Analysis of Anchors and Bracing Configurations with Personal Fall Arrest Systems in Residential Construction

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Abstract

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Falls continue to be a major problem in the residential construction industry and account for a large number of injuries and fatalities each year (US Department of Labor, 2012). The effects of a fall are catastrophic to the workers and their families as well as the construction company and surrounding community. Prevention of these incidents has been the primary focus of organizations such as the Occupational Safety and Health Administration (OSHA). To reduce the number of falls on residential construction sites, OSHA has put forth several standards that require the use of fall protection. Although guidelines have been provided, there have been concerns and complaints regarding the standards as well as methods and materials that should be used.

The goal of this research was to measure the behavior of a five truss roof system with various anchor points and bracing configurations loaded by a horizontal force. A lab built roof system was used to test three different anchor types with three forms of temporary bracing. The materials and methodology used in this testing were based on common materials and practices currently used in the residential construction industry.

The results of this research show that anchors must engage multiple trusses to spread the applied load throughout the roof system. Several forms of temporary bracing such as lateral, diagonal, and sway bracing, are also required to strengthen the roof system allowing it to withstand an applied load.

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1.0 Introduction and Literature Review

1.1 Background

Accidents leading to injuries and fatalities are very common in the construction industry. The cause of injury or fatality can occur from a variety of sources including vehicle collision, electrical shock, use of power tools, falls, etc. (OSHA, 1990). Among these sources of injuries, falls continue to plague the construction industry even with increasing safety regulations and interventions. Falls from height continue to be one of the leading causes of death in the construction industry (Ellis, 2012). Falling from a higher level poses a large concern due to the distance traveled and force of impact withstood. Recent statistics show the severity of fatalities and how they continue to be a problem for workers engaged in construction. The Bureau of Labor Statistics 2011 preliminary results reported that 666 workplace fatalities, out of a total of 4,609, are the result of falls (US Department of Labor, 2012). Figure 1-1 illustrates how the total workplace fatalities in 2011 compare to recent years.

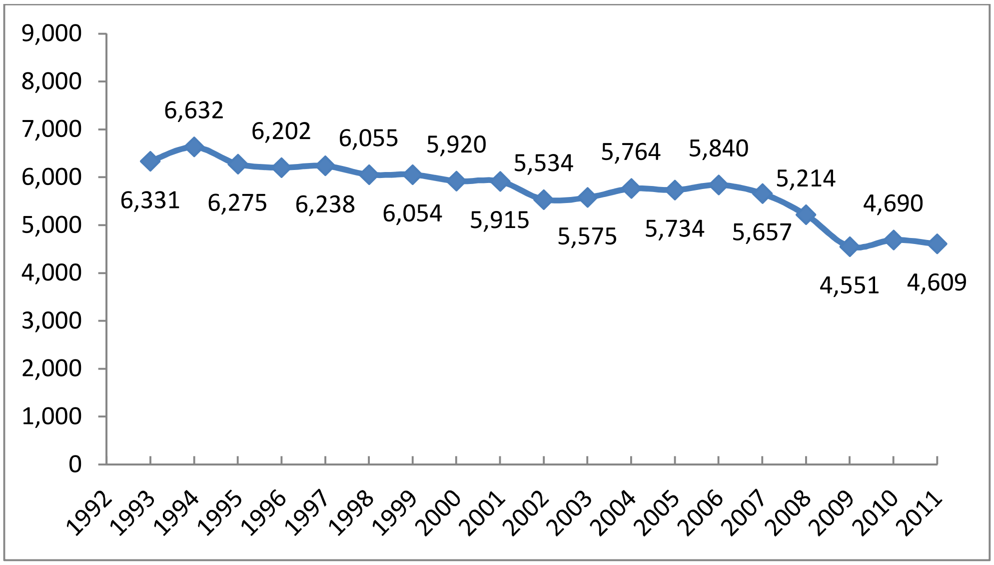

Figure 1-1: BLS data on fatal work injuries from 1993 – 2011

The BLS statistics show that of the 4,609 fatalities in all industries, 14% were direct result of a fall (US Department of Labor, 2012). Of the 666 fatalities from falls, 541 were categorized as falls to a lower level, also referred to as a fall from height (US Department of Labor, 2012). Falls to a lower level are particularly a problem in the construction industry due to the work that involves heights without defined boundaries for preventing falls. In 2008, 43% of the total fatalities in residential construction were the result of a fall to a lower level (US Department of Labor, 2008). These falls are from many different surfaces making it difficult to isolate areas for increased safety regulation and research. In residential construction, in particular, falls from height can occur from a ladder, scaffolding, staging, upper floor, stairs, roof, or even on ground level. Each of these surfaces presents unique threats that pose significant problems to workers and their safety. The workers involved in construction practices on each of these surfaces are at high risk for all types of falls (Lipscomb et al., 2003). Therefore, additional research is required to provide usable means of fall protection for each construction task.

Use of the occupational fall protection set forth by OSHA has indeed lowered the number of injuries and fatalities in the construction industry. Fatal work injuries in the construction industry declined from a total 774 in 2010 to 721 in 2011, a decline of 7% which is the fifth year in a row of lower fatal injuries (US Department of Labor, 2012). Fatal construction injuries are down nearly 42 percent since 2006 however some of this is believed to be due to the economic recession and crash of the housing market in the U.S. (Ellis, 2011). While statistics show that overall there are fewer fatal construction injuries each year, falls from height continue to be a major problem. Figure 1-2 from the (US Department of Labor, 2011) preliminary data shows that in 2011, falls to a lower level accounted for 541 fatal work injuries as stated before. Of those cases, where height was known, 57 percent involved falls of 20 feet or less (US Department of Labor, 2011).

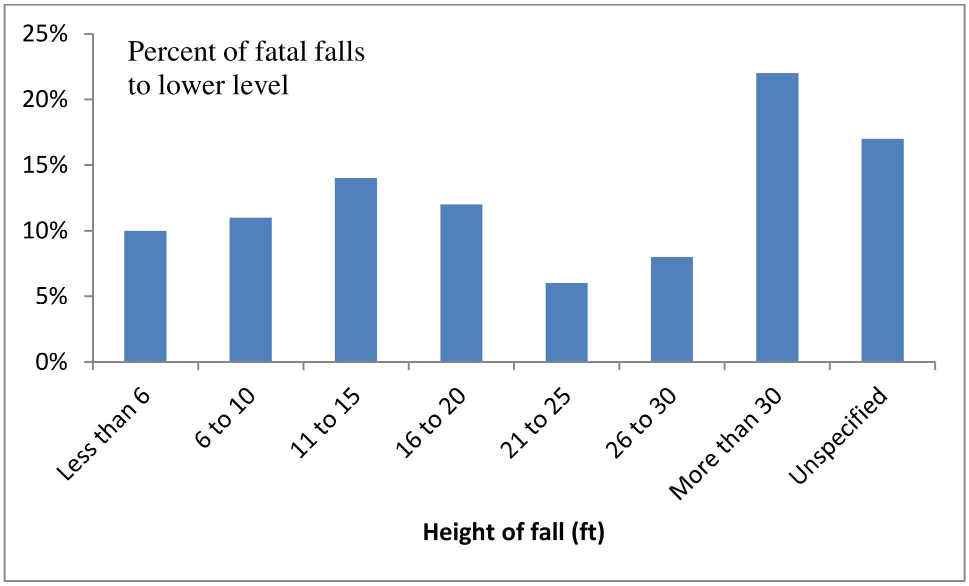

Figure 1-2: Fatal falls to a lower level by height of the fall (BLS, 2012)

The year-end data for 2011 shows a total of 25% at 10 ft. or less (US Department of Labor, 2011). This data illustrates that the danger of falls is present at any height. Therefore, proper fall protection must be enforced and utilized throughout the construction industry to minimize the number of injuries and fatalities caused by falls. Work at all heights should be an area for improved fall protection planning and regulation.

1.2 Residential Construction

Residential Construction is a unique form of building which has a distinctive set of characteristics different from other types of construction. OSHA defines residential construction in directive STD 03-00-001 stating, “An employer is engaged in residential construction where the working environment, materials, methods and procedures are essentially the same as those used in building a typical single-family home or townhouse” (OSHA, 2011a). The same directive goes on to state, “To fall within the definition of residential construction, the building in question must be constructed using traditional wood frame construction materials and methods”(OSHA, 2011a). Traditional materials and methods refer to the use of dimension lumber, oriented strand board, engineered lumber, etc. These materials are often lighter and weaker than the steel used in commercial construction and the heavier lumber used in construction. Because of the use of lighter materials in residential construction, there are fewer locations that can support an anchor for fall protection during construction. These unique building materials and methods of residential construction make it difficult to fabricate guardrails, anchor points, able to withstand the force of a worker falling.

Several studies analyzed occupational injuries and safety compliance in residential construction. In the midst of other injuries, falls continue to be an area of major interest due to the severity of the injuries and difficulty in prevention. Kaskutas et al., (2009) performed audits at 197 unionized, residential worksites over a 1-year period to analyze fall hazard control in residential construction. During the audits, workers were observed to determine if required safety criteria were being met, specifically fall prevention. Overall, on the 197 residential worksites audited, only 60% of safety criteria required was met. Worker age, company size, and lack of training provided were all considered reasons for the unsafe practices taking place. Among all tasks performed, workers had the most difficulty complying with safety standards while they were setting trusses with only 28% of the required safety criteria met. OSHA residential guidelines for truss installation were rarely used during the auditing in the study (Kaskutas et al., 2009). Other domains such as floor openings, ladders, scaffolding, and roof sheathing also showed safety criteria completion of 43%, 67%, 76%, and 81% respectively. In each of these scenarios, there was more compliance to safety guidelines than scenario when trusses were set.

Studies such as Kaskutas et al., (2009), show that injuries in residential construction are difficult to prevent. Rapid changes in the work environment make safety compliance difficult and are often the reason for safety ignorance. Additionally, work crews are smaller and more dispersed than larger commercial projects (Lipscomb et al., 2003), making observation and regulation by safety coordinators, supervisors, and OSHA difficult. Work on residential construction sites often shows that fall protection equipment is infeasible. Workers engaged in residential construction are often younger, have less work experience, and are commonly immigrants (Salminen, 1994). Therefore, the lack safety training, language training, and basic experience with common construction practices often leads to injuries (Kaskutas et al., 2009). Kaskutas et al.,(2009) states in their concluding remarks, “We saw many opportunities to decrease fall risks and improve worker behavior through use of fall arrest equipment and building technologies, training to increase worker awareness of fall risks, contractor required practices to address these risks, and enforcement of existing company safety policies and federal guidelines”. Areas for improvement such as these are common and a small step in each direction could significantly reduce the number of falls in residential construction.

1.3 Regulations and Standards

In an effort to reduce the injuries and fatalities resulting from falls, industrial safety standards have been written to provide guidelines for fall protection. These industrial safety standards give important information regarding fall protection as well as a basis for enforcement. The Occupational Safety and Health Administration (OSHA), and the American National Standards Institute (ANSI) attempt to prevent injuries through the establishment and enforcement of safety standards. OSHA is the organization given responsibility for the general industry and construction industry as well as shipbuilding, and long shoring industries (Ellis, 2011). Using the General Duty Clause, OSHA is allowed to reference established nationally-recognized consensus standards, such as those written by ANSI, if a regulation to address the problem at hand is not available (Ellis 2011).

Over the past twenty years, OSHA along with other standards organizations has set forth several regulations requiring the use of personal fall protection. OSHA proposed a change to Subparts D and I of their General Requirements in 1990 and 2010 regarding personal protective equipment (Ellis, 2011). "On December 16th 2010, OSHA issued STD 03-11-002, *Compliance Guidelines for Residential Construction*, which rescinded STD 03-00-001, *Interim Fall Protection Compliance Guidelines for Residential Construction*" (OSHA, 2011a). STD 03-00-001 was put into place in 1995 and allowed residential workers to bypass fall protection requirements (Miller, 2013). STD 03-11-002 removed these exemptions requiring residential construction to follow the same compliance guidelines as commercial construction.

On March, 15 2013, the STD 03-11-002 guidelines were implemented for all residential construction, including conventional (stick-frame), post-frame and precast concrete (Miller, 2013). From December, 2010 to March, 2013 there was confusion in the residential construction industry regarding compliant fall protection products and practices. The industry went from being unregulated to highly regulated which posed a concern among the workers, contractors, safety personnel, etc. During this period OSHA did not give out citations for disregarding and not conforming to the new standard. This grace period allowed OSHA to provide guidance to the industry as well as answer questions and concerns regarding the amendments. However, as of March 15, 2013, OSHA will be giving citations to contractors in the residential construction industry if they are not complying with STD 03-11-002. Among other standards in the new compliance document, OSHA 29 CFR 1926.501(b)(13) states that, "Each worker engaged in residential construction activities 6 feet (1.8 m) or more above lower levels shall be protected by guardrail systems, safety net system, or personal fall arrest system unless another provision in paragraph (b) of this section provides for an alternative fall protection measure. Exception: When the employer can demonstrate that it is infeasible or creates a greater hazard to use these systems, the employer shall develop and implement a fall protection plan which meets the requirements of paragraph (k) of 1926.502" (OSHA 2011b).

1.4 Occupational Fall Protection

Fall protection can be defined as a backup system designed to prevent a fall from any height while providing a safe means to retrieve the worker (Ellis, 2011). OSHA defines three specific types of fall protection in standard 29 CFR 1926.501(b)(1) as guardrail systems, safety nets, and personal fall protection (OSHA 2011b). Passive fall protection is any fall protection where the worker is not attached to the structure or wearing fall protection equipment (Hindman and Koch, 2012). Both safety nets and guardrails systems are classified as passive fall arrest systems. Active fall protection requires workers to wear a harness and attach to the structure, such as a personal fall arrest system.

Guardrail systems, safety net systems, and personal fall arrest systems are all considered to be occupational fall protection. Guardrail systems are often utilized along building edges and around hazardous openings more than 6ft above the lower level. ANSI Z359.0 defines a guardrail as "a passive system of horizontal rails and vertical posts that prevents a person from reaching a fall edge" (ANSI, 2007). Figure 1-3 is taken from the OSHA Guidance Document on

Fall Protection in Residential Construction (OSHA, 2010). OSHA gives standards for guardrail systems in OSHA 29 CFR 1926.501(b) (OSHA, 2011b).

Figure 1-3: Worker utilizing a guardrail system while working on a roof (OSHA, 2010)

Figure 1-3 is a photograph of a worker on a roof using a guardrail system however there is nothing preventing a fall off of the gable end of the structure. Guardrails are the most common form of fall protection throughout the construction industry (Ellis, 2011). However, in many situations such as Figure 1-3, personal fall arrest systems may still be required for the erection of the guardrails around edges and/or openings allowing a fall of 6ft or more. The construction of a full guardrail system can require a lot of time compared to the time needed to complete roof construction. Time is of the essence in the construction industry and directly corresponds with overall profit. Therefore, workers may avoid the erection of a guardrail system and initially follow the guidelines for a personal fall arrest systems.

Another form of fall protection is required as the worker is constructing a leading edge 6 ft. or more above lower levels per OSHA's requirements in 29 CFR 1926.501(b) (OSHA, 2011b). The worker needs to use a personal fall arrest system or other form of fall protection in this situation due to this requirement. If all forms of fall protection are declared infeasible or create a greater hazard to implement, the employer may create a written fall protection plan that meets all of the requirements of 29 CFR 1926.502(k) (OSHA, 2011c).

Along with personal fall arrest systems and guardrails, safety nets are mentioned as a feasible means of fall protection. Safety nets have been used throughout the general industry to prevent contact with lower surfaces in the instance of a fall. Nets have a valuable safety role and are a popular form of fall protection in the general industry (Ellis, 2011). Figure 1-4, from the OSHA Guidance Document on Fall Protection in Residential Construction, is a photograph of a safety net being used during the erection of a residential structure (OSHA, 2010).

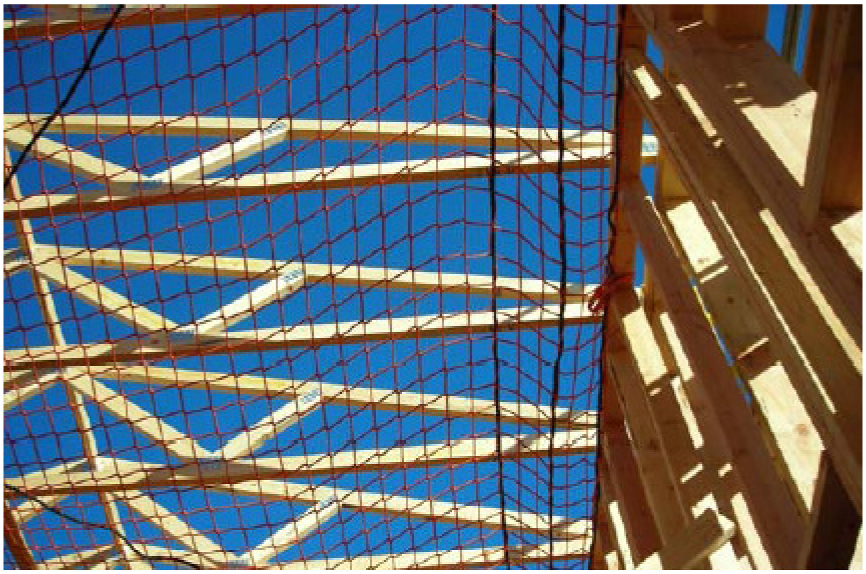

Figure 1-4: Safety nets preventing a fall to the lower level (OSHA, 2010)

Netting can be used for passive fall protection and the collection of debris from work completed above. Safety nets can be a useful means of fall protection; however, there are many factors that hinder use in residential construction. Much like guardrails and other forms of passive fall protection, a second fall protection system must be used in unison with the nets unless there is complete coverage of the area inside and outside the structure. Therefore the net is not considered the primary means of fall protection and is used as more of a backup to a primary system.

Setup of the safety nets is often a cumbersome project and takes a great deal of time. Nets require constant inspection and must be re-tensioned on a frequent basis. A unique feature of residential construction that hinders the use of a safety net is the rapid turnover rate of building tasks. Safety nets must be moved constantly to keep up with the progress of the workers. Additionally, the safety nets make work on the lower levels very challenging and could cause a delay in tasks on the respective level. Because of these factors, safety nets are not a common form of fall protection in the residential construction industry, mainly serving as a backup to an active fall protection system.

1.5 Personal Fall Arrest Systems

Active fall protection refers to a system that prevents a person from contacting a lower surface once a fall has taken place (Ellis, 2011). A popular form of active fall protection in the construction industry is the personal fall arrest system (PFAS). The PFAS is used to arrest a worker in the case of a fall from any working level. The PFAS consists of an anchor, connectors, body harness, and may include a lanyard, deceleration device, lifeline, or suitable combination of these (OSHA, 2011d). The PFAS is preferred in many situations where passive fall protection systems are not feasible. Figure 1-5 is a photograph from the OSHA Guidance Document on Fall Protection in Residential Construction (OSHA, 2010) and illustrates a worker using a PFAS where passive fall protection, such as guardrails and safety nets, is not feasible.

Figure 1-5: Residential construction worker using a PFAS (OSHA, 2010)

While fall arrest systems can be more time and cost efficient than other fall protection systems, there are concerns such as proper design of anchors, ensuring that workers can be arrested before striking the next surface, and the interaction of multiple workers and equipment on the same surface (Hindman and Koch, 2012).

The occupational safety and health association has several requirements for personal fall arrest systems listed in 29 CFR 1926.502(d) (OSHA, 2011c). These requirements include anchor points, lanyards, lifelines, and harnesses. The requirements are put into place to ensure that workers are properly inspecting and using the PFAS components per manufacturer's instructions. In the midst of the material requirements, strength requirements are given for each element of the PFAS including harness, anchor, lifeline, D-rings, lanyards, snap hooks, and many more components. These requirements are critical to the performance of the system as a whole.

In addition to the fall protection requirements set forth by OSHA, proper bracing of the roof system is strongly encouraged. Among bracing types, there are several forms of temporary bracing that are recommended by the Structural Building Components Association, SBCA. The SBCA is an organization with a goal to promote the safe, economic, and structurally sound use of structural building components (SBCA, 2012). The SBCA's *Guide to Good Practice for Handling, Installing, Restraining, and Bracing of Metal Plate Connected Wood Trusses* states that "webs that require continuous lateral restraint must also be diagonally braced for rigidity" (SBCA, 2012). Lateral restraint bracing or sheathing must be installed during truss erection to properly brace the trusses. Diagonal bracing should be installed along the same web member planes that require continuous lateral restraint. Diagonal bracing should be attached starting with the first 5 trusses (SBCA, 2012). The purpose of temporary bracing is to brace the trusses to prevent them from falling over or collapsing. This information was utilized and continuous lateral restraint as well as diagonal bracing was included in the research per BCSI instructions.

1.6 Anchor Points

Among all of the components of the personal fall arrest system, the anchor and anchor point have been heavily targeted due to their variable connections and strength capacities. In commercial construction, anchor points have not been of concern due to the stronger materials and structures for the anchors to be attached to relative to the loads generated by a falling worker. A worker tied-off to a large steel beam has little concern about failure of the steel beam as a result of a fall. However, light frame construction, such as the post-frame and residential industries, use much different materials and provides fewer places to safely anchor a PFAS to. After OSHA's final amendment requiring fall protection in the light frame construction industries, many workers have had difficulty finding surfaces and members that would withstand the load in the case of a fall if attached to. The entire system is compromised if the anchor point cannot hold the worker in the event of a fall. This problem has been not been addressed and many organizations have requested more information on proper anchor points throughout each phase of the construction process (OSHA, 2011a). Organizations such as the National Association of Home Builders have come forth and claimed that OSHA's compliance guidelines are insufficient for the industry and have requested revisions providing more information (OSHA, 2011a). Due to this confusion throughout the industry, research is needed to identify and analyze possible anchor points for a PFAS.

Many anchors marketed for residential construction, have been introduced since OSHA's amendment requiring fall protection. These anchors come in a variety of different forms and can be attached to multiple surfaces and members. Some anchors are designed to be used temporarily and must be removed after the task has been completed. Permanent anchors are available as well and can be left in place for future use. Other than temporary and permanent anchors, roofing anchors are often categorized by themselves due to their unique properties and attachment methods.

Roofing anchors are a highly critical area of research because of the work at height creating a higher risk of falling while performing a roofing task. Roofing anchors are often designed to be attached to the truss system either directly, or through layers of roofing materials such as shingles, tarpaper, and sheathing. Figure 1-6 shows an anchor attached to a single wooden truss.

Figure 1-6: Anchor attached to a single truss

The Occupational Safety and Health Association specifies the requirements for fall protection systems in OSHA 29 CFR 1926.502(d)(15) stating:

> *1926.502(d)(15) Anchorages used for attachment of personal fall arrest equipment shall be independent of any anchorage being used to support or suspend platforms and capable of supporting at least 5,000 lbs. (22.2 kN) per employee attached, or shall be designed, installed, and used as follows:*
>
> *1926.502(d)(15)(i) as part of a complete personal fall arrest system which maintains a safety factor of at least two; and*
>
> *1926.502(d)(15)(ii) under the supervision of a qualified person.*

The safety factor of at least two refers to the maximum arresting force of an worker with a full body harness, which is 1,800 lbs. according to OSHA CFR 1926.502(d)(16)(ii) (OSHA, 2011c). As a result, 3,600 lbs. is the required strength of the engineered anchor point as opposed to 5,000 lbs. This is a standard that is also approved by the current ANSI fall protection code (Ellis, 2011). A complete personal fall arrest system is simply that in which an engineer or qualified person approves of. Therefore anchor point engineering can utilize the 2:1 safety factor to provide a reliable anchor point in situations where 5,000 lbs. may not be reached (Ellis, 2011).

In addition to the 2:1 safety factor, OSHA CFR 1926.502(d)(12) states that, "self-retracting lifelines and lanyards which automatically limit free fall distance to 2 feet or less shall be capable of sustaining a minimum tensile load of 3,000 pounds applied to the device with the lifeline or lanyard in the fully extended position" (OSHA, 2011c). This further reduces the strength requirement for an anchor point if a self-retracting lanyard is used. Self-retracting lanyards are a device that allows a worker to pull the line out of a "drum" as they proceed further away from the anchor point. In the case of a fall, the self-retracting lanyards have a centrifugal breaking or locking mechanism that slows the worker for a controlled descent (Ellis, 2011).

1.7 Previous Research

Previous research on personal fall arrest system anchors was performed by Hindman and Koch, (2012). The testing was used to determine if fall arrest anchors attached to roof trusses could be used to carry the load in the case of a fall. Single, mono-slope trusses of 3:12 and 6:12 slopes were tested with a post-frame construction anchor attached at both the peak and eave of the trusses. Each test was loaded at a displacement rate of 1 inch/min to prevent sudden failure. The trusses were each attached to two stem walls with truss bracing enhancer connections, which had a much higher strength than conventional hurricane straps.

The ultimate load of various tests at the peak and eave of the trusses is shown in Table 1-1. Ultimate loads for this research were low due to the design of the anchor/truss connection and the lack of stability in the truss. Failure in each test was attributed to the truss-wall connections due to the rotation of the truss and anchor attachment. Results from this research recommend that a personal fall arrest system should never be anchored to a single, un-braced truss due to the large moment and concentrated load placed at the anchorage point. This testing illustrates the need to examine multiple braced truss assemblies to increase the loads carried by the anchor.

Table 1-1: Ultimate load results of single mono-slope truss testing (Hindman & Koch, 2012)

Slope	Location of Anchor	Ultimate Load (lbs.)
3:12	Peak	125
	Eave	417
6:12	Peak	78
	Eave	375

The post frame anchor performed well in the previous testing by Hindman and Koch, (2012) and was not damaged after being used for multiple tests. The anchor was never the source of failure in previous testing and each test demonstrated failure in the truss and truss connectors in which the anchor was fastened to. Fall arrest systems are commonly used in post frame construction and anchors such as this one are popular due to their rigidity and ease of use once fastened to a truss. The anchor will be considered the “control” sample of the experiment considering the previous data acquired and based on the fact that its response to mechanical testing is known.

Injuries and fatalities resulting from falls plague the construction industry and will continue to do so if compliant fall protection methods and materials are not brought forth. Personal fall arrest systems are a popular form of fall protection and have the potential to reduce the number of incidents that result from falls. Further research must be performed in order to find feasible anchor points for personal fall arrest systems in residential construction.

1.8 Goal and Objectives

The goal of this research was to measure the behavior of a five truss roof system with various anchor points and bracing configurations loaded by a horizontal force. Two objectives were required to achieve this goal:

1) Examine the behavior of wood truss, residential bracing methods on the strength of 5-truss assemblies.
2) Examine the behavior of wood truss, residential and post frame anchors on the strength of 5-truss assemblies.

1.9 Significance

Injuries and fatalities in the construction industry occur every day, falls are a major source. Regardless of the information put forth by OSHA, confusion and lack of reliable information are hindering safety measures in residential construction. There is a need for technical information related to the strength of wood truss assemblies. Research is needed on the anchor points and bracing methods when erecting a roof system to provide the industry with a better understanding of anchoring a personal fall arrest system to a roof system.

Fulfillment of the objectives of this research will provide data to benefit construction industry. Workers, safety coordinators, superintendents, and others will have the information on the use of anchors and bracing methods to influence the design of their complete fall arrest systems.

2.0 Methods and Materials

2.1 Introduction

This chapter discusses the materials and methods used for testing the PFAS anchors. The testing methods and equipment are based on previous testing performed to analyze fall arrest anchors connected to trusses (Hindman and Koch, 2012). The anchors used in this study were recommended based on previous research experience, the compliance guidelines set forth by the Occupational Safety and Health Administration (OSHA, 2010), and current practices in the residential construction industry. Three different anchors were tested with three different bracing configurations to measure anchor point strength for use with a personal fall arrest system. The testing procedure was designed to load the roof system and anchor in the weakest plane, perpendicular to the alignment of the trusses. This loading was determined to be the weakest plane of the roof system, since the load tends to fold the trusses over, similar to environmental loads discussed by (Bohnhoff, 2011). The test procedure and loading direction were designed to replicate a worker falling over the gable end of the roof which would load the trusses along the weak axis in a horizontal direction.

2.2 Materials

This section describes the materials used to perform this research. Each of the methods and materials described were chosen to represent typical construction practices. The anchor types tested are known to have been successfully used in at least one construction industry such as post frame, commercial, residential, etc. All three bracing materials and methods are in accordance with the Structural Building Component Association (SBCA, 2012). The bracing materials and methods are known and utilized throughout the residential construction industry.

2.2.1 Roof Trusses

The trusses used for this study were selected based on the common dimensions and roof pitches in residential construction as well as the minimum size required for the test setup to resemble a typical roof system. As opposed to commercial construction, residential roofs are characteristically steep-sloped. According to OSHA construction regulations 29 CFR 1926.501(b)(11), each worker on a steep-slope roof (greater than 4:12 pitch) must use fall protection (Ellis, 2011). On residential-type roofs with slopes of 4:12 or less, a safety monitor alone may be used as long as the ground to eave height does not exceed 25 feet and is considered unprotected, leading edge work (Ellis, 2011). A 4:12 roof pitch was chosen for the research based on these details and the design of the test setup. Roof trusses were manufactured from southern pine #2 2x4 dimension lumber and the webbing and truss plates designed based on manufacturer's software. Figure 2-1 is a diagram of the trusses used for the study.

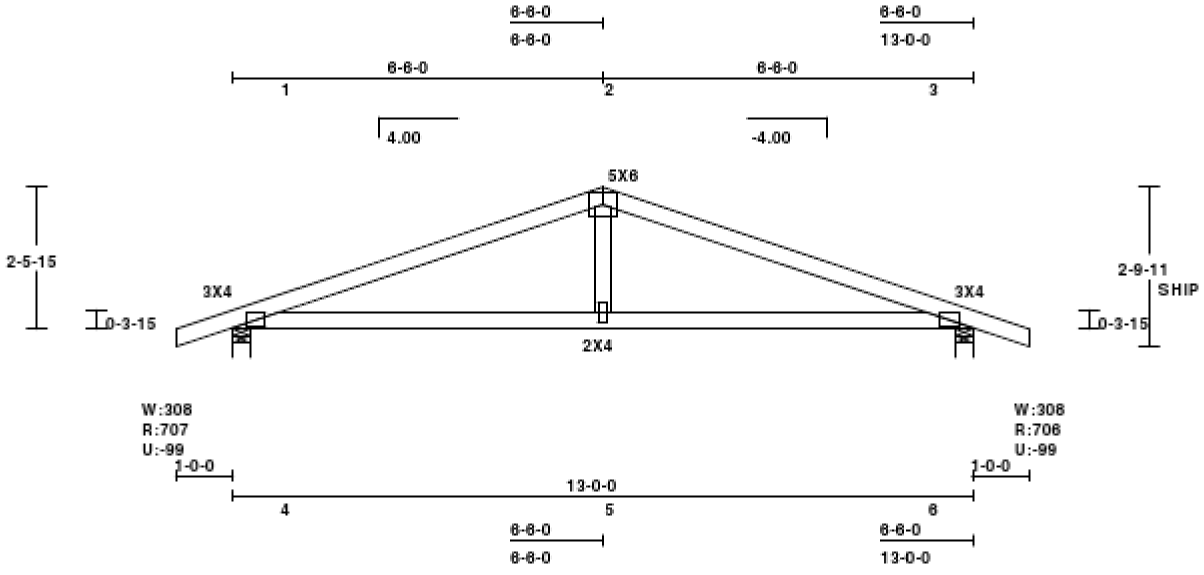

Figure 2-1: King post roof truss specifications

2.2.2 Bracing

Three different types of top chord bracing were compared in this study. All bracing materials and methods were in accordance with the SBCA's *Guide to Good Practice for Handling, Installing, Restraining, and Bracing of Metal Plate Connected Wood Trusses* (SBCA, 2012). This manual illustrates the proper temporary bracing for conventional truss systems and is often delivered with truss packages, including the trusses used for this research.

The first method was to fasten wood bracing to the inside of the top chords of the trusses (Figure 2-3). The wooden braces were all cut to a length of 22 1/2" and nailed into the trusses with 2 16d sinker nails at each truss. The length of the braces allowed for them to fit in-between the trusses while maintaining a truss spacing of 24" on center. Braces were placed approximately 2 feet up from the eave of the trusses as well as 2 feet down from the peaks. Bracing placed at the peaks of the trusses was placed on the side opposite of the anchor.

The second method was to fasten wood bracing to the top of the top chords of the trusses (Figure 2-2). The wooden braces were all cut to an approximate length of 25 ½ inches and nailed into the two trusses with 2 16d sinker nails at each truss. The length of the brace allowed for it to span to the outer edge of both trusses providing an overlap with the adjacent brace. The next brace was lapped above or below depending on placement. Braces were placed approximately 2 feet up from the eave of the trusses as well as 2 feet down from the peaks. Bracing placed at the peaks of the trusses was placed on the side opposite of the anchor.

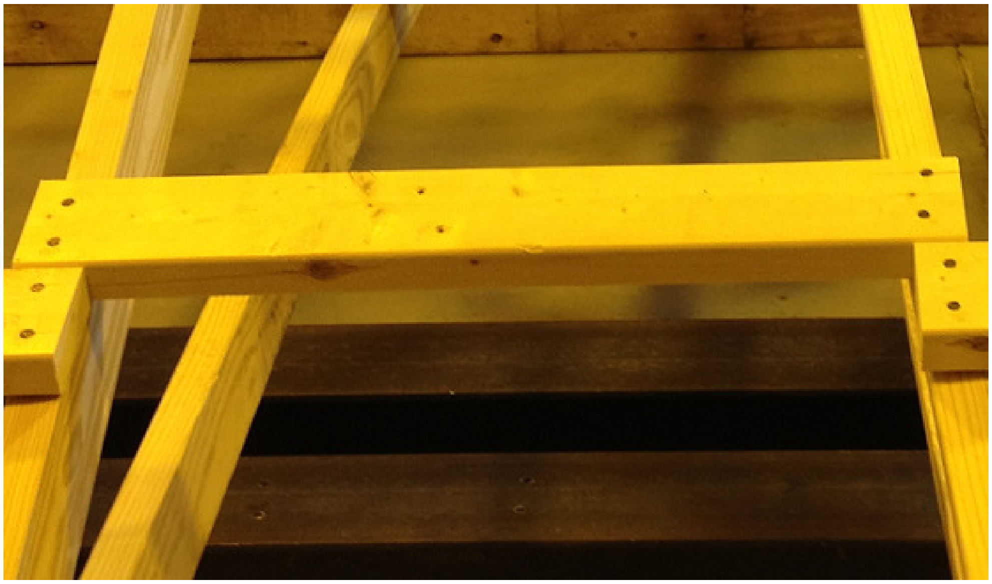

Figure 2-2: Wood bracing installed on-top of trusses

Figure 2-3: Wood bracing installed in-between trusses

The third bracing method utilized an engineered steel brace. The product chosen for engineered steel bracing is the MiTek STABILIZER® (Figure 2-4). The MiTek STABILIZER® is formed from 20 gauge galvanized steel with a yield strength of 40ksi (Mitek, 2013). This particular bracing method is advertised to locate the trusses at the correct spacing while providing temporary and permanent bracing. The MiTek STABILIZER® is designed without nails to make the bracing process easier and eliminate problems that can occur from hand nailing or gun nailing. The metal prongs are approximately ¼ inch long and are hammered into both top and side of the truss top chords. Installation is much faster due to this simplified connection. This metal restraint was chosen as a comparison to temporary wood bracing.

Figure 2-4: Engineered steel bracing installed in-between the trusses

In accordance to the SBCA's *Guide to Good Practice for Handling, Installing, Restraining, and Bracing of Metal Plate Connected Wood Trusses* diagonal bracing should be used with top chord bracing (SBCA, 2012). All three of the top chord lateral bracing methods were braced diagonally by one 2x4 extending from peak to eave on either side of the truss assembly (Figure 2-5). 2 16D nails attach the diagonal bracing to each of the 5 trusses in the assembly.

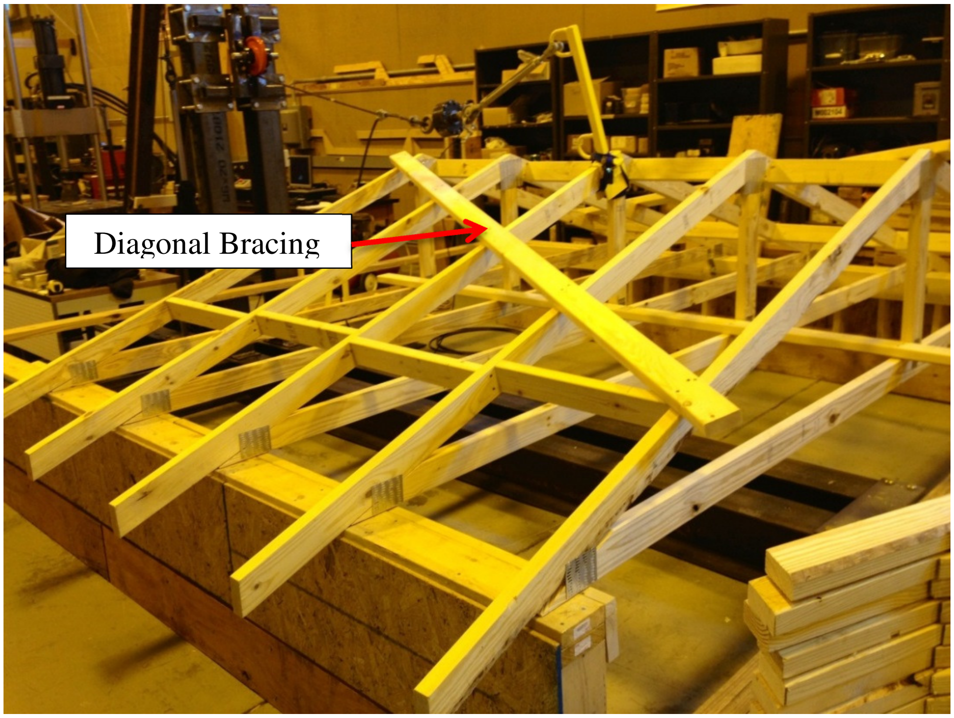

Figure 2-5: Diagonal bracing configuration on an in-between braced truss assembly

Following the application of diagonal bracing, it is suggested by the SBCA to install lateral restraints on the bottom chord of the trusses. Lateral bracing was also attached the bottom of the trusses much like the lateral restraint on the top chords (Figure 2-6). The lateral bracing of the bottom chord was a 10 foot long 2x4 attached with 2 16D sinker nails at each truss in the assembly (Figure 2-6)

Figure 2-6: Bottom chord bracing configuration

2.2.3 Anchors

Many anchors have been introduced to the market for use in each field of construction. Anchors tend to be more of a necessity in industries that construct light frame structures as compared to other structures which have tie-off points throughout the building. Light frame construction requires safe, strong anchors for a fall arrest system to be used. Wide varieties of these anchors have met a 5,000 lb. capacity and have been referenced by OSHA in their compliance guidelines. For this study, three anchors were chosen based on their popularity and design.

2.2.3.1 Post Frame Construction Anchor

The post frame construction anchor (Figure 2-7) was chosen for this project based on previous research performed to analyze a fall arrest system from post frame construction

(Hindman and Koch, 2012). The anchor was specifically designed so that it could be attached to the top chords of post frame roof trusses (2x6 to 2x10) to provide an uninterrupted tie-off point during construction. It is fastened to the truss with two 16d sinker nails located on the top of the anchor. In addition to the nails, it is recommended that a nylon strap be wrapped around the anchor-base to provide additional support and strength.

The location of the anchor was chosen based on previous testing (Hindman and Koch, 2012), strength predictions and usability of the PFAS that would be attached to the anchor. Anchor points should be located above the workers head to eliminate slack in the lifeline which may lead to additional free fall or swinging (Ellis, 2011). Anchors work the best when positioned 7 to 7 ¼ ft. above the worker (Ellis, 2011). Therefore the anchor was placed at the peak of the middle truss in the five truss system.

Figure 2-7: Post frame construction anchor

2.2.3.2 Cross Arm Strap

Figure 2-8 is a photograph of a cross arm strap used for this study. This strap is a typical, heavy duty strap that meets all OSHA requirements and is used throughout every phase of construction. Straps are commonly used as anchors due to high strength, low cost, versatility, and ease of use. Straps are often preferred over other anchors which can be cumbersome and difficult to use considering the fast turnover rate of typical construction tasks. The strap, model number 8185K/6FTBK, was manufactured by Miller Fall Protection for use when tying off to structural members. The strap was 6 ft. long, 2 in. wide and made of Kevlar webbing with a D-ring at one end and a choke off loop at the other end. The strap is rated to carry 5,000 lbs. and should be attached to overhead beams and structural members (Miller, 2013).

Figure 2-8: Cross-arm strap

2.2.3.3 Spreader Bar

A spreader bar is the only anchor type that OSHA specifies to be used with no sheathing on the roof, therefore the only anchor specified by OSHA for use during truss erection, is the spreader bar (OSHA, 2011a). This anchor allows workers to use a fall arrest system while erecting trusses as well as for subsequent roof construction. Workers can remain attached to the spreader bar during all roof tasks and do not have to move the anchor point to another location. Figure 2-9 is a photograph of the spreader bar.

The spreader bar, model number SAS-1010, is manufactured by Big Rock Supply. A cold rolled steel section of 48” spans over three trusses or rafters spaced at 24” on center. This spreader bar applied load over a larger area if a fall were to occur. Detent ball lock pins 3/8” diameter are used to attach the legs of the spreader bar to the top chords of the 2x4 trusses.

Figure 2-9: Spreader bar anchor

2.3 Methods

This section describes the experimental setup used to measure the behavior of wood trusses with different fall arrest system anchors and bracing. Each of the materials listed were used in accordance to the manufacturers specifications. The methods in this experiment were designed to load the roof system with a horizontal load perpendicular to the plane of the trusses. This experimental setup tested the strength of the anchor as well as the strength of the bracing and truss connections. The horizontal loading was chosen to load the roof structure in its weakest plane (out of plane) as if a fall occurred over the gable end of the structure.

2.3.1 Horizontal Application of Load Test (HALT)

To test the mechanical strength of the anchors and temporary bracing, a test machine labeled the HALT (Horizontal Application of Load Test) was constructed (Figure 2-10). The HALT used a hydraulic cylinder placed in a vertical position (not visible in picture – inside steel frame at left) to pull on a steel cable threaded through a series of pulleys. The pulley closest to the truss can be adjusted up or down on the steel frame so that the anchors can be tested at varying positions along the trusses. The hydraulic cylinder was controlled by an integrated data acquisition system. The cylinder had a maximum capacity of 7,000 lbs. and a maximum distance of travel of 20 inches. A ½" braided steel cable attaches the cylinder to the test system and contains an integrated 5,000 lb. load cell. A turnbuckle attaches the steel cable to the anchor and can be adjusted to reduce slack in the cable.

The HALT loading location is approximately six inches above the peak of the trusses to place the maximum load possible on a ridge mounted anchor. The loading location demonstrated the most appropriate connection point considering the anchor should be placed above the workers at all times.

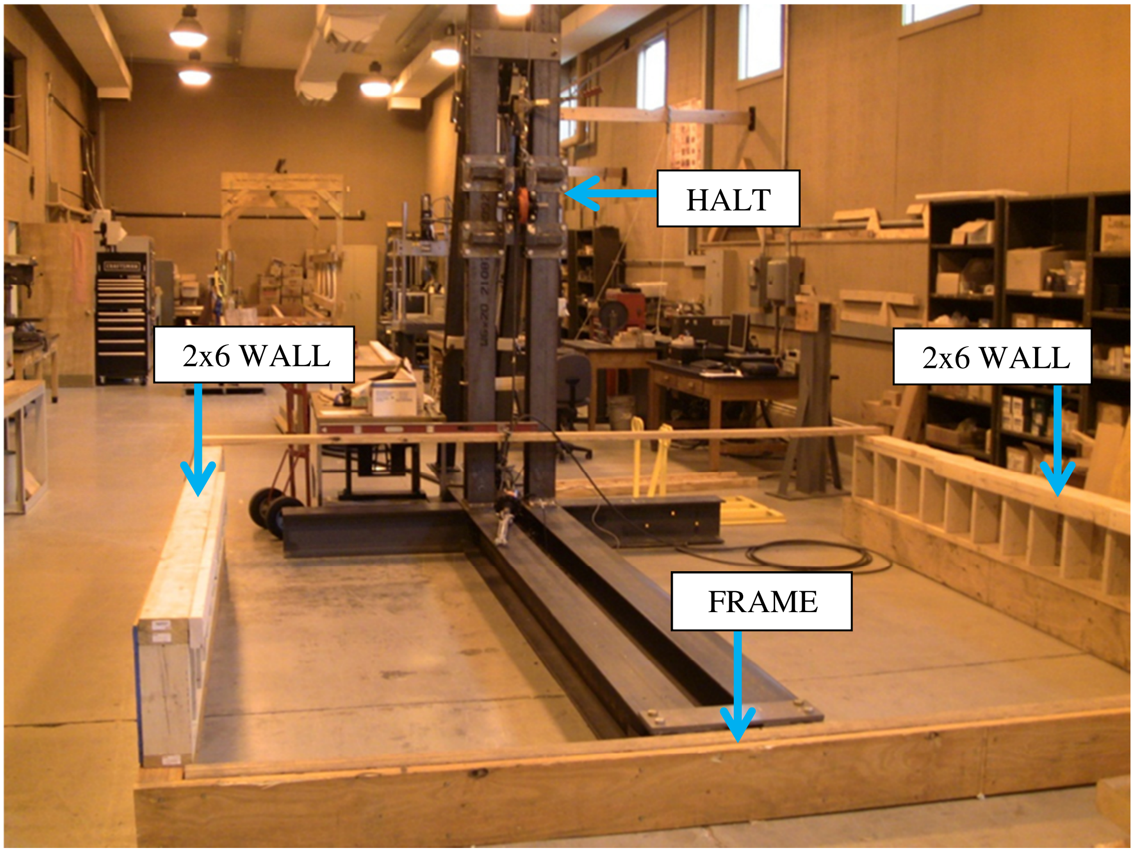

Figure 2-10: Horizontal application of load test (HALT) and test frame

The test frame was rigidly designed so that the stresses placed on the trusses are kept on the trusses and the truss-to-wall connection. The test frame was built with laminated veneer lumber (LVL) due to its strength and hold down weight. Three 9 1/8 inches wide LVL beams were attached with the screws placed 24 inches on center. The three LVL sections were attached to form a large "U" with a span of exactly 13 feet (Figure 2-10). This particular shape of the frame was chosen so that the setup could be moved in any direction to provide the best alignment for testing. For this study, the test frame was bolted to the concrete floor to reduce overturning forces from the horizontal load.

Two 2x6 stem walls with studs at 12 inches on center were built and screwed into the LVL test frame (Figure 2-10). The stud spacing of 12 inches on center was chosen to provide stability and to ensure that the walls were not the source of failure during the testing. Each of the walls was sheathed on one side with 7/16 inch thick oriented strand board (OSB) to further provide lateral stability and model a finished wall system. A 2x4 ledger strip was screwed flush to the top plate of the wall on the interior of the frame. The ledger strip prevented the truss-to-wall connectors from damaging the walls. The ledger strip was inspected after each test and replaced when damaged. A 13 foot long 2x6 was placed across the span of the walls closest to the HALT to stiffen the frame and to ensure that the span remained exactly 13 feet during testing (Figure 2-10).

2.3.2 Experimental Setup

The experimental setup was designed to provide the most effective mechanical testing of the anchors and bracing. Five trusses (Section 2.2.2) at 24" on center were placed on the test frame. The peaks of the trusses were aligned 6 inches to the right of the centerline of the HALT tester. The six inch allowance allowed centric loading of the anchor to prevent moments or eccentric loading. The adjustable pulley of the HALT was adjusted to the proper height for each anchor type and leveled. The cable then aligned with each of the anchors applying the horizontal load perpendicular to the plane of the trusses. Alignment of the cable and trusses was checked prior to testing and monitored during each test.

Each truss was fastened to the test frame with an RT7A-TZ Double Plate Hurricane Seismic Anchor manufactured by USP Connectors at each wall. This anchor type is commonly used for a truss-to-plate connection. Figure 2-11 is a photograph of the strap in use for the experiment.

Figure 2-11: Hurricane strap application for testing

In typical roof construction, hurricane clips are installed along with the permanent bracing which is prior to the erection of all of the trusses. A single toenail is commonly used to fasten the truss to the top plate of the wall until the hurricane clips are installed. To strengthen the roof system during erection, it is recommended to install the hurricane clips as the trusses are being erected. This allows for a much stronger connection and can help prevent failure at the truss-to-plate connection during the roof construction. Therefore, it is recommended that truss-plate connectors be added to the truss system before anchoring a personal fall arrest system to it.

Each test consisted of new trusses and new connections. Anchors were used for only three tests and were inspected prior to each test to check for damage from the previous test. If the anchor was damaged, it was replaced with a new anchor. The test frame was built to withstand multiple applications of load and was also inspected prior to each test. Each hurricane clip was nailed into the 2x4 ledger plate. When the 2x4 ledger plates became damaged from the testing, the plates were replaced.

All mechanical testing was performed at a displacement rate of 15 in/min. This rate was chosen based on the results of a displacement and speed study and correlated well with impact loading.

2.3.2.1 Full Factorial Test Plan

The HALT was used to test three anchor types and three bracing methods to measure the load of the anchor. The best anchor point would be considered the anchor and bracing combination with the greatest load, without the anchor failing in a catastrophic manner. Each of the three anchors was tested with the three bracing methods for a total of nine tests. Replications of each test were not performed due to the complexity of the individual tests. The experimental variables tested are shown in Table 2-1.

Table 2-1: Experimental setup of full factorial testing

Full Factorial			
Anchor Type	**Bracing Types**		
	Wood in-between	Wood on-top	MiTek STABILIZER
Post Frame Anchor	X	X	X
Cross-arm Strap	X	X	X
Spreader Bar	X	X	X

2.3.2.2 Additional Testing

In addition to the nine tests shown in Table 2-1, two identical tests were performed once all other testing was completed. The purpose of the additional testing was to improve the max load of the best anchor and bracing combination tested in Table 2-1. Additional bracing, often referred to as "sway bracing" was added as an additional form of temporary bracing. Sway bracing can be utilized to form a triangle perpendicular to the plane of the trusses to prevent trusses from folding over (SBCA, 2012). The sway bracing consisted of a 2x4 attached to the king posts of each truss with 2 16D sinker nails. Figure 2-12 below shows sway bracing installed per SBCA instructions.

Figure 2-12: Sway bracing attached to king posts of a truss system

2.3.3 Measurements of Load and Deflection

Several measurements were recorded during the testing to compare the different anchors and bracing. Loads were measured with a 5,000 lb. load cell, mounted close to the cable attachment on the anchor. Figure 2-13 is a photograph of the load cell and cable mount to an anchor.

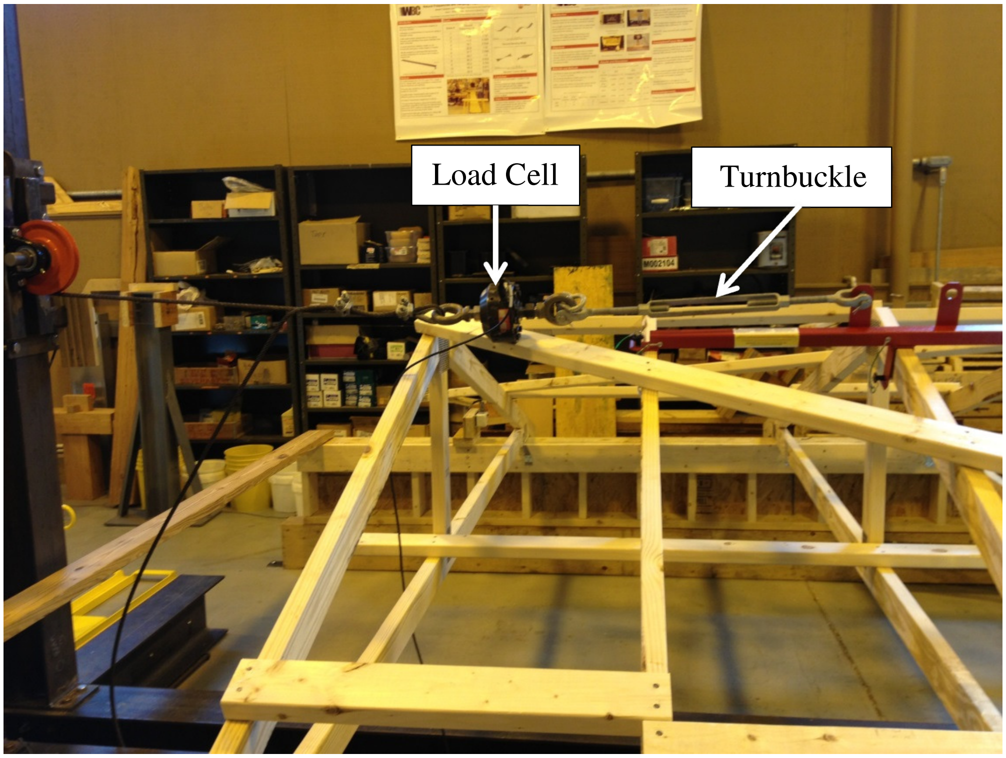

Figure 2-13: Load cell attachment to anchor

Displacement was measured using a string potentiometer attached in the midspan of the top chord of the truss located closest to the HALT (Figure 2-14), as well as a string potentiometer at each wall of the same truss (Figure 2-15). The displacement measured at the top chord was used to determine the amount of deflection at both truss-plate anchors as well as the peak of the trusses.

Figure 2-14: String potentiometer at truss-wall connection

Figure 2-15: String potentiometer attached to the peak of the truss

3.0 Results and Discussion

This section describes the results of tests performed to evaluate the anchor and bracing methods. Each test resembled a different anchor/bracing configuration. Both anchors and bracing methods failed in similar modes for each test. However, each configuration performed differently and presented unique failures dependent on both anchorage type and bracing configuration. Documentation of these failure modes and performances is presented in this section.

3.1 Post Frame Anchor (PFA)

Results of the PFA testing are given in Table 3-1. The PFA did not perform well when compared to the other anchor types. The temporary bracing of the roof system provided strength that prevented deflection. Therefore the load was concentrated at the anchor point which was the source of ultimate failure in each test. The PFA connection point is much higher than that of the other anchors which results in a large moment arm on the single top chord that it is attached to. The moment on the single truss led to truss plate failure and lead to ultimate failure in the trusses as well as the bracing. The PFA was the only anchor determined as the source of ultimate failure. The anchor is not rated to carry 5,000 lbs. and began to fail once the load reached a max load of 752 lbs.

Table 3-1: Results of post frame anchor testing

Bracing Type	Ultimate Load (lbs.)	Displacement (in.)	Failure Mode
In-Between	726	1.83	PFA
On-Top	752	4.40	On-Top Bracing
Engineered Steel	571	5.90	Engineered Steel Bracing

These failure modes are similar to that of previous testing using the PFA for single trusses (Hindman and Koch, 2012), though the loads were significantly higher due to the multiple trusses and bracing included in the experimental setup. Figure 3-1 is a photograph of the PFA attached in each test involving this anchor type.

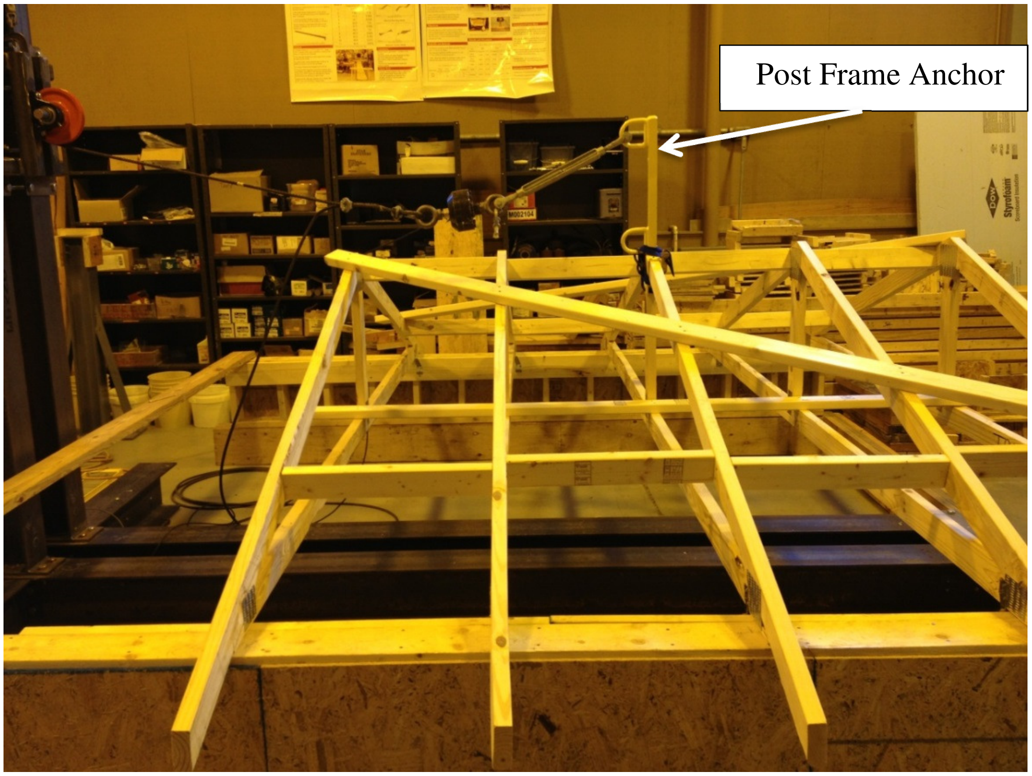

Figure 3-1: Anchor attachment for post frame anchor tests

3.1.1 Post Frame Anchor and In-Between Wood Bracing

The in-between wood bracing performed well with the RFAS anchor compared to other bracing methods and reached an ultimate load of 726 lbs. A moment was placed on the anchor by the height of the PFA. Figures 3-2 and 3-3 are photographs of the PFA.

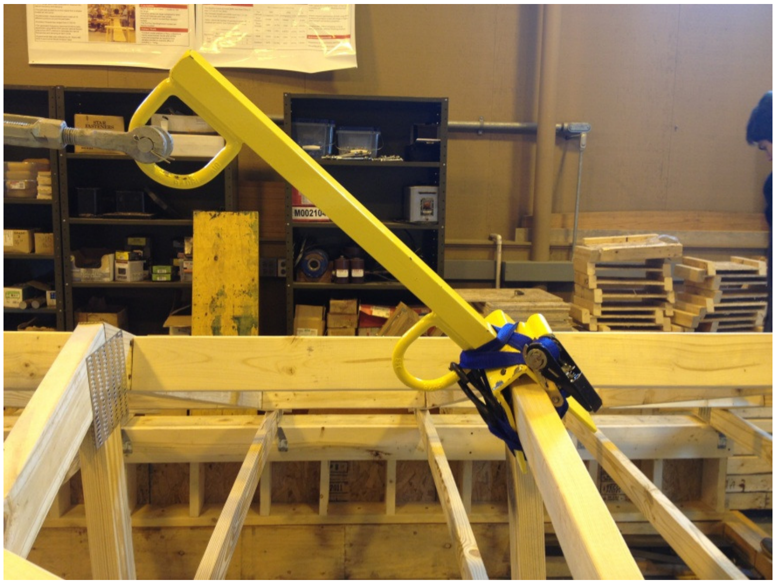

Figure 3-2: Failure in the PFA (front)

Figure 3-3: Failure in the PFA (back)

The brackets of the PFA over the truss failed, which then transferred the load to the strap wrapped around both the anchor and the truss. If the strap was not used in the connection, the anchor would have failed and disconnected from the truss. As well as failure in the anchor, failure in the bracing was observed where the nails withdrew from the end grain of the blocking (Figure 3-3). Nailing into the end grain of the wood bracing is a generally weak connection and should be avoided whenever possible. However, withdrawal nailing is recommended for this type of bracing (SBCA, 2012). Although the nails withdrew from the bracing, the deflection of the truss resulted in a "pinching" of the in-between bracing, where the corner of the bracing embedded into the truss chord (Figure 3-4). The in-between blocking continued to carry load as the truss deflected due to this "pinching" performance. Though the bracing system performed well, the ultimate failure was in the anchor itself. As the brackets failed, the load was concentrated solely in the strap. Ultimately, the PFA anchor itself failed due to excessive rotation.

Figure 3-4: “Pinching” action of the in-between bracing

The load vs. displacement curve of the PFA and in-between bracing is shown in Figure 3-5. The drop in load of the load vs. displacement curve around 1.1 inches was due to the slip of the anchor. The moment on the anchor resulted in a brittle failure of the anchor brackets. As the brackets failed, the anchor began to slip off the truss, resulting in the final drop of load. The final drop in load is the result of the anchor slipping off of the truss where the load was then transferred to the strap which could not sustain the stresses placed upon it.

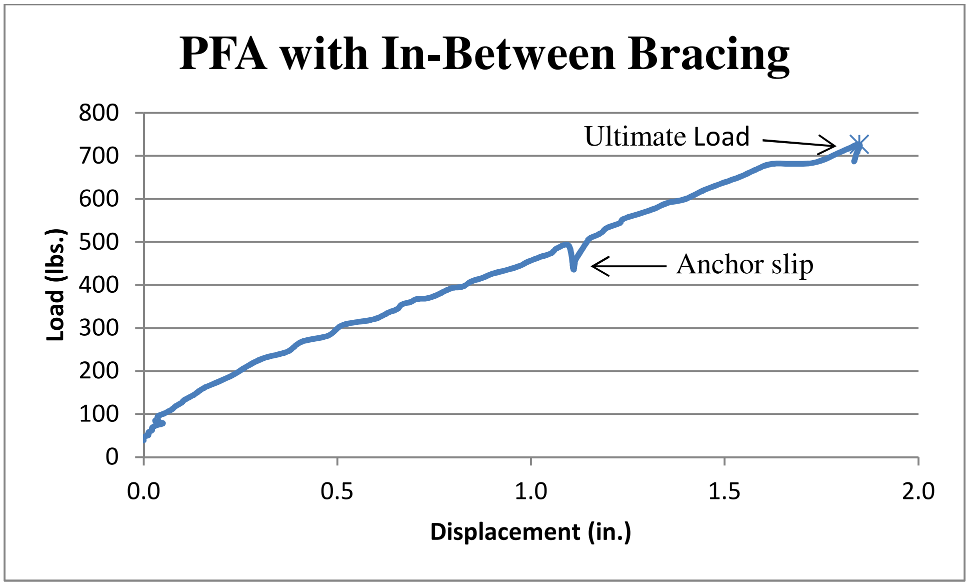

Figure 3-5: Load vs. displacement curve for PFA and in-between bracing

3.1.2 Post Frame Anchor and On-Top Wood Bracing

The on-top wood bracing performed well with the PFA and reached an ultimate load of 752 lbs. This was the highest ultimate load associated with the PFA. The nails placed in the top of the wood bracing generated shear forces, as opposed to the withdrawal forces at the end-grain in the in-between bracing. The PFA was not damaged due to transfer of load through the truss system. The nails connecting the bracing to the trusses withdrew from the top of the truss while splitting it parallel to the grain. The splitting was a direct result of the shear forces generated at the nail connection. Figure 3-6 is a photograph of the withdrawal of the nails from the top chord of the truss. Figure 3-7 is a photograph of the truss splitting parallel to grain at the connection point.

Figure 3-6: Withdrawal of the bracing with PFA **Figure 3-7:** Truss splitting with PFA

The PFA did not fail due to the failure in the bracing system and trusses surrounding it. Therefore the post frame anchor was unharmed and remained intact and connected to the truss. Though the anchor performed well, the bracing and trusses failed abruptly resulting in a low maximum load when compared to other tests. Figure 3-8 is a photograph of the PFA after the testing was complete.

Figure 3-8: PFA after testing with on top bracing

The system deflected more than the in-between bracing test due to the loss of strength in the system when the bracing and truss connections failed. Figure 3-9 is a graph of the load vs. displacement curve of the PFA and on-top bracing.

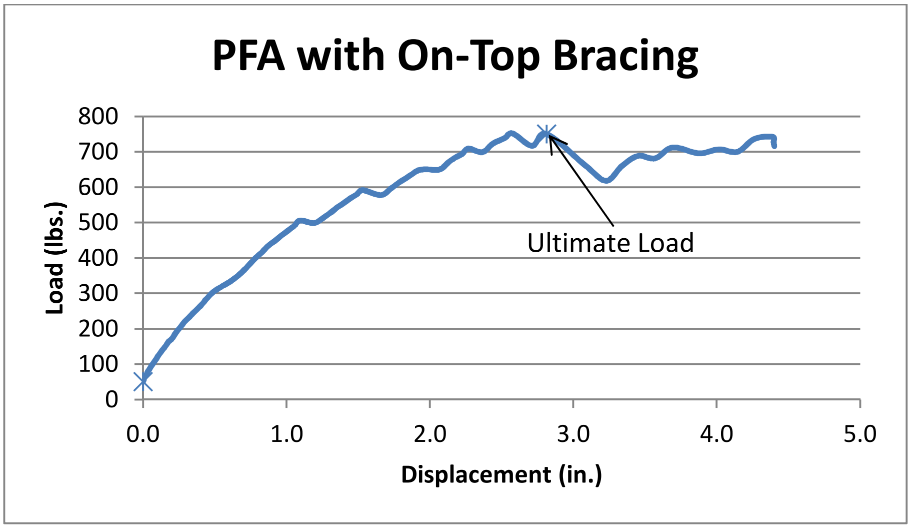

Figure 3-9: Load vs. displacement curve for PFA and on-top bracing

Prior to the ultimate failure at 752 lbs., the on-top bracing began to withdraw from the trusses shown in Figure 3-9 as the small peaks prior to ultimate failure. Ductile failure can be seen as the anchor maintained load after ultimate failure (Figure 3-9), as opposed to the brittle failure of the in-between bracing. The on-top bracing configuration had greater deflection, and preserved the anchor point on the truss system when compared to the other bracing methods. Though the failure modes were different, the ultimate load was similar to the PFA and in-between bracing test previously performed.

3.1.3 Post Frame Anchor and Engineered Steel Bracing

The engineered steel bracing did not perform as well as the wood bracing in this test with an ultimate load of 571 lbs., which was the lowest ultimate load of all of the PFA testing. The bracing was placed on the trusses similar to the on-top wood bracing (Figure 3-10). This allowed for easy installation however the penetration into the trusses is very small.

Figure 3-10: Engineered steel bracing installation

During testing, the prongs withdrew from the trusses as the truss system deflected. As deflection increased, the braces were placed in compression causing buckling (Figure 3-11) and withdraw of the prongs from the top chord of the truss (Figure 3-12). As each brace failed, the load was transferred to another brace, resulting in the failure of multiple braces.

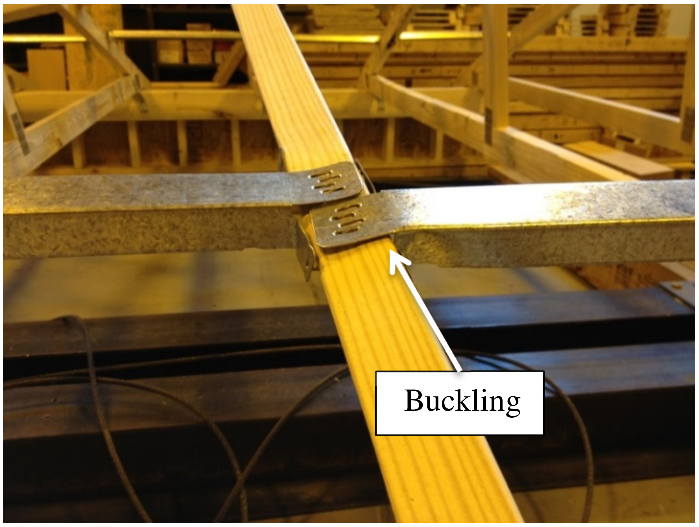

Figure 3-11: Buckling in the engineered steel bracing

Figure 3-12: Bracing withdrawal

Failure in the engineered steel bracing resulted in a low ultimate load of 571 lbs. and a large deflection due to the loss in strength. The load vs. displacement curve of the PFA with engineered steel bracing is shown in Figure 3-13.

The load displacement curve shows the result of the failures in the engineered steel bracing. A total of five braces failed in the test and the data shows five drops in load resulting from each of the braces. Once the engineered steel bracing began to fail, the diagonal bracing helped to carry the load until another steel brace failed. This failure type is not ideal and should be avoided to prevent complete failure in the truss and bracing system.

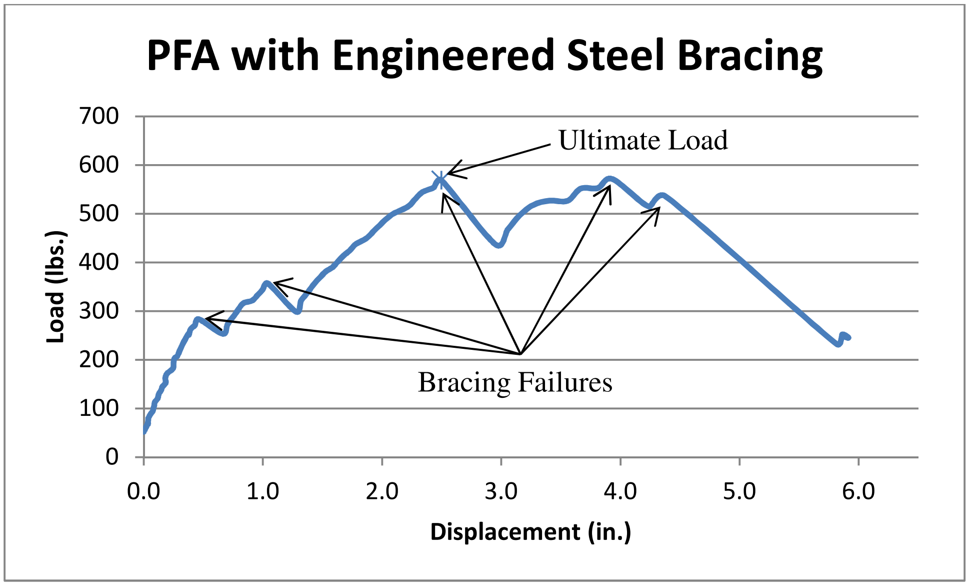

Figure 3-13: Load vs. displacement curve for PFA and engineered steel bracing

3.2 Cross Arm Strap

The cross arm strap is a very popular anchor throughout the construction industry due to its lightweight and versatility on the job. The cross arm strap can be placed on any structure or member approved to carry the required load and does not pose any harm to the strap itself. The strap is ideal for use in the residential construction industry when suitable anchor points are available. The cross arm strap performed well in the testing and produced some of the highest loads in all of the testing conducted. The strap laid flat on the trusses reducing the moment arm placed on the single truss that was observed with the PFA, allowing the load to be distributed throughout the roof system and to preserve the anchor point. Results from the cross-arm strap testing are shown in Table 3-2.

Table 3-2: Results of cross-arm strap testing

Bracing Type	Ultimate Load (lbs.)	Displacement (in.)	Failure Mode
In-Between	1,412	5.42	Truss Plate at Anchor Point
On-Top	875	4.49	On-Top Bracing
Engineered Steel	1084	6.16	Engineered Steel Bracing

When tested, the cross arm strap was placed around 2 trusses, placing the D-ring connection near the center of the 5 truss system. The strap was placed at the same height and position as the previous anchor to strictly limit the loading eccentricities. Figures 3-14 and 3-15 are photographs of the cross arm strap attached to the truss system.

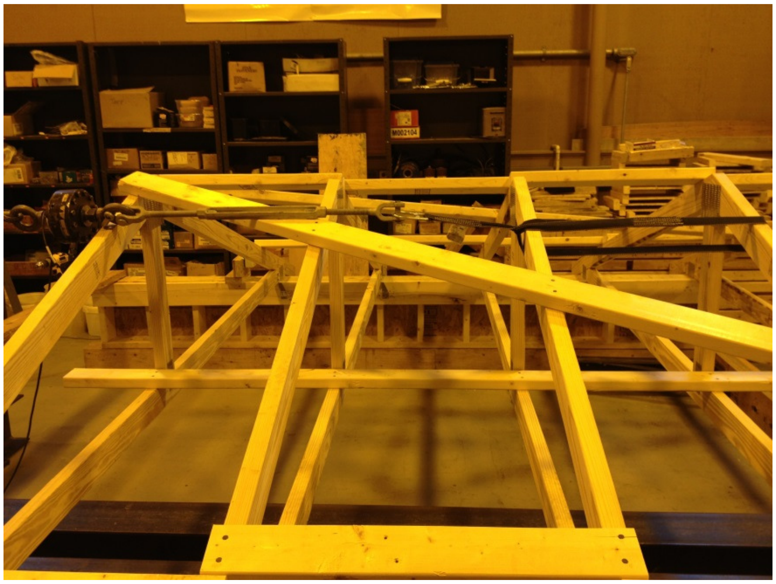

Figure 3-14: Strap connection (front)

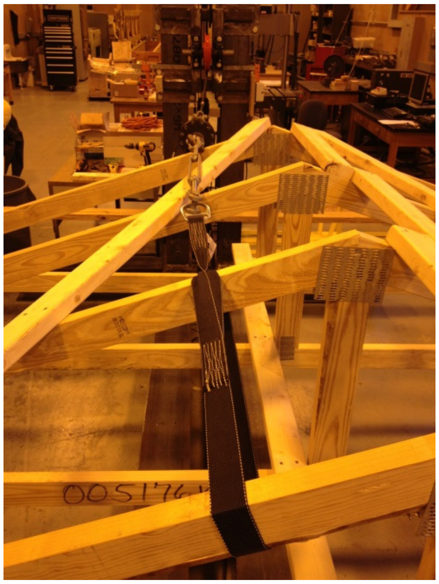

Figure 3-15: Strap connection (side)

The strap performed well during testing and was never the source of failure. However, the strap did not distribute the load across multiple trusses as predicted and applied a concentrated load on the truss furthest from the D-ring. The loop of the strap tightened as the load increased and did not transfer the load to the "front" of the truss due to the direction of the loading. Ultimate failure was observed as a concentrated load applied to a single truss. The following sections discuss the performance of the cross arm strap with each of the three bracing methods.

3.2.1 Cross Arm Strap and In-Between Wood Bracing

The in-between wood bracing performed well with the cross arm strap reaching an ultimate load of 1,412 lbs. As with the PFA, the in-between bracing was “pinched” between the trusses as the deflection increased. Though the nails withdrew from the end grain of the bracing, the bracing continued to carry load placed on the truss system. Due to the performance of the bracing, the load was concentrated on the truss furthest from the D-ring. This single truss failed at the peak truss plate and was the only source of ultimate failure in the system. This failure mode is due to the inability for the system to engage multiple trusses. Figure 3-16 shows the system after the testing was complete. Figure 3-17 shows the failure in the peak truss plate.

Figure 3-16: Cross-arm strap and in-between wood bracing

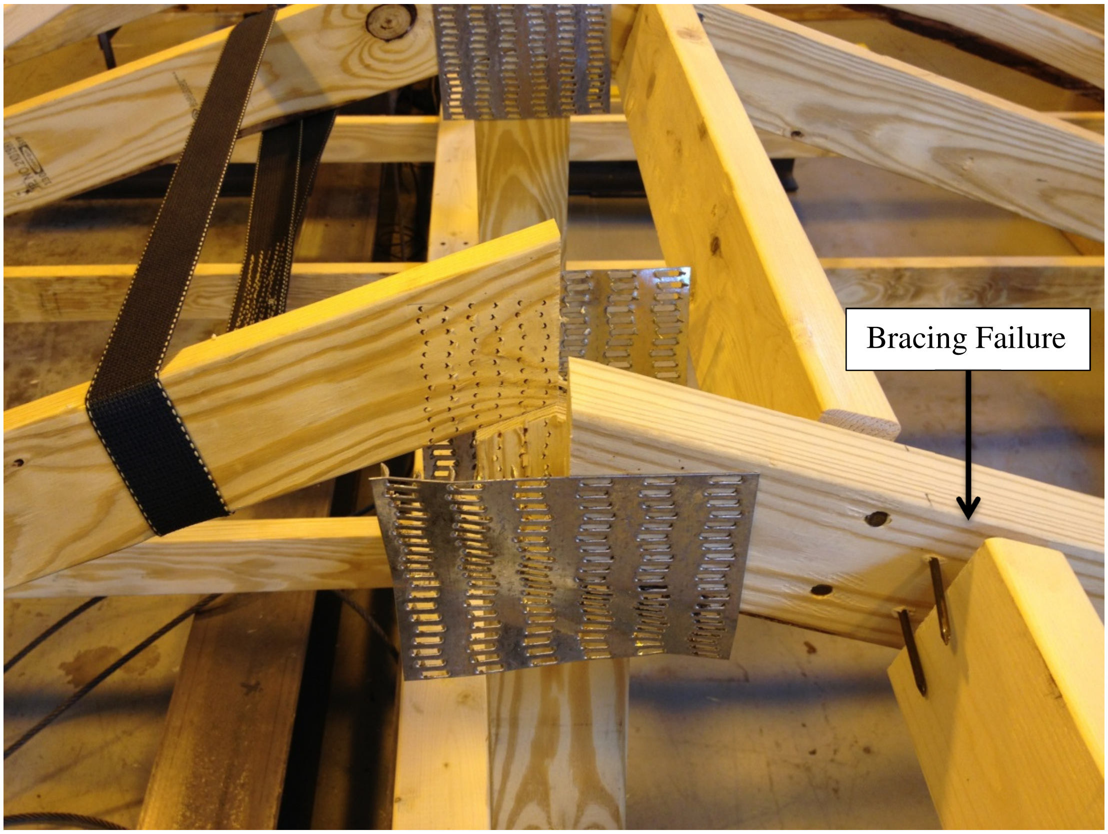

Figure 3-17: Failure in the peak truss plate located at the anchor point for strap and in-between bracing

The system as a whole worked well with both straps and bracing performing as they should. The in-between bracing remained intact at each location except the brace located closest to the anchor point which failed in withdrawal as shown in Figure 3-17. Regardless, after the nails withdrew the bracing continued to carry the load due to the pinching performance which yielded high loads and low deflection.

The load vs. displacement curve for the cross arm strap and in-between bracing is shown if Figure 3-18. The system achieved an ultimate load of 1,412 lbs. which was the highest of all of the full factorial testing. There are few drops in load as the in-between bracing did not fail. Ultimate failure occurred when the truss plate closest to the anchor point failed.

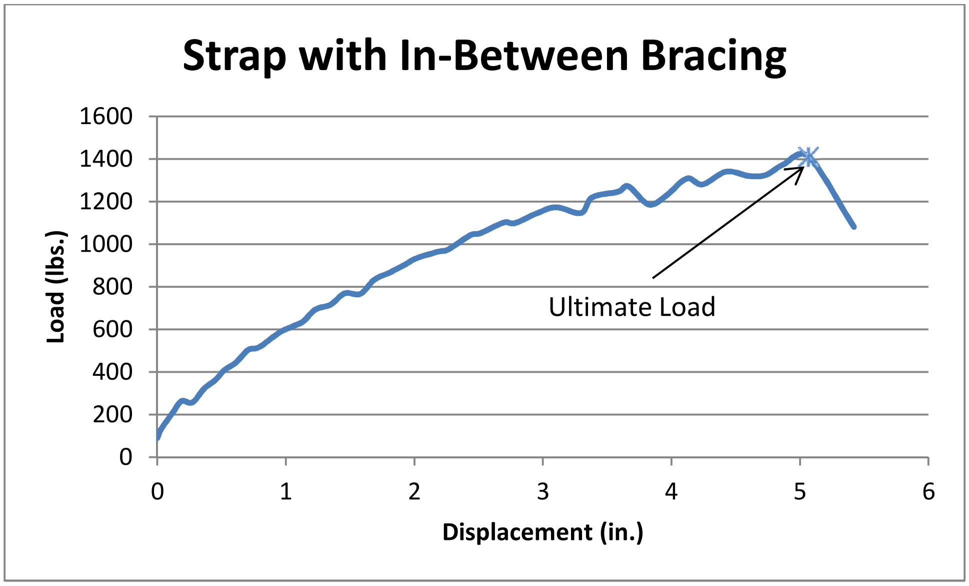

Figure 3-18: Load vs. displacement curve for strap and in-between bracing

3.2.2 Cross Arm Strap and On-top Wood Bracing

The on-top bracing performed poorly when used in a system with the cross arm strap with an ultimate load of 875 lbs. Although the ultimate load was less than the other cross-arm strap tests, the load was greater than the PFA testing. As the trusses were loaded, the bracing began to withdraw from the trusses in a similar fashion as the PFA and on-top bracing due to rotation of a single truss. After the brace closest to the anchor point withdrew, the roof system lost strength and multiple braces failed as a result (Figure 3-19). As each brace failed, the load was transferred to another brace that was soon unable to maintain its rigidity. The cross-arm strap was not damaged during the test and the anchor point was preserved.

The on-top bracing withdrew from the trusses (Figure 3-20) and in some cases split the truss parallel to the grain (Figure 3-21). As the system deflected, the diagonal bracing began to withdraw from the truss as well. The greatest amount of failure in the bracing was located near the anchor point.

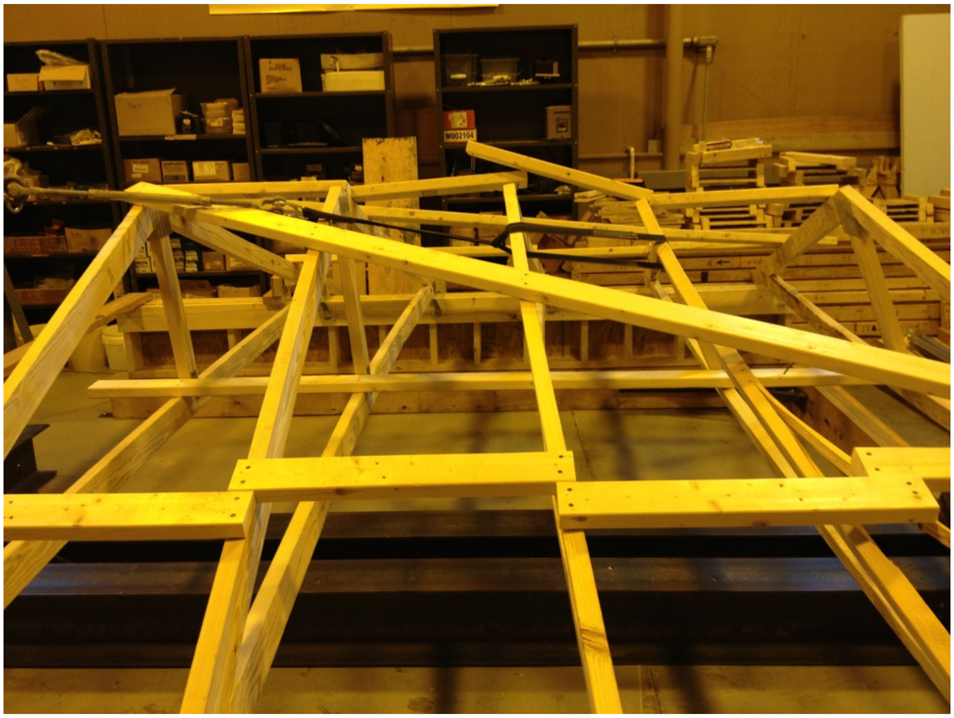

Figure 3-19: Failure in the on-top wood bracing & diagonal bracing

Figure 3-20: Withdrawal from the trusses

Figure 3-21: Splitting of the trusses

The cross-arm strap load was concentrated on a single truss and only reached an ultimate load of 875 lbs. The load vs. displacement curve shows the initial failure in the temporary bracing located closest to the anchor point (Figure 3-22). The initial failure was a brittle failure a loss of strength similar to the PFA testing. After the initial failure, multiple braces failed in a more ductile manner until the ultimate load was reached. The system was able to recover from the initial failure; however, the ultimate load was only slightly higher than the load at the initial failure. The system experienced little deflection because both failure and deflection were located towards the center of the roof system. Once the bracing failed and strength was lost, deflection of the system increased as deflection of the trusses with the strap attached increased.

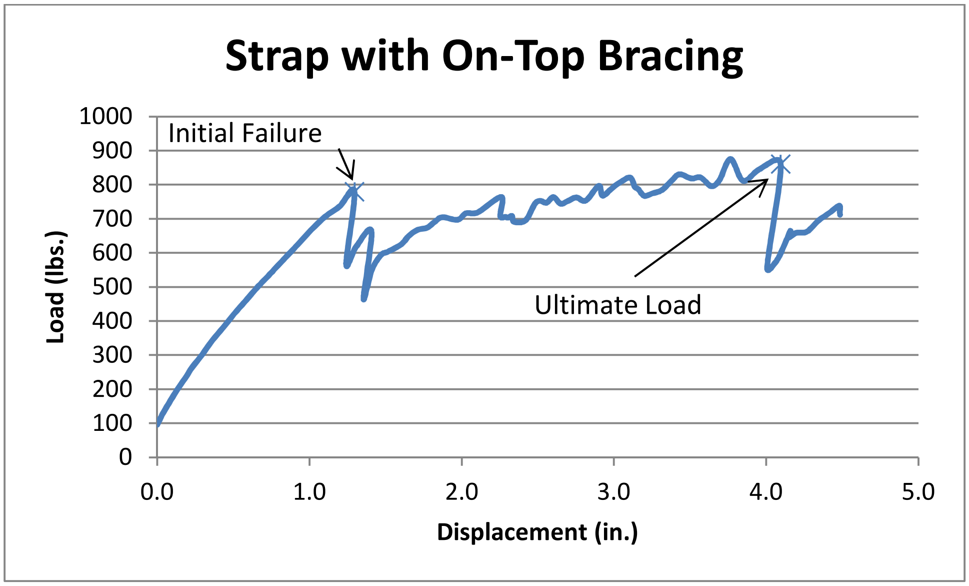

Figure 3-22: Load vs. displacement curve for cross-arm strap and on-top bracing

3.2.3 Cross Arm Strap and Engineered Steel Bracing

The engineered steel bracing performed well with the cross-arm strap, but still demonstrated the same behavior observed in PFA and engineered steel bracing testing. The ultimate load reached 1,049 lbs., which was the greatest load of all tests utilizing the engineered steel bracing. As the truss system was loaded, multiple braces withdrew from the top of the trusses, mainly the braces located on the same trusses as the strap. As these braces failed, the single truss carrying the load began to deflect significantly (Figure 3-23).

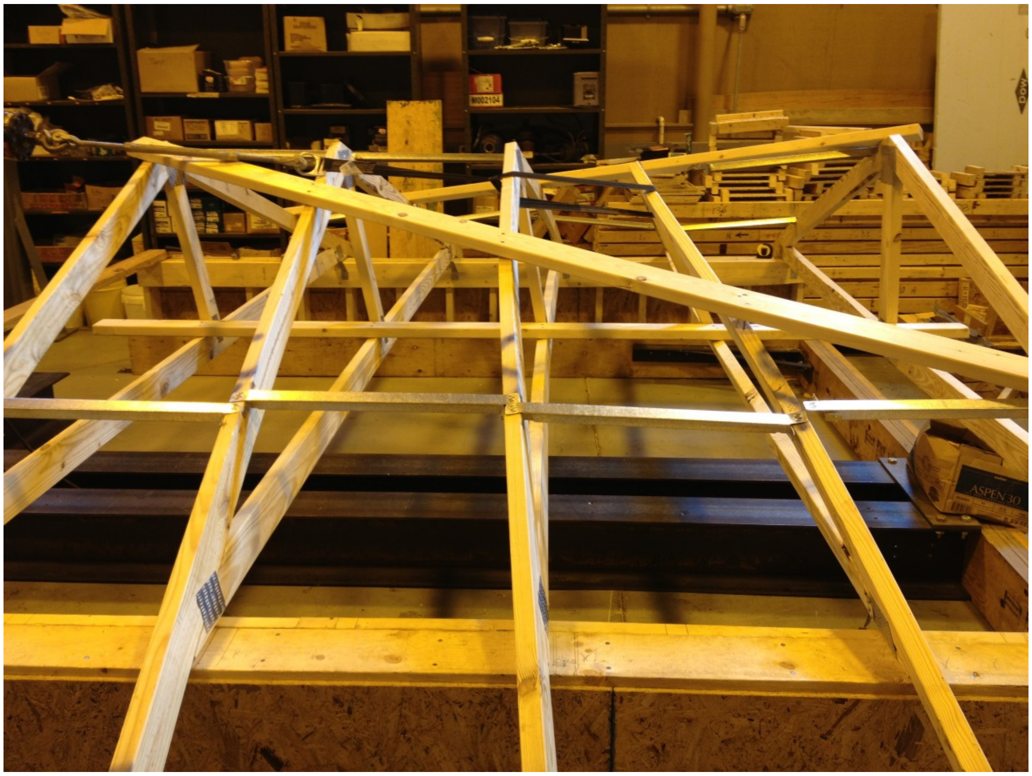

Figure 3-23: Cross-arm strap with engineered steel bracing

The failure mode shown in Figure 3-23 is similar to the PFA anchor with the on-top wood bracing. The concentrated load placed at the anchor point was the primary reason for failure. The single truss was the source of failure as well as the element with the greatest deflection. The engineered bracing prongs were withdrawing from the trusses as the system deflected (Figure 3-24). As each brace failed, the other braces carried more load and become more susceptible to failure. This can be categorized as a "domino" effect among the braces. Additionally, as the system was loaded and the engineered steel bracing failed, the diagonal bracing withdrew from the tops of the trusses.

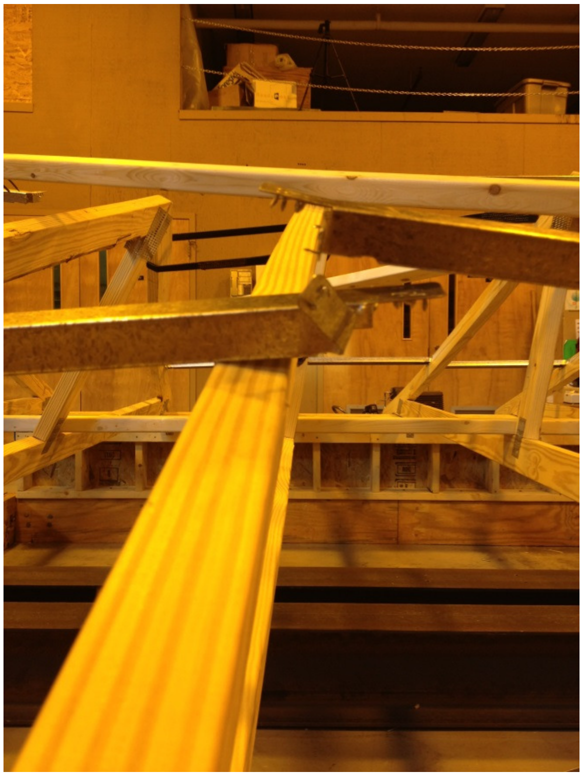

Figure 3-24: Failure in the engineered steel bracing

The load vs. displacement curve for the cross arm strap with engineered steel bracing is shown in Figure 3-25. The decreases in load correspond to failures in the engineered steel bracing withdrawing from the truss, or withdrawal of the diagonal bracing. Fewer failures in the bracing were observed compared to previous tests using the engineered steel bracing which resulted in an ultimate load of 1,084 lbs. The force in the cross-arm strap was concentrated on a single truss and was not transferred throughout the truss system. The greatest amount deflection was located in the single truss carrying the concentrated load from the strap and the anchor point was not preserved. The roof system as a whole did not experience much deflection due to this.

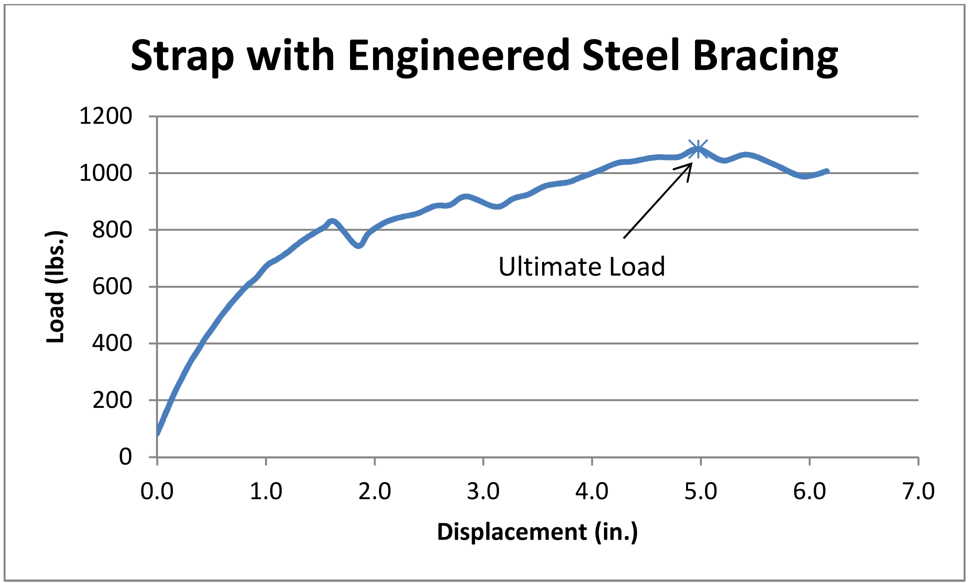

Figure 3-25: Load vs. displacement curve for strap and engineered steel bracing

3.3 Spreader Bar Anchor

The spreader bar anchor engages multiple trusses to strengthen the anchor point and align the top chords at 24 inches on center. The spreader bar provides two separate anchor points and is rated to carry 5,000 lbs. The spreader bar can be placed on three 2x4 or 2x6 trusses and is equipped with high quality detent locking pins to ensure that it is secure to the roof system. The spreader bar can be used with or without roof sheathing making it the superior product for truss erection.

Failures were dispersed throughout the system in the temporary bracing, trusses, and hurricane clips attaching the trusses to the wall. Due to the deflection of the roof system, the brackets attaching the spreader bar anchor to the trusses were damaged during each test. Therefore a separate spreader bar was used for all three tests. Table 3-3 gives the results of the spreader bar tests.

Table 3-3: Results of the spreader bar testing

Bracing Type	Ultimate Load (lbs.)	Displacement (in.)	Failure Mode
In-Between	1245	12.24	Truss Plate at Anchor Point
On-Top	1320	10.56	On-Top Bracing
Engineered Steel	919	14.57	Engineered Steel Bracing

When tested, the spreader bar was placed on the middle three trusses per manufacturer's instructions so that the anchor point being tested aligned with the middle of the truss system, a similar position to the other anchors tested. The anchor performed well and engaged multiple trusses allowing for the load to be dispersed throughout the system. Although the spreader bar was never the source of ultimate failure, it was damaged in each test which required replacement. Figure 3-26 is a photo of the spreader bar attached to the test setup.

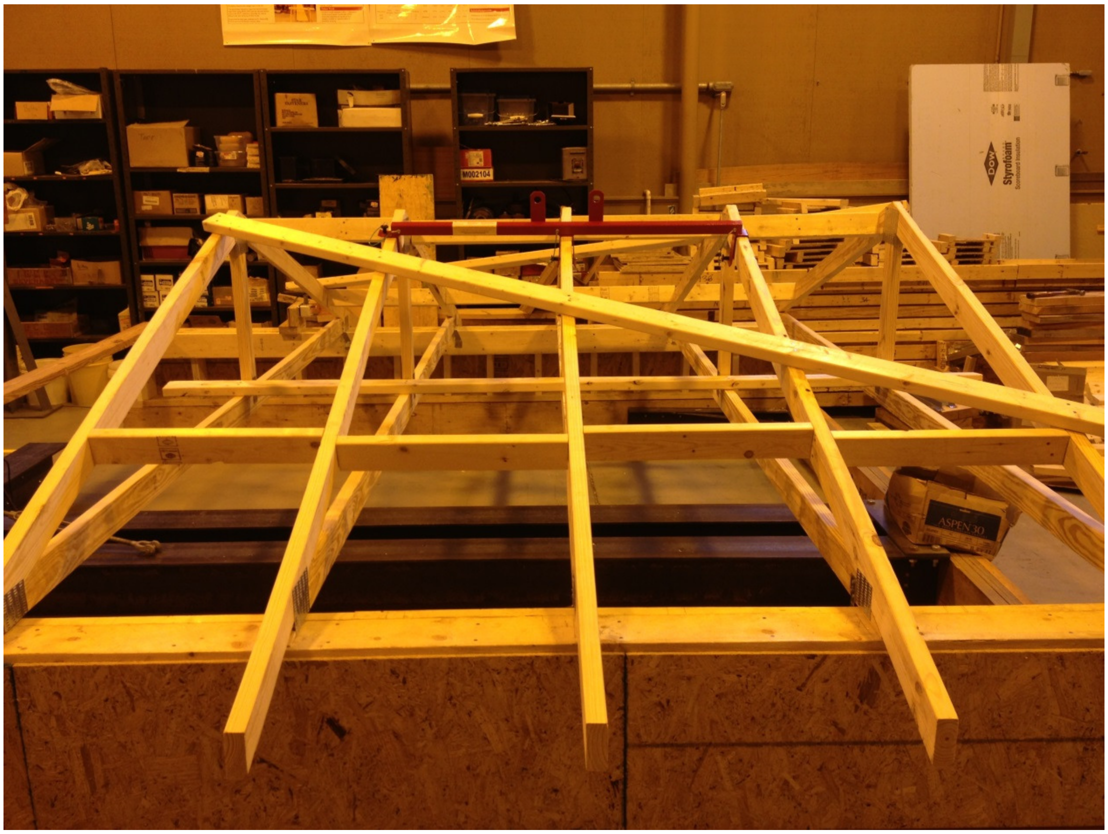

Figure 3-26: Spreader bar anchor test setup

3.3.1 Spreader Bar Anchor with In-Between Wood Bracing

In-between wood bracing performed well with the spreader bar anchor reaching an ultimate load of 1,245 lbs. The in-between bracing was pinched as the trusses deflected allowing the system to maintain strength and distribute the load. A large amount of deflection was observed throughout the system due to the strength provided by the in-between bracing and the spreader bar anchor. Racking of the entire system resulted in multiple failures of the in-between bracing, diagonal bracing, trusses, spreader bar, and hurricane clips (Figure 3-27).

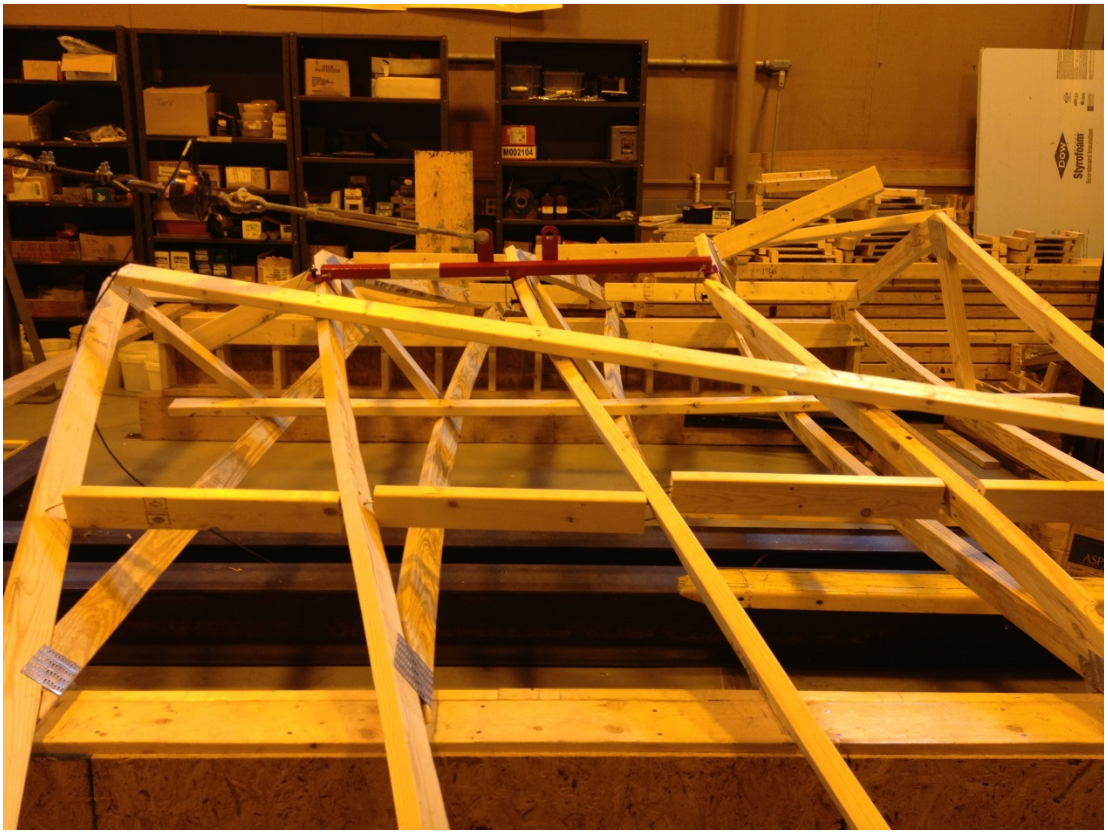

Figure 3-27: Spreader bar and in-between bracing failure

The deflection and multiple failures experienced when testing the spreader bar anchor with in-between wood bracing is shown in Figure 3-27. The image demonstrates the pinching phenomenon previously observed with in-between bracing. The good performance of the bracing as well as the good performance of the anchor distributed the load throughout the roof system. This reaction is ideal because it removes any concentrated loads that may result in an abrupt failure.

Though the system performed very well, several modes of failure were noted once the test was complete. Every component of the roof system failed in some way because of the high loads and deflection and the anchor point was not preserved.

Failure in the bracing and trusses was determined to be the source of ultimate failure (Figure 3-28). Several of the in-between wood braces completely withdrew from the trusses. This failure was primarily due to the large deflection of the trusses. The spreader bar bent at the attachment brackets on the three trusses (Figure 3-29). The brackets were bent in a similar fashion as that of the post frame anchor as they were both separated. Though the brackets of the anchor failed, the spreader bar remained attached to the structure and provided strength throughout the duration of the testing.

Figure 3-28: Failure in bracing and trusses

Figure 3-29: Failure in spreader bar

The system achieved an ultimate load of 1245 lbs. as well as deflection due to the good performance of both the anchor and the bracing. The initial and ultimate failure occurred when the truss failed as it split parallel to the grain (Figure 3-28). From that point on, the load remained the same as the system showed a more ductile failure. Both spreader bar anchor and in-between bracing maintained the load. The reaction of this configuration provides a relationship that helps to preserve the anchor point while maintaining a constant load. The load vs. displacement curve of the spreader bar anchor and the in-between bracing is shown in Figure 3-30.

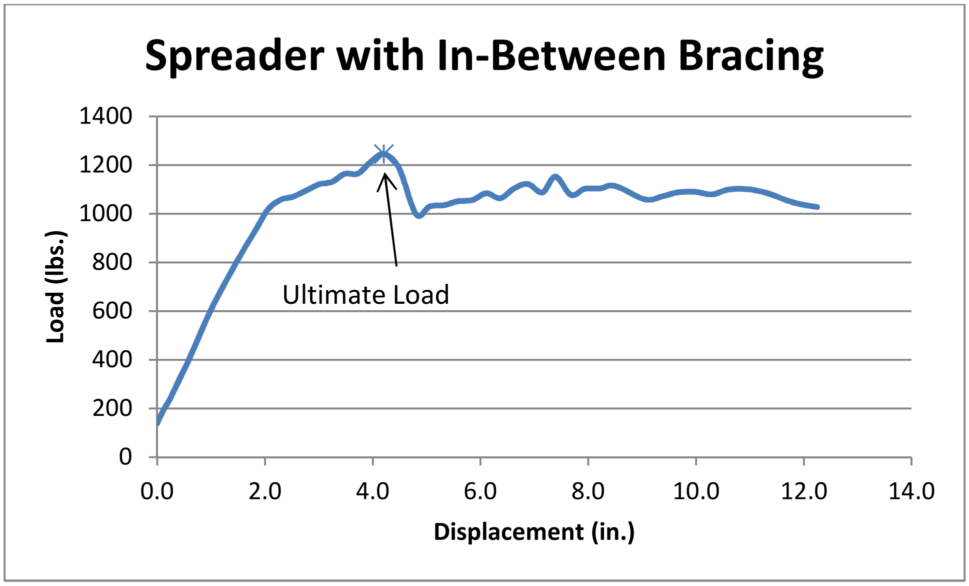

Figure 3-30: Load vs. displacement curve for spreader bar and in-between bracing

3.3.2 Spreader Bar Anchor and On-Top Wood Bracing

On-top wood bracing performed well when used with the spreader bar anchor and achieved an ultimate load of 1,320 lbs. The deflection resulted in failures similar to the spreader bar anchor with on-top wood bracing. As the system deflected, both the on-top bracing and the diagonal bracing withdrew from the trusses. Eventually, the spreader bar anchor bracket attached to the truss system began to fail. Figure 3-31 shows the failure of the spreader bar and on-top bracing.

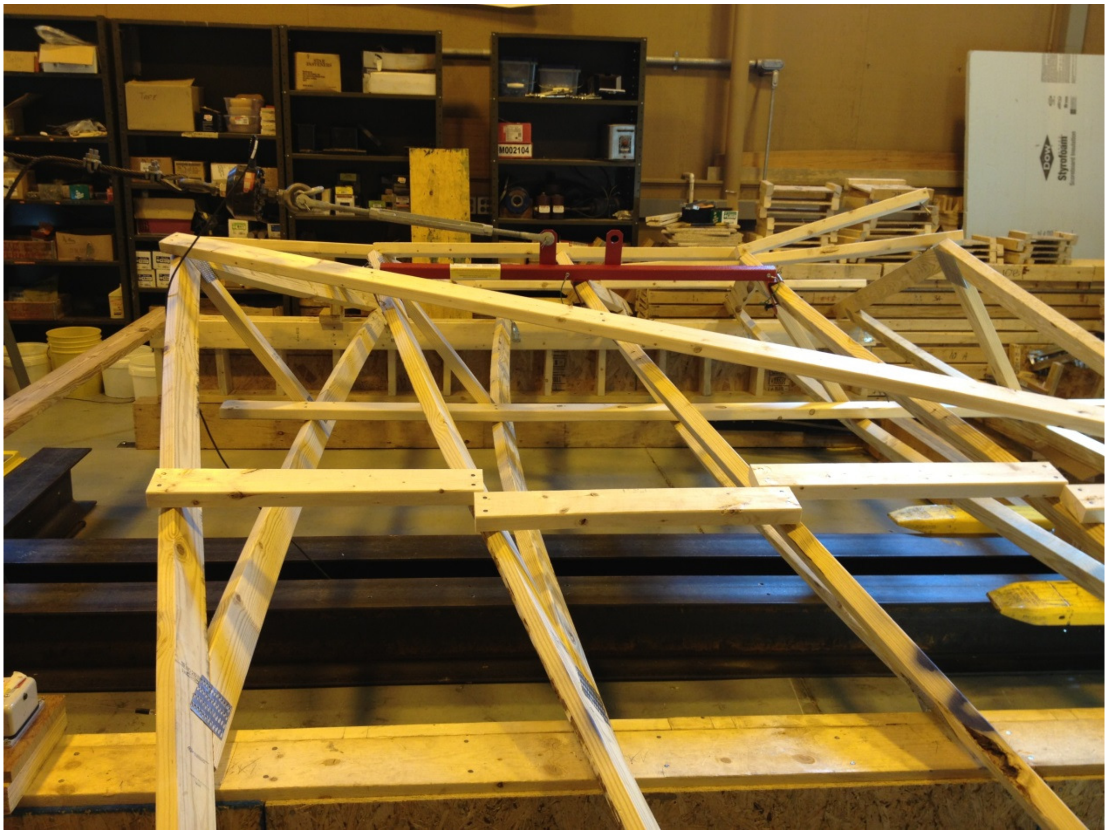

Figure 3-31: Spreader bar and on-top bracing failure

The deflection observed in Figure 3-31 occurred once the load was applied to the roof system. Failure was observed in the on-top bracing, diagonal bracing, spreader bar, as well as the hurricane clips attaching the roof structure to the walls. The primary source of failure was both the on-top bracing and the diagonal bracing. Withdrawal from the trusses resulted in loss of strength in the system (Figure 3-32). The diagonal bracing and on-top bracing withdrew from the trusses in several different locations. However, this failure mode was the result of the system reacting to the load in the appropriate manner.

Figure 3-32: Failure in the diagonal bracing and anchor

The truss system performed well and maintained constant load after the ultimate failure had been reached which prevented a significant drop in load. The 20 inch pull distance proved to be sufficient considering the load remained constant after reaching 5 inches. Though the failure was in the bracing, the bracing configuration performed well as it was able to keep its strength and withstand the stresses from the load throughout the test. The overall deflection is high due to the deflection in the entire roof system as opposed to specific members. The spreader bar performed similar to previous testing and was damaged at the brackets. Though the anchor and temporary bracing both failed, they performed well as a system preventing abrupt failures which lead to an ultimate load of 1,320 lbs. and preserved anchor point. The load vs. displacement curve for the spreader bar anchor and on-top wood bracing is given in Figure 3-33.

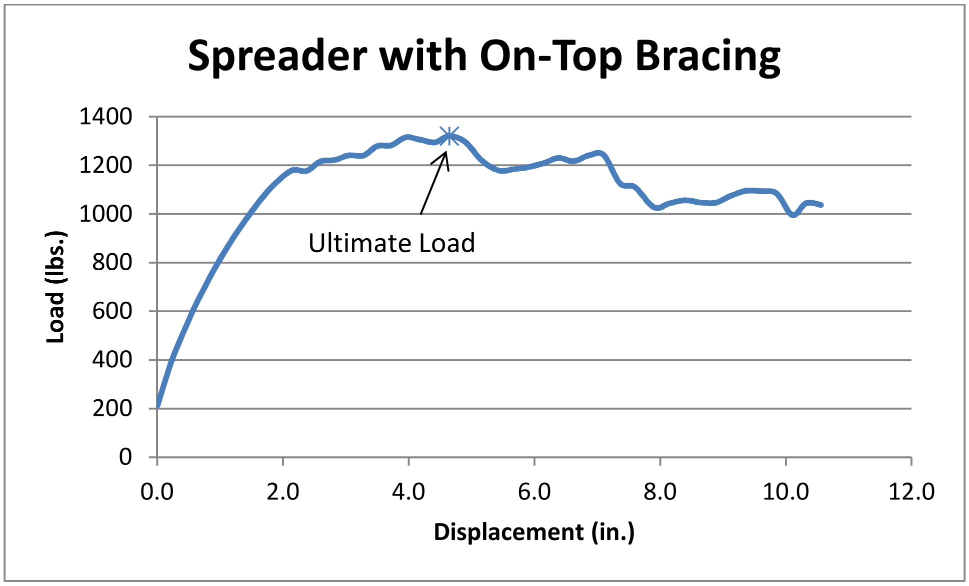

Figure 3-33: Load vs. displacement curve for spreader bar and on-top bracing

3.3.3 Spreader Bar Anchor and Engineered Steel Bracing

The engineered steel bracing did not perform as well as the wood bracing when used with the spreader bar anchor and reached an ultimate load of 919 lbs. Multiple steel braces withdrew from the trusses abruptly causing a significant decrease in the load. The engineered steel bracing was the primary source of failure and resulted in a high deflection as well as a low ultimate load. Figure 3-34 shows the failure in the spreader bar and engineered steel bracing

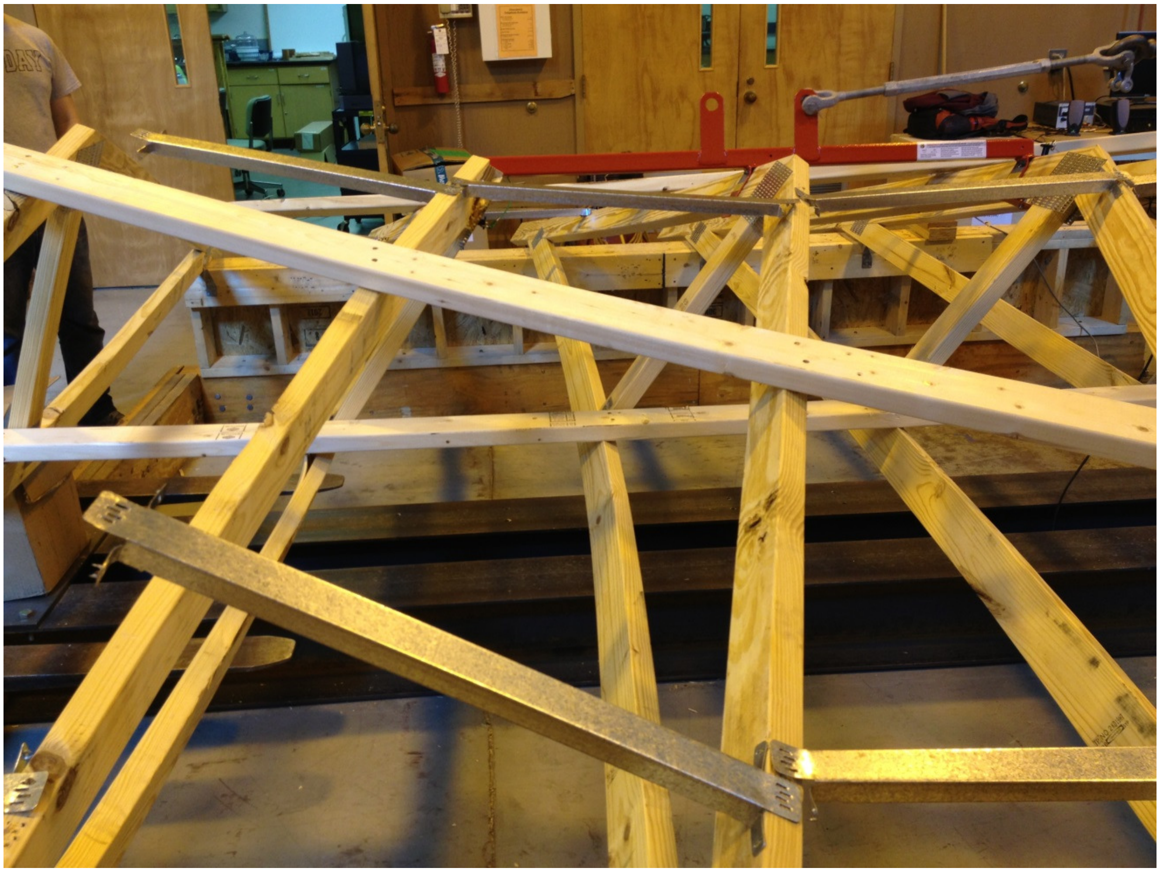

Figure 3-34: Spreader bar and engineered steel bracing failure

Multiple engineered steel braces completely withdrew from the trusses as the load increased (Figure 3-34). When one of the steel braces failed, the load was transferred to another brace which would fail as well. As the steel bracing failed, the trusses deflected significantly resulting in failures in the diagonal bracing as well as the spreader bar. The primary source of failure was located in the engineered steel bracing.

The short penetration of the prongs resulted in withdrawal and abrupt failure in the bracing which resulted in a low ultimate load. As each of the steel braces failed, the deflection of the system increased, resulting in failures in the diagonal bracing, spreader bar, and hurricane clips. Figure 3-35 is a photograph of the engineered steel bracing withdrawing from top and sides of the truss.

Figure 3-35: Failure in the engineered steel bracing

The load vs. displacement curve shows multiple drops in load resulting from failures of the engineered steel bracing. After the initial failure, the roof system reduced load as each brace failed, then regained load until the next failure. As the engineered steel bracing failed, the stresses from the loading were transferred to the diagonal bracing, bottom chord bracing, and spreader bar. Without the diagonal and bottom chord bracing, the abrupt failures of the steel bracing would have resulted in complete failure of the roof system. Though the system was able to maintain the load placed on it, the deflection continued to increase which ultimately lead to failure. The abrupt failures in this test are not ideal however the roof system recovered from the failures and was able to maintain its strength throughout the test. Therefore, it can be noted that the system performed in an appropriate manner and the anchor point was preserved. Figure 3-36 is the load vs. displacement curve of the spreader bar anchor with the engineered steel bracing.

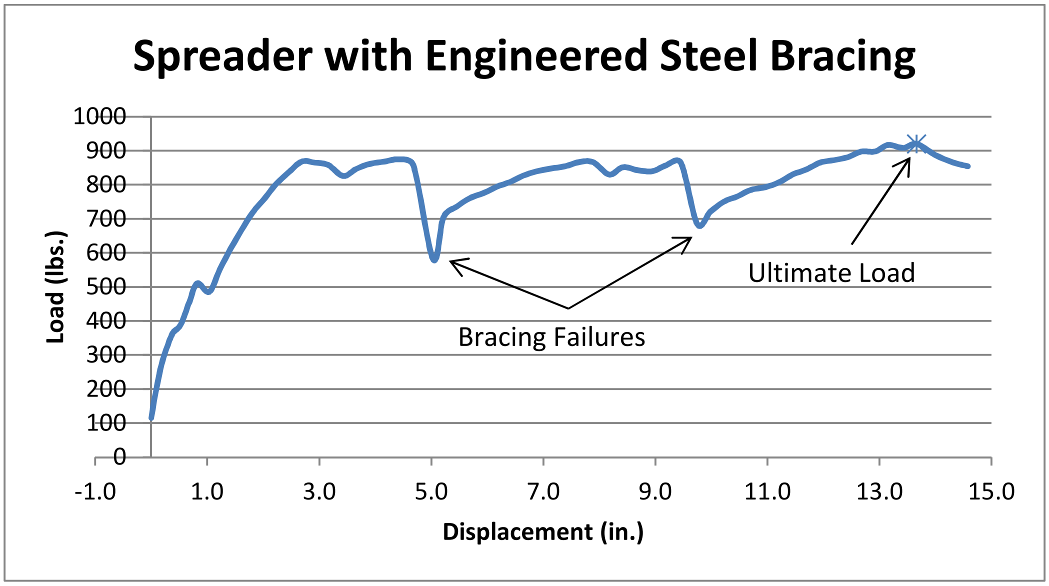

Figure 3-36: Load vs. displacement curve for spreader bar and engineered steel bracing

3.4 Additional Testing

Additional testing was performed to examine anchor and bracing methods based on observations from the previous experiments. Considering the ultimate loads, deflection, and performance of the roof system, the best anchor and bracing configuration was the cross-arm strap with in-between wood bracing. Also, “sway bracing” (Figure 3-37) and changing the in-between bracing location to the same side as the anchor were used to strengthen the truss system (Figure 3-38).

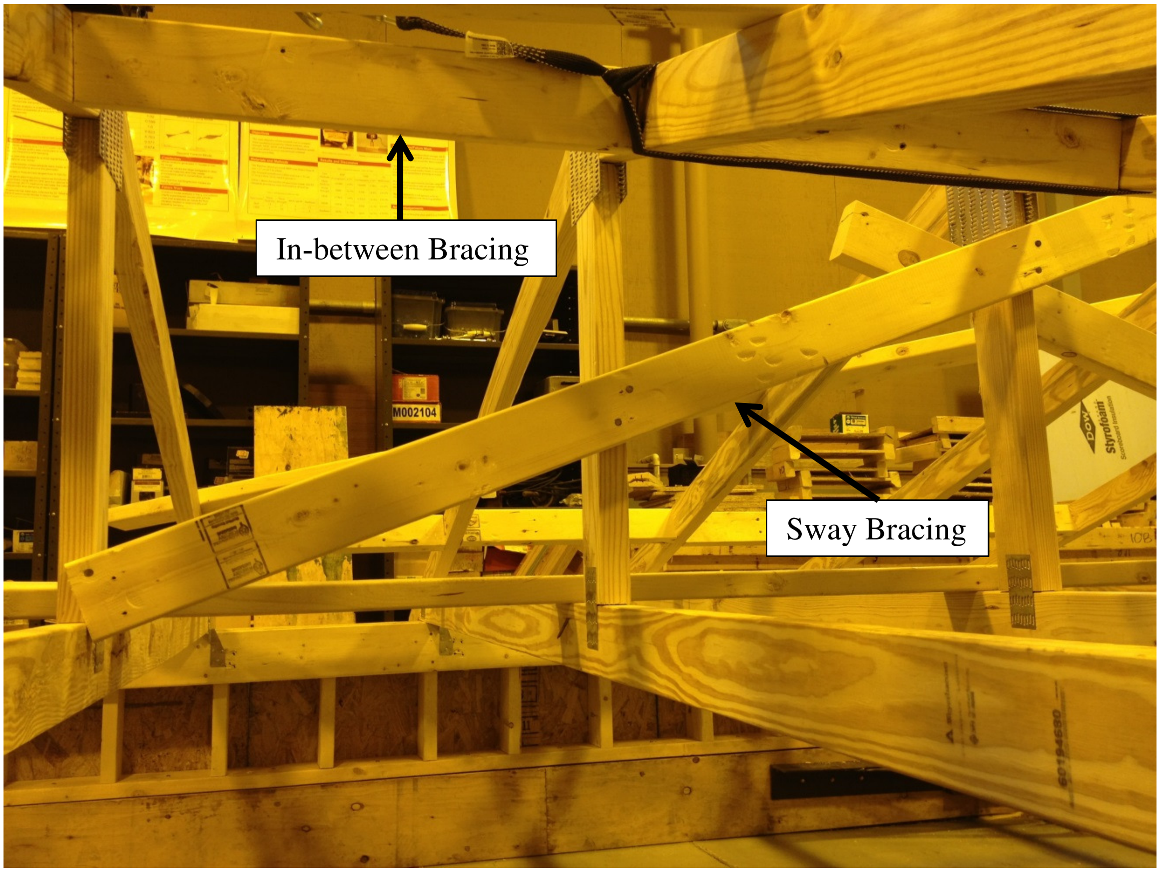

Figure 3-37: Sway bracing attached to king posts of the trusses

Figure 3-38: In-between bracing placed on the same side as the anchor

Sway bracing forms a triangle perpendicular to the plane of the trusses to prevent out of plane movement and system buckling (SBCA, 2012). Sway bracing used extended from the king post of the center truss to the bottom chord each outside truss. This particular type of bracing was chosen based on observations of the failure modes of the previous tests. Prior tests showed failure in the trusses as the trusses folded over or bent at the truss/wall connection when the load was applied.

The in-between bracing was moved to the same side as the anchor to stiffen the trusses and prevent failure at the concentrated load. Previously, the bracing was placed on the opposite side of the truss so that it was not in the way of the anchor. However, after the previous testing, the bracing would prevent the strap from cinching and only loaded one truss which provided strength. The better connection should disperse the load reducing failure at the single truss. The location of the bracing still complies with the SBCA with the only difference being the side of the roof system the brace was placed on. Figure 3-39 is a photograph of the test setup for both tests performed.

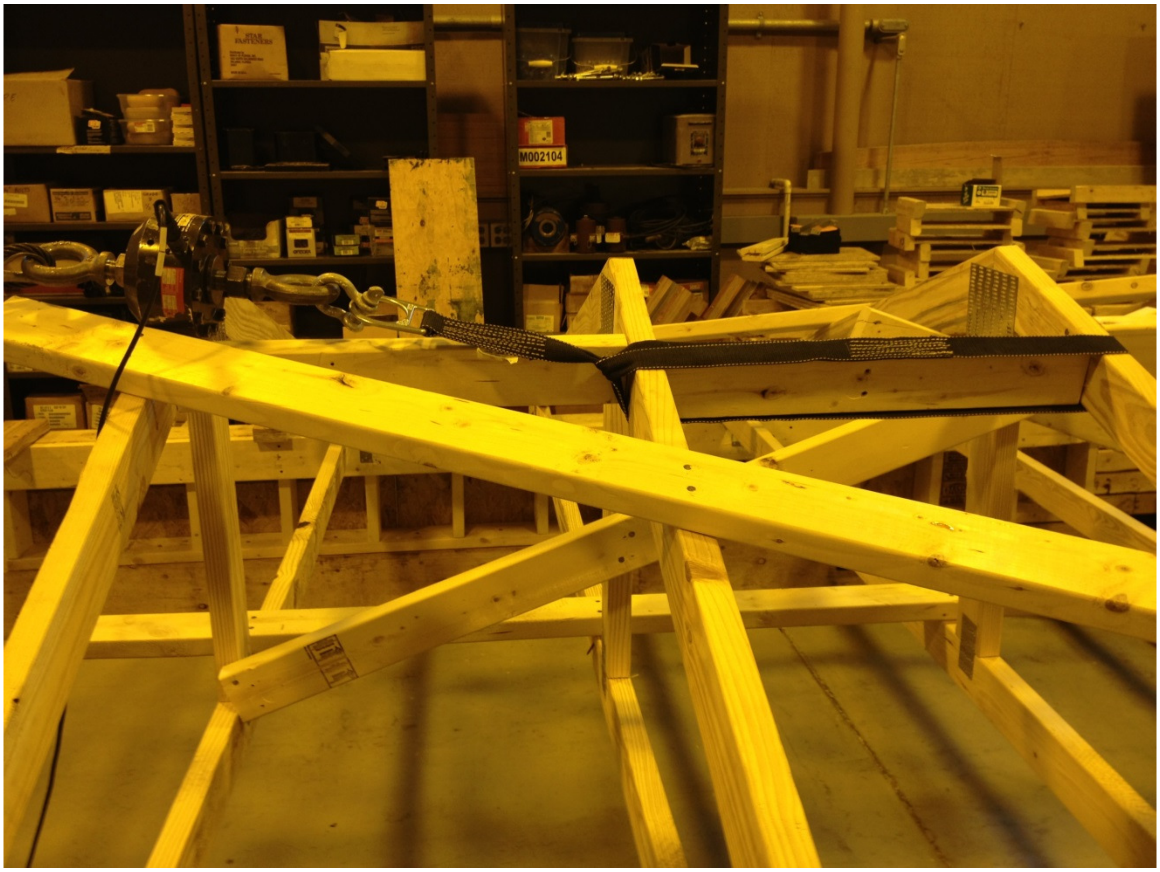

Figure 3-39: Test setup for additional testing

3.4.1 Response of Additional Testing

Movement of the in-between wood bracing and addition of the sway bracing proved to add load to the roof structure. The in-between bracing places near the strap anchor provided a greater distribution of load spread over multiple trusses. In previous testing of the cross-arm strap and in-between bracing, the failure was located at the truss plate of the single truss due to the concentrated load applied by the cross-arm strap. With the in-between bracing at the same location as the anchor, the load was transferred throughout the system as opposed to a single truss. This load transfer produced better performance of the truss system. Results of the additional testing are given in Table 3-4.

Table 3-4: Results of the additional testing

Test Number	Ultimate Load (lbs.)	Displacement (in.)	Failure Mode
1	1,812	14.16	Defect in Outside Truss
2	2,436	16.57	Bottom Chord of Outside Truss

The sway bracing proved to be an important addition to the roof structure. Previous testing showed an overturning, or racking, of the trusses which created large deflections. As the trusses began to rack, the lateral and diagonal bracing withdrew from the trusses, which lead to a loss in strength and eventually failure of the truss system. The sway bracing greatly reduced the racking of the trusses by reinforcing the peaks of the trusses. The load was transferred from the anchor point to the sway bracing which prevented the trusses with the anchor attached from overturning. Since the trusses carrying the greatest load did not overturn, other elements in the system did not rotate.

3.4.2 Results of Additional Test #1

Failure in the truss system came when the load was transferred along the sway bracing to the bottom chord of the truss closest to the HALT. This failure was expected due to the large load placed on the sway bracing as it resisted the overturning of the trusses (Figure 3-40). After the truss system failed, a large defect was found at the point of failure. A large bark pocket was located inside the bottom chord of the truss which lead to the ultimate failure (Figure 3-41).

If the defect was not present, the max load would have been greater. However defects such as bark pockets (Figure 3-41) may be observed in trusses and should be accounted for when considering fall protection. The good performance of the bracing allowed the system to exceed all loads that were previously documented.

Figure 3-40: Failure in the truss

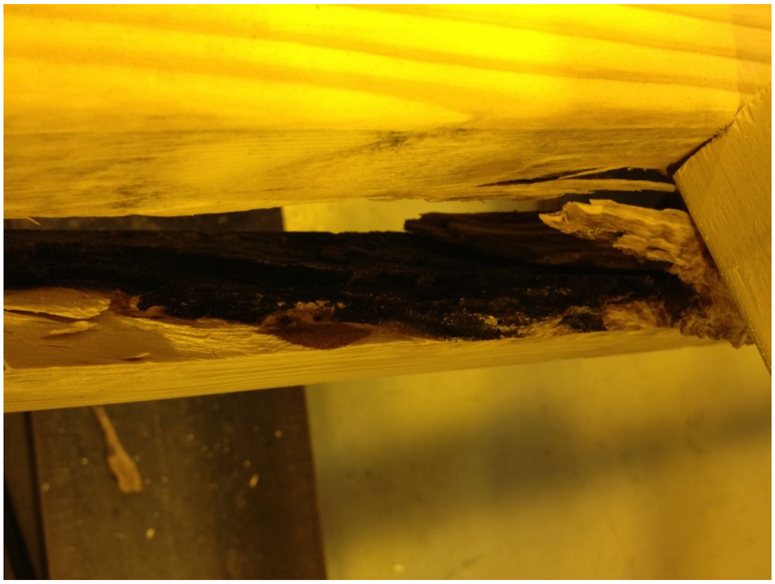

Figure 3-41: Bark pocket located at the failure point

This test had an ultimate load of 1,812 lbs. and an overall displacement of 14 inches. The ultimate load was greater than previous testing, while the displacement is approximately the same despite the higher load. Once the system reached ultimate load, corresponding to failure at the first truss, the trusses began to rack. The failures lead to a series of load drops as well as a large increase in displacement and did not preserve the anchor point. Figure 3-42 is the load vs. displacement curve of the first additional testing.

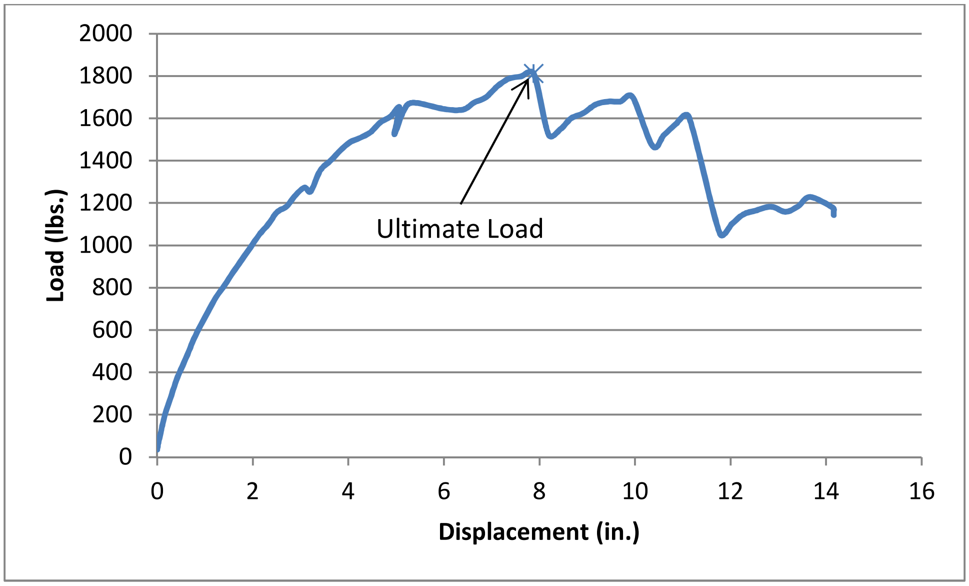

Figure 3-42: Load vs. displacement curve for additional test #1

3.4.3 Results of Additional Test #2

The second of the additional tests repeated the same configuration as the first additional test. The lateral and diagonal bracing performed similarly to the previous test. Although the test showed many similarities to that of the first additional test, the failure mode was completely different. Ultimate failure was located in the bottom chord of the truss located closest to the HALT (Figure 3-43). As the load transferred from the sway bracing into the bottom chord of the truss it began to bend which eventually lead to failure in the wood (Figure 3-44). As seen in Figure 3-43, there was deflection in the outside truss due to the addition of the sway bracing. In addition to the reduced deflection, this test provided the greatest load of all the tests.

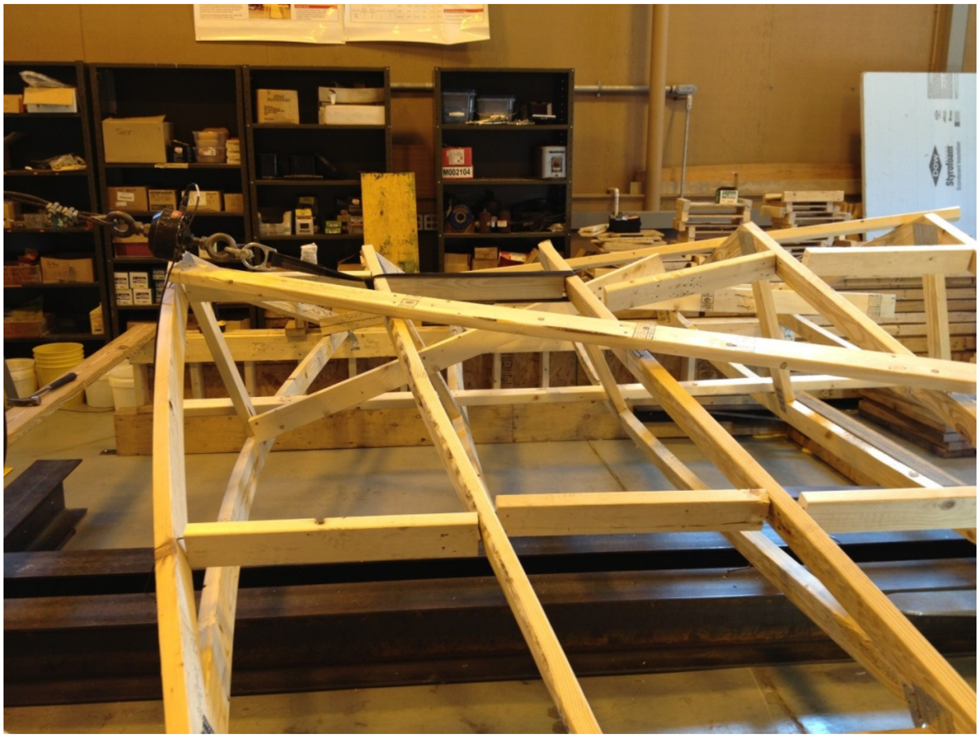

Figure 3-43: Additional test #2 failure

Figure 3-44: Failure in the bottom chord of the truss

The load displacement curve shows the load reached 2,436 lbs. This is the greatest ultimate load of all the tests. Both of the additional tests showed greater loads than previous testing because of the addition of the sway bracing as well as the movement of the in-between bracing to the same side as the anchor point. These methods are both minor steps when bracing a roof system that proved to increase the strength of the truss system. To reach an anchor point strength that is compatible with OSHA regulations, both the lateral bracing location and sway bracing must be considered and implemented where needed. Figure 3-45 provides the load vs. displacement curve of the second additional test.

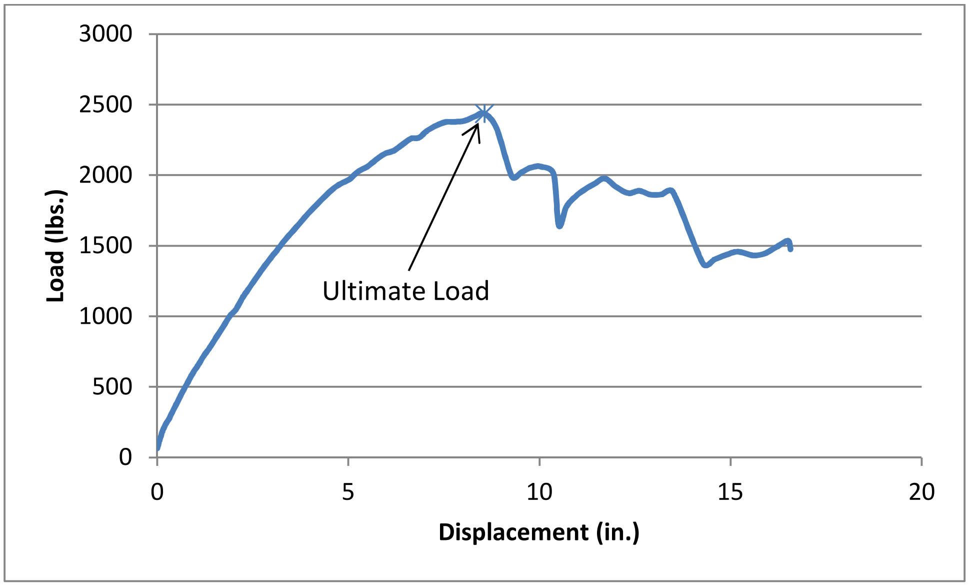

Figure 3-45: Load vs. displacement curve for additional test #2

3.5 Summary of Ultimate Loads and Failures

A summary of the maximum loads and failure modes is given in Table 3-5.

Table 3-5: Summary of maximum loads and failure modes

Full Factorial		
Bracing Type	**Ultimate Load (lbs.)**	**Failure Mode**
Post Frame Anchor		
Wood in-between	726	Post frame anchor
Wood on-top	752	On-top bracing
Engineered Steel	571	Engineered steel bracing
Cross-arm Strap		
Wood in-between	1,412	Truss plate at anchor point
Wood on-top	875	On-top bracing
Engineered Steel	1,084	Engineered steel bracing
Spreader Bar Anchor		
Wood in-between	1,245	Truss plate at anchor point
Wood on-top	1,320	On-top bracing
Engineered Steel	919	Engineered steel bracing
Additional Testing		
Wood in-between	1,812	Defect in outside truss
Wood in-between	2,436	Bottom chord of outside truss

3.5.1 Anchor Comparison

Each of the anchors used in this research was selected based on design and application in the field. The post-frame construction anchor was the "control" for the testing because of previous research and represented anchors that attach to a single truss. The cross-arm strap represented strap anchors widely used throughout the construction industry. The spreader-bar anchor represented a unique form of anchor that braces and engages multiple trusses while providing an anchor point.

Of the three anchors, the post-frame anchor produced the lowest maximum loads since only one truss was engaged. The anchor placed a moment on the single truss which lead to failure at the anchor point. Additionally, the post-frame anchor was the only anchor to be the source of ultimate failure. The brackets of the anchor were not capable of withstanding the moment applied by the loading. The strap placed around the post-frame anchor was used for precautionary measures and was often the only element maintaining the attachment of the anchor and truss. Previous research concluded that a personal fall arrest system should not be anchored to a single truss (Hindman and Koch, 2012). The testing discussed in this paper supports that conclusion.

The cross-arm strap performed well in the testing and was the only anchor that did not fail and was chosen for the additional testing. The strap was very durable and could provide an anchor in the field that may be reused several times before replacement. The cross-arm strap did create a concentrated load on a single truss much like the post-frame anchor. However the cross-arm strap did not apply the moment that the post-frame anchor did due to the lower height of the strap laid flat on the trusses. The location of the bracing is also key to using the cross-arm strap. With the bracing on the opposite side of the trusses as the strap, nothing prevented the single truss from carrying the concentrated load. When the bracing was moved to the same side as the strap, the load was dispersed throughout the system as it engaged multiple trusses. The engagement of multiple trusses was crucial for the performance of the truss system. With the proper bracing configuration, the cross-arm strap is capable of providing a reliable anchor point.

The spreader bar anchor provided the greatest average load among the three anchors. The multiple truss engagement and design of the spreader bar braced three trusses, as opposed to the previous anchors which placed a concentrated load on a single truss. The load was spread throughout the truss system by the anchor and helped to maintain the overall strength. The spreader bar was not the source of ultimate failure in this testing. However, the spreader bar was damaged during each test which required it to be replaced. Considering the cost of the spreader-bar anchor is 3 times more than the other anchors, the need to replace the anchor after the instance of a fall could influence anchor selection.

3.5.2 Bracing Comparison

In-between wood bracing proved to be the most reliable form of bracing and lead to the greatest ultimate loads. The results show that the in-between bracing was not the source of failure in any of the testing performed. The ability of the in-between bracing to pinch in-between the trusses allowed the bracing to continue to transfer load through the truss system. Tests that utilized the in-between bracing showed fewer failures in the bracing than other bracing tests. Locations of failure occurred in the anchors as well as the trusses themselves. This was related to the added strength provided by the in-between bracing. The in-between bracing was the only configuration that maintained contact between trusses throughout the duration of the test.

On-top wood bracing did not perform as well as the in-between bracing and was the source of failure in each test it was utilized in. As the system deflected, the on-top bracing withdrew from the tops of the trusses and failed to provide support to the system. The load was then transferred into the diagonal bracing as the on-top bracing failed. The diagonal bracing was not capable of carrying the load by itself so it too would withdraw from the trusses. A more consistent attachment method of bracing should be used.

The engineered steel bracing performed poorly in the testing and was the source of failure in each test it was utilized in. The bracing was very easy to install and the design provided permanent bracing as well as temporary bracing. The prongs were much easier to nail into the trusses and did not require the use of nails. During testing, many of the metal prongs withdrew from the wood soon after the load was applied. This lead to a “domino effect” of failures as the load transferred from one brace to another. The abrupt failures in the bracing lead to a significant loss strength of the roof system.

4.0 Summary and Conclusions

4.1 Summary

The goal of this research was to measure the behavior of a five truss roof system with various anchor points and bracing configurations loaded by a horizontal force. Although fall arrest requirements are given by OSHA, there are several areas requiring further research such as anchor points during roof erection. Anchor points and bracing methods that can be used during the erection of a roof were the primary focus of this research project.

Testing was performed on three different anchor types as well as three different forms of temporary bracing to measure maximum loads that could hold a worker if they were to fall from a roof. The three anchor types tested represent common anchors currently used in the construction industry. The three bracing methods of attachment were also common to the construction industry and are recommended by the Structural Building Components Association (SBCA). The methodology of this research represented out of plane loading of a truss system.

4.2 Conclusions

The following conclusions were derived from the testing performed in this research and should be used by a qualified individual to determine a feasible anchor point and bracing method during the erection of roof trusses.

- Preservation of the anchor point is key to providing a reliable fall arrest system.
- To reduce the load applied at the anchor point, multiple trusses must be engaged by both the anchor and bracing to transfer the load throughout the roof system.

- It was confirmed that you should not attach a fall arrest system to an anchor that engages a single truss.
- Anchors that lay flat on the roof system do not apply as much of a moment to the truss system and should be used whenever possible.
- Short member, temporary lateral restraint bracing should be used and nailed in-between the trusses to strengthen the roof structure. This bracing should be installed on the same side of the roof system as the anchor point or on both sides of the roof.
- It was confirmed that diagonal bracing should be used along with temporary lateral restraint and installed on the first five trusses and every set of five that follow.
- Sway bracing is a crucial element of the truss system and should be installed to prevent the trusses from overturning when a lateral force is applied.

4.3 Limitations

This project was designed to test anchorages and bracing configurations for use with a personal fall arrest system. Several limitations were noted and are listed in the following section.

- Due to the design of the Horizontal Application of Load Test (HALT), the maximum pull distance was limited to 20 inches. Though each of the tests failed prior to the 20 inch maximum, simulation of a fall could not be completed with a limited pull distance.
- The maximum load rate of the HALT was 20 in/min. Considering a fall from a roof system presents an impact load on the anchor point, a fall scenario could not be recreated and the results of the study should not be compared to an impact load.
- Each of the tests was loaded horizontally. Although this was determined to be the worst loading direction, the loading direction of a fall would be both horizontal and vertical.

- A full scale roof system could not be created due to space requirements and the design of the HALT therefore only one roof truss design and slope was tested.
- A small sample size prevented an accurate statistical analysis of the testing.
- Due to the time and resources expended on each test, only one test of each configuration was performed. Statistical testing of the results could not be completed due to the small sample size of the tests.

4.4 Future Research

Future research should be performed on anchor points for a fall arrest system utilizing an impact load on a full scale roof system. Drop tests should be performed on a residential structure using the anchor types and bracing methods that were tested in this study. This testing will provide results that replicate that of the loading during a fall scenario and can be used to determine whether or not the anchor point meets OSHA's fall protection criteria.

Additional loading directions should be tested in order to determine the worst plane of loading. A fall from a roof would apply horizontal as well as vertical forces to an anchor point and should be considered for future research.

Fasteners such as ring-shank nails and screws should be utilized in future testing to measure the difference in withdrawal tendencies throughout the roof system.

Roof systems with varying amounts of sheathing should be tested to measure the load capabilities of a roof with sheathing as opposed to strictly temporary bracing.

Future research should be performed on building a roof system on the ground before hoisting it into place using conventional craning methods. This process is known as truss rafting and is quickly becoming a popular form of roof erection in the residential construction industry. Building the roof system on the ground minimizes fall hazards that are presented if the roof is built on the structure. The rafted structure also provides a place to attach fall arrest anchors as needed for the subsequent construction practices.

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