members, psi

Equation 3-5 required the calculation of the critical buckling design value for bending members, \(F_{bE}\). The critical buckling design value for bending members represents the value for this particular beam at which failure would occur due to beam twist or roll. This factor becomes more important as simply supported beams increase in overall length. The equation used for the critical buckling design stress for bending members was

\[
F_{bE} = \frac{K_{bE} \cdot E'}{R_B^2} \quad \text{Equation 3-6}
\]

- \(K_{bE}\) Euler buckling coefficient for beams
- \(E'\) tabular design modulus of elasticity, psi
- \(R_B\) slenderness ratio of bending member

An Euler buckling coefficient for beams, \(K_{bE}\), of 0.439 was used because the header consisted of visually graded lumber. The slenderness ratio, \(R_B\), of the header was calculated using the following equation:

\[
R_B = \sqrt{\frac{\ell_e \cdot d}{b^2}} \quad \text{Equation 3-7}
\]

- \(\ell_e\) effective length, inches
- \(d\) beam depth, inches
- \(b\) beam breadth, inches

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Equation 3-7 requires that the beam’s effective length be calculated. The effective length was determined using the ratio between the original length and the depth of the beam. This ratio is important in cases where uniformly distributed loads are applied to simply supported beams. Two equations determine the effective length for this situation. The first equation requires that the ratio be less than seven. The second equation requires that the ratio be greater than or equal to seven. The dimensions calculated in this design resulted in a ratio of 7.78. Since this was greater than seven, the following equation was used to determine the effective length $\ell_e$:

$$\ell_e = 1.63\ell_u + 3d \quad \text{Equation 3-8}$$

$\ell_u$ original beam length, inches

$d$ beam depth, inches

The effective length, $\ell_e$, calculated from equation 3-8 was equal to 145 inches.

This effective length was substituted into equation 3-7 and a slenderness ratio, $R_b$, of 24.4 was calculated. This calculated slenderness ratio, $R_b$, was used to determine the critical buckling design stress, $F_{bE}$ in equation 3-6. The critical buckling design stress for a 2 by 10 inch (nominal size) number 2 southern pine beam is 1178 psi. The final variable remaining in equation 3-5 was the adjusted tabular design stress in bending for the beam, $F_b^*$, that incorporated all of the other eight design factors. In this particular case, all of the other design factors were determined to be equal to one. This resulted in an $F_b^*$ that is equal to the original tabular stress value for the beam, 1050 psi. For this beam, the critical
buckling design stress was higher than the adjusted tabular design stress for bending alone. This was due mainly to the short support span of the beam. A short beam would be more likely to fail due to shear or bending stress than a severe deflection or twist in the beam. This resulted in a beam stability factor, $C_L$, of 0.859. The final design header stress in bending, $F_b'$, was 902 psi. When comparing this to the actual header stress, $F_b$, this header was oversized by a factor of roughly 2.5.

These design values apply to both the six foot outer and six foot inner headers. The only difference between the two during the construction phase was that a single 2 by 10 header was placed on the two outer lines of columns while a 2 by 10 header was placed on each side of the inner line of columns. Rafters will rest and attach to one outer and one inner header. This ensures that only one quarter of the roof tributary area is supported by each of the four lines of 2 by 10 headers over the crop curing area.

The three headers with fourteen foot column spacings were designed in the same manner utilizing the 24 psf roof design load. The two outer fourteen foot headers each supported a 14 by 6 foot tributary roof area. This resulted in a similar 6 square feet of tributary area per linear foot of the header. Keeping the 24 psf roof design load in mind, this equated to a uniformly distributed load of 144 pounds per foot of header length or 12 pounds per inch of header length. Using this distributed load and equation 3-3, the maximum moment, $M_{\text{max}}$, applied to the fourteen foot outer beam was 42,336 inch-pounds. With a much larger maximum moment applied, a stiffer beam will be required. For the
fourteen foot outer header, three 2 by 10 boards were used in this calculation. The boards were assumed to be touching and laminated together with fasteners. This created a header with a depth and breath of 9.25 inches and 4.5 inches, respectively. Equation 3-4 was then used to determine the actual header bending stress, \( f_b \). The actual header bending stress for the laminated outer header was 660 psi.

The design header bending stress, \( F_{b'} \), was calculated in the same manner as before with the six foot column spacings. The first step in determining the design header bending stress was to determine the values of the nine design factors that adjust the tabular design values. All of the tabular design values for 2 by 10 inch number 2 southern pine lumber were still the same as with the previous calculations. The temperature, wet service, load duration, incising, flat use, and form factors were all the same as before. The size factor, as mentioned previously, is incorporated into the tabular values for components that are less than twelve inches. The repetitive member factor was the most noticeable change. Since the new header will consist of three members that touch, load-share, and will be uniformly loaded through the rafters, a repetitive member factor of 1.15 was used in the calculation of \( F_{b^*} \). This meant that the adjusted tabular design stress in bending, \( F_{b^*} \), used in equation 3-5 was now equal to 1,208 psi.

The next step required determining the effective length of the header. The ratio of original length to header depth was still greater than seven. This allowed the use of the same effective length equation 3-8. The new effective length was
302 inches. Using equation 3-7, the new slenderness ratio, $R_B$, was 11.7. This allowed the new critical buckling design stress for bending members, $F_{bE}$, to be calculated from equation 3-6. The only change to the inputs of this equation was the change in the slenderness ratio, $R_B$. The new critical buckling design stress for bending members, $F_{bE}$, was 5,096 psi. This value, once substituted into equation 3-5, resulted in a new beam stability factor, $C_L$, of 0.985. The new beam stability factor reduced the final design header bending stress to 1,190 psi. This resulted in a fourteen foot outer header that was oversized by a factor of 1.8.

The fourteen foot inner header could not simply be designed by doubling the outer header. This was true for several reasons. First of all, it would be both impractical and difficult to place six boards across the driveway. Secondly, due to the width of the beam required to support this area, the rafters from both sides of the structure will rest on a single beam. To resolve these problems, a third header beam was designed.

The fourteen foot inner header was again designed using the same method as the two previous headers. This header shared many of the same values as the fourteen foot outer header. The load duration, incising, wet service, temperature, size, flat use, form, and repetitive member factors were identical to the previous fourteen foot header. The adjusted tabular stress value, $F_{b*}$, remained identical as before at 1,208 psi. The roof tributary area supported by this header was 14 by 12 feet. This equated to 12 square feet per foot of header length. This distributed load was double that of the outer headers at 288 pounds per foot of header length or 24 pounds per inch of header length. Using equation 3-3, the maximum
moment, $M_{\text{max}}$, was determined to be 84,672 inch-pounds. This was substituted into equation 3-4 and the actual header bending stress, $F_b$, was calculated using four laminated 2 by 10 inch no. 2 southern pine boards. The result of this calculation was an actual header bending stress, $F_b$, of 990 psi.

The design header bending stress, $F'_b$, was calculated in the same manner as the previous fourteen foot header. The ratio of original length to beam depth did not change, so equation 3-8 still applied. Even though the effective length was the same as before, the slenderness ratio, $R_B$, was different due to the increased overall beam breadth of six inches. The new slenderness ratio, $R_B$, was 8.80. Substituting this number into equation 3-6, a new critical buckling design stress for bending members, $F_{bE}$, was calculated. The new critical buckling design stress was very large at 9070 psi. The beam stability factor was then determined by substituting this value and the adjusted tabular design value into equation 3-5. The new beam stability factor, $C_L$, was 0.992. This was even closer to one, denoting that this header was more stable against lateral buckling than the fourteen foot outer headers. Multiplying this final design factor by the adjusted tabular bending stress resulted in a design header stress, $F'_b$, of 1,199 psi. Comparing this value to the calculated actual header bending stress, the header was oversized by a factor of 1.2.

All four of the headers were designed to use similar components. Various quantities of 2 by 10 no. 2 southern pine lumber were required to meet design load requirements. The common use of 2 by 10 boards was selected based on the largest header. The fourteen foot inner header required four 2 by 10 boards and
was only oversized by a factor of 1.2. The fourteen foot outer headers required only three 2 by 10 boards and was oversized by a factor of 1.8. This was an acceptable oversize for both of the fourteen foot headers. The six foot headers were oversized by a factor of 2.5. While this was a safe design, the headers were oversized enough that a smaller header could have been used in its place. The larger boards increased the overall cost of the six foot headers. This was overlooked to increase the aesthetics of the building design and allow common building materials to be used for all of the headers.

3.2.4.2 Construction

Headers spanning the outer columns, spaced six feet apart, consisted of a single 2 by 10 inch dimension lumber as seen in figure 3-12. The headers spanning the six foot spaced, center columns consisted of a 2 by 10 dimensioned lumber board on each side of the column as seen in figure 3-13. The three headers over the driveway were significantly stiffer. The two outer driveway headers consisted of three laminated 2 by 10 dimension lumber boards. The center driveway header consisted of four laminated 2 by 10 inch dimensioned lumber boards. In addition to the header boards on the two outer lines of columns, a 3-1/2 by 3-1/2 by 3/8-inch steel angle was installed the length. This angle was bolted through the outer drive way headers with one-half inch carriage bolts. This angle was designed to be later used as a track for a hoist system. Two more lengths of angle were installed on the center posts, four feet from the top. All four lengths of angle were supported underneath by a length of 2 by 12 lumber.
scabbed onto the posts by a minimum of ten 16d nails at each post. All the angle and supports were not incorporated into the design calculations as load stiffening members. They were designed as an added safety factor for roof loading when the hoist was not in use and were meant to provide extra load support for a hoisting system only.

3.2.5 Walls

The gable end walls were designed to be fully sheeted with the same 26 gauge sheet metal as the roofing. The same 3 by 15 ft sections were used to cover the end-wall up to the gable as shown in figure 3-14. Sheets had to be trimmed to fit over the gable area. Trim pieces overlapped the roofing and end-wall sheet metal preventing water from entering the structure at this interface. Additional trim pieces covered the edges along the length of the outer columns. This covered the sheeting’s sharp edge acting as both a safety feature as well as providing some styling.

The structural underlayment consisted of 2 by 4 inch dimension lumber laid flat in horizontal girts on a two foot spacing as shown in figure 3-15. This was reinforced by 2 by 4 inch dimension lumber boards nailed diagonally across the horizontal girts as shown in figure 3-16. Each girt was additionally attached to each column using engineered hurricane brackets to prevent uplift.

The longitudinal walls were left open with provisions for curtain installation during the curing season. Due to the narrow column spacing this wall required little reinforcement beyond the support provided by the roofing
system. Figure 3-17 exhibits how boards were cut and nailed diagonally to the outside of the six columns on each of the two longitudinal walls leaving the driveway unobstructed. One by four inch boards were used to reinforce these longitudinal walls.

3.3 EXPERIMENTAL METHOD

Upon completion of the prototype structure, the authors wanted to collect design data parameters affected by the cut-notch harvested burley tobacco. The largest design parameter that affected the structural design was the crop load duration. The effective weight placed by the crop on the structure over the length of the curing season effects the overall load duration factor. In wood design, this can translate into a significant change in the sizing of load supporting structures. The authors wanted to collect field data during a single curing season utilizing the prototype curing structure to analyze the weight of cut-notch harvested plants on wire-frame racks. The decision was made to use load cells to weigh two of the wire-frame racks and record this weight over the length of the curing season.

3.3.1 Experimental Design

Load cells were incorporated into the four legs of the two wire-frame racks. This was accomplished by cutting a notch out of the end of each leg as shown in figure 3-18. A hole was drilled in the top of this notch to allow a bolt to attach the load cell and a metal spacer to the wire-frame rack's leg. A welded metal bracket was bolted through the wood to stiffen the wire-frame rack's leg.
where the notch was cut. This allowed the rack to sit on the same “rackmount” as the other wire-frame racks in the structure. Figure 3-19 is an actual photograph of two legs from different racks sitting on the “rackmount”. In this case, the photograph was taken facing one of the center columns. A “rackmount” on either side of the column provides a place for legs from two wire-frame racks, resulting in a total of four legs resting on the column on this tier. Four load cells were used on each wire-frame rack. One of the racks utilized 1,000 lb load cells (1-K) for a total of 4,000 lbs at full load and the other rack held 2,000 lb load cells (2-K) for a total of 8,000 lbs at full load. This difference in the type of load cells used was due to availability, but gave the research the ability to compare load cells with different weight ranges. Both load cells incorporated a Wheatstone bridge that had a 3 mV output per volt of bridge excitation at full weight load. The excitation voltage was provided by a laptop computer through a National Instruments load cell board. This board handled signal conditioning and provided an internal signal gain of 10. An additional signal gain of 10 was provided by the National Instruments data acquisition card bringing the total gain for the system to 100.

Using two different ranged load cells brought many questions. The biggest challenge was the difference in resolution. Both load cells incorporated internal Wheatstone bridges that used a transfer function of three millivolt per volt of bridge excitation. The laptop with the attached board was able to produce an onboard excitation value of 2.5 volts. This meant that when 2,000 pounds of weight for the 2-K load cells or 1,000 pounds of weight for the 1-K load cells was applied a total of 7.5 millivolts would measured across the output wires of both
types of load cells. For the 1-K load cell this meant that every pound of weight was equal to 7.5 microvolts. The 2-K load cells equated to only 3.75 microvolts per pound of weight. This resulted in a resolution difference of two. To overcome this problem, a signal gain of 100 was introduced by the load cell board and data acquisition card. This increased the measured signal values for the 1-K and 2-K load cells to 0.7 millivolts and 0.375 millivolts, respectively. This was a much more measurable signal, but one can quickly see that the 1-K load cells required a much lower resolution analog to digital converter than the 2-K load cells. Assuming resolution to the closest pound of weight was required; the 1-K load cells only required that the signal be measured to the ten thousandth of a volt while the 2-K load cell required the signal be measured to one millionth of a volt. This meant that a device that is able to measure the 2-K load cell signal to a specified resolution will be capable of measuring the 1-K load cell signal with double the resolution. In the case of this research, the 2-K load cells were measured with a resolution of one pound and the 1-K load cells were measured with a resolution of one-half pound.

The load cell equipped wire-frame racks were both placed on the lower tier of the structure. The racks were placed in the middle of the room (third wire-frame rack out of five), but each was placed in a different room. One wire-frame rack was placed in the room exposed to the open, northern side of the structure and the second wire-frame rack was placed in the room exposed to the open, southern side of the structure. This placement allowed the authors to observe
any differences that may present themselves due to differences in northern and southern exposure.

Nine tenths of an acre of burley tobacco was planted at the Central Crop Research Station in Clayton, NC. This burley tobacco was harvested and placed in the prototype structure to cure on August 15, 2007. The burley tobacco was harvested by hand as shown in figure 3-20 and piled on a trailer in the field. The loaded trailer was pulled into the driveway area as shown in figure 3-21. Each stalk was notched using a stationary notcher mounted in the driveway area of the structure. Wire-Frame racks were hand-set into the structure and workers stood on the lower tier of racks to hang the plants on the upper tier. Racks furthest from the driveway were filled first on each tier. The entire structure was filled in this manner as shown in figure 3-22. Curtains were added to the sides open to the north and south approximately one week after harvest. The first week, without curtains to restrict airflow, permitted adequate wilting to help prevent barn rot.

3.3.2 Data Acquisition

Signals generated by the eight wire-frame rack load cells were processed by a data acquisition card in the laptop computer. A custom Labview® (National Instruments, Austin, TX) program was used to access the eight signals and convert them to weight data. The Labview® program was able to sample the signal at 10 hertz and determine the voltage for a one second interval. This voltage was converted into a corresponding weight for each load cell and
recorded to a file. Every 60 seconds these weight data were averaged and the corresponding average weight over a minute was written to another file. This small time interval was chosen since the laptop used for storage placed little restriction on file size and higher resolution could be obtained. Data were collected over a six week period from the date of harvest. An algorithm was developed to filter the collected data into larger time intervals. This algorithm was written to parse a comma delimited text file containing the individual raw weight data for each load cell, sort these data according to the desired time interval, and build a new comma delimited text file with the modified data.

3.3.3 Data Manipulation

Short data collection intervals allowed for a very high resolution during the curing period. This high resolution created thousands of data points. The process of analyzing the collected data became more rigorous due to the vast number of points describing the time period. To overcome this problem, the data were manipulated by an algorithm that logically reduced the number of data points while still maintaining the overall dataset’s integrity. Basically, this algorithm was able to reduce the resolution of the dataset by a desired amount (by a factor of 5 in this case). Data was then analyzed using this new lower resolution dataset. The lower resolution dataset allowed for a more general overview of the characteristics by plotting this set versus time. Specific areas of interest could then be identified along the timeline. These areas along the
timeline were noted and then new datasets could be generated from these areas using the original, high resolution dataset.

The algorithm used to generate the lower resolution datasets was written using the PHP: Hypertext Preprocessor scripting language. This language was chosen due to its abilities to parse text files easily, its availability, and the lack of the need to compile when used on a PHP enabled server. The script was able to open a comma delimited text file named “barndata.csv” for reading and another text file named “barndata_chop.csv” for writing. The first line in the original text file was read by the script and then parsed according to the corresponding label for each value in the line. This method was successful because all of the weight data for a specific point in time along the dataset was located in one line of the comma delimited text file. Each of these parsed values was associated with a variable in the script. All of the variables for a particular time period were arranged in an array or list. A detailed description of these variables can be found within the script comments in the appendix of this paper. A desired time period of five minutes was selected for this particular example. To sort these newly stored variables, a simple modulus was required. The variable representing the time in minutes, “$tm” was subjected to the modulus function, fmod(). This function divides the value of the subjected variable by a desired number, in this case five for a five minute time period, and returns the remainder of this operation. This remainder was then stored as the variable “$r”. If the remainder was determined to be equal to zero, then the value of the time variable, “$tm”, was divisible by the desired time period (5 minutes). If this
condition was met, the script then wrote to the new comma delimited text file, “barndata_chop.csv”, a single line containing the parsed data currently stored in the array. The original comma delimited text file, “barndata.csv” was then indexed by a single line. The process repeated starting with parsing this new line into the array while overwriting the old values for each variable. This process continued until the “end of file” was reached. At this point, the word “done” was echoed to the screen and the two open comma delimited text files were then closed by the script. The result upon executing this script was the creation of a new comma delimited text file that contained only the desired resolution time period data. This script was written to allow it to be executed on a web server with the proper permissions or through the command line. The desired time period for the new dataset could be easily changed by editing the value of “$desiredtm” near the beginning of the script.
Figure 3-1  Four legged wire-frame rack loaded with burley tobacco

Figure 3-2  Modified wire-frame rack design
Figure 3-3 Modified wire-frame rack storage

Figure 3-4 Structure design isometric
Figure 3-5 Structure floorplan

Figure 3-6 Rackmount isometric

Beveled Guides for Easier Rack Placement
\[ q = 0.00256 \times V^2 \times K_zG \times I^2 \]

Q = effective velocity pressure, psf
V = Wind velocity for extreme winds @ 33’ elevation, mph
\( K_zG \) = Combined exposure and gust factors
I = Structural importance factor

Figure 3-7  Effective wind velocity pressure calculation

Gable Roof

Case I & II

\[ A = (0.7) \times (18.7 \text{psf}) = 13.1 \text{psf} \]
\[ B = (0.2) \times (18.7 \text{psf}) = 3.74 \text{psf} \]
\[ C = (0.5) \times (18.7 \text{psf}) = 9.34 \text{psf} \]

Figure 3-8a  Wind load diagrams for gable roof scenario
Umbrella Gable Roof

Case I
A

→ Wind

Case II
B

→ Wind

Crop

A = (0.6)*(18.7psf) = 11.2psf
B = (1.0)*(18.7psf) = 18.7psf
C = (1.1)*(18.7psf) = 20.5psf

Figure 3-8b  Wind load diagrams for umbrella gable roof scenario

\[ P_s = R * C_e * I * C_s * P_g \]

\( P_s \) = Roof snow load
\( R \) = Roof snow factor
\( C_e \) = Exposure factor
\( I \) = Structural importance factor
\( C_s \) = Slope factor
\( P_g \) = Ground snow load

Figure 3-9  Effective roof snow load calculation
Figure 3-10  Rafter reinforcement

Figure 3-11  Column notching to accept headers
Figure 3-12 Outer six foot span headers

Figure 3-13 Inner six foot span headers
Figure 3-14 Gable end wall front

Figure 3-15 Gable end wall girts
Figure 3-16  Gable end wall reinforcement

Figure 3-17  Open longitudinal wall
Figure 3-18  Wire-Frame rack modification for load cells

Figure 3-19 Wire-Frame rack with load cells on rackmounts
Figure 3-20  Hand cutting of tobacco before placing on a trailer

Figure 3-21  Loaded trailer in the structure’s driveway
Figure 3-22  Hand notching and hanging of the tobacco in the structure
Table 3-1  Dead load components for the roofing system

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roofing</td>
<td>26ga Metal</td>
<td>1 psf</td>
</tr>
<tr>
<td>Purlins</td>
<td>2x4 in boards 2 ft o.c.</td>
<td>0.7 psf</td>
</tr>
<tr>
<td>Rafters</td>
<td>2x8 in boards 2 ft o.c.</td>
<td>1.9 psf</td>
</tr>
</tbody>
</table>

Table 3-2  Design load for the roofing system

<table>
<thead>
<tr>
<th>Combination</th>
<th>Addition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load + Snow Load</td>
<td>3.6 psf</td>
<td>13.0 psf</td>
</tr>
<tr>
<td>Dead Load + Wind Load</td>
<td>3.6 psf + 11.2 psf</td>
<td>14.8 psf</td>
</tr>
<tr>
<td>Dead Load + Live Load</td>
<td>3.6 psf + 20.0 psf</td>
<td>23.6 psf</td>
</tr>
</tbody>
</table>
4. RESULTS

Data were collected for the prototype curing structure during the 2007 curing season at the Central Crops Research Station in Clayton, NC. Nine tenths of an acre of burley tobacco was harvested and placed in the prototype structure on August 15th. Two forms of data were collected during the cure: visual curing data in the form of photographs, direct observations and quantitative structural loading data in the form of wire-frame rack weight.

4.1 Visual Curing Stage Identification

Throughout the curing process, visual changes to the crop were noted each visit and pictures were taken to document many of the major changes. The harvested tobacco made many color changes on its way to a desirable cured color. This process occurred gradually across the stalk. Older, more mature leaves provided the first signs of a new color while younger, less mature leaves closer to the top of the stalk soon followed suit. Examining each leaf individually, the leaf lamina was the first area to show change. Figure 4-1 is an example of leaf lamina changing colors. In this picture the lamina is changing from a yellow color to a more desirable red-brown. The leaf stems tended to change color only after the entire leaf lamina color changed. Using this visual information, three distinct curing stages were identified for the crop in the prototype curing structure: the green stage, the yellow stage, and the brown stage.

The initial color stage identified was the green stage. This stage persisted from the time of harvest to approximately one week elapsed (five to seven days). The
stage was represented by a majority of green or light green leaf lamina along most of the stalk as seen in figure 4-2. Some yellow and brown were present on the edges of the more mature leaves. Overall the leaves lost most of their bulk and turgor by the end of this stage. For this particular season, the upper stalk leaves remained this lighter green color for well beyond the first week of curing. Even so, the majority of the leaves lost most of their chlorophyll during the first five to seven days.

The second color stage identified was the yellow stage. The yellow stage had the longest duration of approximately two weeks. During this period, the majority of leaves were of a yellow color with some browning of the edges of the leaf lamina as shown in figure 4-3. The lower stalk leaves began to darken and brown. This was especially true for those that were overly ripe when harvested. Yellowing of the individual leaves began at the tip and progressed toward the petiole. The stalks remained a pale green color throughout this stage of the curing process. By the end of the stage, even the tips of the stalks, previously green, had shifted to a yellow color. There were a few places where green could be found in the tips even after the completion of this stage. This coloration was due to immature leaf harvest and occurred most commonly in plants that had unregulated secondary leaf ('sucker') growth.

The final color stage identified was the brown stage. This stage marked the fourth and final week of the cure. During this stage of curing, the leaf lamina across the entire stalk shifted to a tan or reddish brown color as shown in figure 4-4. The resulting color depends on the curing season and the maturity of the leaves at harvest. It was during this stage that the amount of moisture within the leaf
structure was most noticeable. Leaves checked midday were noticeably brittle compared to ones checked early in the morning or late in the evening. This was a direct result of the increased effect of the diurnal fluctuation of humidity on the final stages of curing. Spatial effects on leaf moisture were highest during this stage of curing. Stalks located near the edges and along the driveway of the structure tended to vary in moisture more so than those located in the interior.

4.2 Wire-Frame Rack Load Duration

Quantitative structural loading data were collected from harvest until stalks were removed from the structure for market preparation. The structural loading data were documented through the collection of individual wire-frame rack weights for two of the twenty wire-frame racks. Data were collected over an extended time period of roughly 90 days post harvest. This point was the time at which the tobacco was removed from the structure, ensuring that any significant changes in weight would be captured by the dataset.

Upon examining the collected data, a period of roughly 38 days was selected. This time period captured the entire 28 day curing process as well as a ten day post-curing weight collection period. This time period was also selected because by the end of the time range over 50 percent of the original rack weight was lost and the weight loss rate was approaching zero. The weight data were collected for two wire-frame racks with one utilizing 2,000 lb load cells (2-K) and the other utilizing 1,000 lb load cells (1-K). The summation of all four load cells on each rack was plotted verses time elapsed in figure 4-5. The weight data collected for the two wire-frame
racks followed very similar curves. Both curves were downward sloping reaching a similar asymptotic weight of approximately 350 lbs. This curve suggested that the data followed a simple first order differential for decay and was more specifically an exponential decay solution to this differential equation. This solution was confirmed by inputting the data for the selected period into SAS - Statistical Analysis Software® (Cary, NC). Table 4-1 contains the output using the built-in regression analysis to find a log-linear regression of the dataset. Figure 4-6 presents the specific solutions for the 2-K and 1-K data sets that were calculated using this information noting an R-squared value of 0.93 and 0.95, respectively.

Closer inspection of the data highlighted noticeable changes in the general slope trend of the curve. These changes in the instantaneous slope occurred at points along the timeline corresponding to one, three, and four weeks of elapsed curing time. These changes happened to mark the same period of changes noted for the visual curing stages. Figure 4-7 presents the collected quantitative loading data overlaid with the visual curing stages observed previously. The initial green stage sector of data tended to follow a diurnal fluctuation in weight with a steeper loss of weight during the day than the gain in the evening. This local mannerism of the data made a noticeable change around day 5 to 7 upon entering the yellow stage. The diurnal fluctuation remained, but the rate at which weight was lost was not as great as before. Following the same pattern as before, the local mannerism of the data changed around day 19 to 21 upon entering the brown stage. It was at this point the diurnal fluctuations in weight could be readily distinguished since the local increase
and decrease in weight neared equilibrium. After the end of the brown stage (day 28), the rate of weight loss leveled out to around 350 pounds.

Taking this thought one step further, the data were separated into the three visual curing stages to allow a multi-linear regression analysis. This analysis allowed the authors to examine the estimated linear rate of weight loss for each curing stage and compare rate changes between individual stages. Figure 4-8 presents this multi-linear regression approach utilizing four curing stages: green, yellow, brown, and cured. One can see that the calculated rate of weight loss was highest during the green stage and lowest during the cured stage. As the leaf progressed from one stage to the next chronologically, the rate of weight loss was reduced by approximately a factor of two. This reduction was evident at the green/yellow transition and the yellow/brown transition. The brown/cured transition reduced the rate by a factor of approximately five, but little can be said with certainty due to the low r-squared value for the cured stage. This local change in rate supports the previous assumption that the entire dataset can be described using a first order decay differential equation.
Figure 4-1  Leaf lamina color change

Figure 4-2  Green curing stage
Figure 4-3  Yellow curing stage

Figure 4-4  Brown curing stage
Figure 4-5  Overview of weight loading
General First Order Differential

\[ \frac{dy}{dt} = -0.021y \]

2-K Specific Solution

\[ y(t) = 669.412 * e^{-0.021t} \]

1-K Specific Solution

\[ y(t) = 682.607 * e^{-0.021t} \]

Figure 4-6  Decay differential equation and solutions
Figure 4-7  Overlay of the visual curing stages
Figure 4-8  Breakdown of loading data by visual curing stage
Table 4-1 Linear regression data for the load cell racks

<table>
<thead>
<tr>
<th></th>
<th>2-K</th>
<th>1-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.934</td>
<td>0.952</td>
</tr>
<tr>
<td>Intercept</td>
<td>6.51</td>
<td>6.53</td>
</tr>
<tr>
<td>Slope</td>
<td>-0.021</td>
<td>-0.021</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

This research focused on developing a prototype curing structure for burley tobacco and utilizing this structure to gain insight on crop-specific structural loads. Several research goals were identified and discussed in previous sections. These goals were incorporated into the design objectives. These objectives included: utilizing wire-frame racks, arranging these wire-frame racks into multiple tiers at a central location, and isolating individual wire-frame racks for study. A small prototype structure was then designed and constructed at the Central Crops Research Station in Clayton, NC. The structure was utilized in the cure of burley tobacco during the 2007 season. The structure consisted of a two tier, post-frame design and held twenty wire-frame racks. Racks rested directly on the structural columns to remove any obstruction when lifting or lowering the wire-frame racks into place.

The aim for this design was that it would remain simple enough that it could be easily constructed by a grower with a minimal amount of previous carpentry skills and that most of the components could be produced from locally produced lumber. The construction of this building was completed using no. 2 southern pine dimension lumber and simple fasteners. All cuts, notches, and joints remained simple enough that a semi-skilled carpenter could produce a similar structure successfully. The no. 2 southern pine dimension lumber was chosen because local species of pines harvested for lumber would have a similar structural strength. The difference being that locally produced lumber would be “rough cut” so that thicknesses and widths may vary from one board to the next. The biggest structural
concern with “rough cut” lumber occurs when the lumber tends to err on the thin size. Foreseeing this, the design was conceived with “rough cut” lumber in mind. Beams and columns were oversized enough to allow fluctuations in the actual size of the boards and timbers used in their construction. The overall design was devoid of any critical joints or sections where variations in lumber sizes would further complicate the construction process.

Crop-specific structural loading was measured using load cells mounted on two specially designed wire-frame racks. Individual weight data was collected during the entire curing process. This weight data was plotted versus time. The resulting curve was determined to be a simple first order differential equation for decay. This decay equation expresses many natural phenomenons such as cooling and moisture loss. Moisture loss of the curing tobacco plant was concluded to have the most significant impact on the overall wire-frame rack weight change.

Visual data collected proved to describe color stages during the cure. Green, yellow, and brown color stages were used to divide the collected rack weight data into separate datasets. These datasets were determined to have different weight loss rates that decreased by a factor of two between chronological adjacent stages. Each color stage dataset contained noticeable fluctuations in weight that followed diurnal patterns in humidity change. This diurnal effect was more significant in the latter curing stages. The effective weight loss for the green stage was 25 percent of the initial weight. An additional 25 percent was lost during the yellow stage, while only roughly 6 percent was lost during the brown stage.
Beyond the structural design, the focus of this research was to draw insight on the crop-specific loading of the structure. Actual loading numbers for burley tobacco were collected for the 2007 season, but little can be drawn in respect to guidelines predicting crop load. One season and curing location provides little confidence to any prediction algorithm. This research provided a single season’s worth of data. A more long term data collection of multiple seasons will be required to increase confidence. Even though crop load guidelines cannot be drawn from this data, conclusions can be drawn about crop-specific structural load durations.

Structural design and more specifically wood design are heavily influenced by loading factors. Structural load duration affects the required size of components necessary to handle a specific load under a specific time period. Some building components such as wood can handle a higher load for a short duration. Smaller, cheaper components can then be used where load durations are short. As mentioned earlier, better than half of the rack weight was lost during the first month of the cure and more specifically a quarter of the rack weight was lost in the first week of the cure. This sudden loss suggests that the load duration is very short when compared to other loads on the building. After a complete cure, the total crop load is removed to prepare the crop for market. This total crop duration depends on individual grower practices. Typically, no more than six months elapse between harvest and the last market day for the season. According to the research, a structure should see 100 percent of the load directly at harvest and that will be reduced to 75 percent after one week. After three weeks, only 50 percent of the load is seen by the structure. From one month elapsed until crop removal, less than 50 percent of the initial load
is seen by the structure. Structures designed to hold stalk-cut burley tobacco can be built much more economically when keeping this relationship in mind.

There are various possibilities for future work in structures for curing stalk-cut burley tobacco on wire-frame racks. This system provides an excellent base for further development in mechanizing the placement of harvested stalks and racks into the structure. The structure has adequate attic space for installing a hoisting system for lifting the racks into place. Metal track provisions were installed during initial building construction to allow for future mechanization efforts. Further collection of similar time elapsed weight data for comparison would help confirm the conclusions drawn from this research and help define crop-specific structural loading guidelines. Time studies could be conducted to explore labor savings over other competing systems. Lastly, the economic feasibility of such a curing system for use by growers should be further explored.
6. Literature Cited


7.1 Weight Data Manipulation Code

```php
<?php
/* **********
* Barn Data Sorter
* barndatadivide5.php
* JMLong
* 110107
**********/

/VARIABLE DESCRIPTIONS
$tm = time (minutes)
$lc2k1 = value of load cell #1 on the 2K load cell rack (lbs)
$lc2k2 = value of load cell #2 on the 2K load cell rack (lbs)
$lc2k3 = value of load cell #3 on the 2K load cell rack (lbs)
$lc2k4 = value of load cell #4 on the 2K load cell rack (lbs)
$lc2ksum = sum of all the load cells on the 2K load cell rack (lbs)
$lc1k1 = value of load cell #1 on the 1K load cell rack (lbs)
$lc1k2 = value of load cell #2 on the 1K load cell rack (lbs)
$lc1k3 = value of load cell #3 on the 1K load cell rack (lbs)
$lc1k4 = value of load cell #4 on the 1K load cell rack (lbs)
$lc1ksum = sum of all the load cells on the 1K load cell rack (lbs)
**********/

//Common Variables
$delimiter = ","; //denotes the text file delimiter, usually a comma
$endofline = "\n"; //denotes "end of line", varies with program that wrote the text file
$desiredtm = 5; //denotes the desired new time period for data

//opens the text file for read only
$handle = fopen('barndata.csv', 'r');
//exits upon 'file not found error'
if (!$handle) {echo 'ERROR: Unable to open file.'; exit;}

//opens a file for writing
$fhandle = fopen('barndata_chop.csv', 'w');

//loop to execute until the end of the original file has been reached
while (!feof($handle)) {
    $line = fgets($handle); //Grabs a line of the original file
```
// Splits this line up using the $delimiter character into individual variables
list ($tm, $lc2k1, $lc2k2, $lc2k3, $lc2k4, $lc2ksum, $lc1k1, $lc1k2, $lc1k3,
$lc1k4, $lc1ksum) = split ($delimiter, $line);

// Returns the modulus of the Time($tm) with 5 minutes
$r = fmod($tm, $desiredtm);

// Writes all lines divisible by 5 minutes to the file
if ($r == 0) {
    fwrite($fhandle, $tm);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc2k1);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc2k2);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc2k3);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc2k4);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc2ksum);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc1k1);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc1k2);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc1k3);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc1k4);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $lc1ksum);
    fwrite($fhandle, $delimiter);
    fwrite($fhandle, $endofline);
}
$handle++; // indexes the original file pointer
}

echo 'done'; // indicates on screen completion

// closes the text files
fclose($handle);
fclose($fhandle);