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ENGINEERING SPORT SAFETY: A STUDY OF EQUESTRIAN CROSS COUNTRY EVENTING

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ABSTRACT OF THESIS

ENGINEERING SPORT SAFETY:
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The sport of equestrian cross country eventing has seen many serious and even fatal injuries due to rotational horse falls in recent years. The sport originally consisted of horse and rider teams jumping stationary, wood fences. However, in a move towards increasing safety for horses and riders, frangible and deformable safety devices have been emerging in the field. This thesis provides an overview of safety designs that are currently available and those that are on the horizon. Also, a path-finder method of evaluating and developing safety fence designs was outlined and applied to two distinct designs, a hinged gate and a collapsible table fence. A full size prototype of the hinged gate was constructed and tested in the field in two different locations. The collapsible table fence design was developed and then a ½ geometric scale prototype was constructed to demonstrate design feasibility and to analyze design development challenges.

KEYWORDS: Equestrian, Cross Country Eventing, Rotational Falls,
Safety Fence Designs, Frangible Technology

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______August 02, 2010_______

ENGINEERING SPORT SAFETY:
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Katherine M. Kahmann

The Graduate School

University of Kentucky

2010

ENGINEERING SPORT SAFETY:
A STUDY OF EQUESTRIAN CROSS COUNTRY EVENTING

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Mechanical Engineering in the College of Engineering
at the University of Kentucky

By

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Lexington, Kentucky

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2010

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During the course of this project, numerous field experts, safety device designers, and other researchers have been consulted. While the list is too exhaustive to show here, I would like to thank all of these individuals whose input has been very helpful in this research and all contributors who are mentioned during this thesis. In particular, I would like to thank all individuals from the United States Equestrian Federation and the United States Equestrian Association who have made this project possible as well as Mick Costello and his Jump Building Team at the Kentucky Horse Park. I also would like to particularly thank the researchers at the University of Bristol and TRL in England, as well as individuals from British Eventing for their contributions.

The funding for this project was provided by the United States Equestrian Federation, the United States Equestrian Association, and through the Lexmark Graduate Fellowship. I would like to thank all three of these sponsors for their generous support and for making this work possible.

Finally, I am thankful for all of God’s blessings in my life and the direction he has given me. I want to thank my family (both old and new) for all of their love and support and many hours of listening to my ramblings about research challenges and triumphs. Thank you to my dad, Paul Kahmann, for the helpful discussions and suggestions. I would especially like to thank my best friend (and fiancé) for his love and support he has given me throughout our many years of going through engineering school together.

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Chapter 1: Introduction

1.0 Cross Country Eventing Safety

The sport of equestrian eventing is a three-phase competition consisting of dressage, cross country, and stadium jumping. The competition can be spread out over three days or compressed into one day. In 1912, eventing made its debut at the Olympic Games in Sweden. As stated by the International Equestrian Federation (FEI), the purpose of the sport was, and still is, to 'show the rider's spirit, boldness, and perfect knowledge of his horse's paces and their use across country and to show the condition, handiness, courage, jumping ability, stamina, and speed of the well trained horse' [26]. An example of an eventing competition is the Rolex held every year at the Kentucky Horse Park in Lexington, Kentucky.

While the sport has been around since 1912, in the last 10 years serious and fatal injuries have occurred to horses and riders, largely due to rotational falls. A rotational or somersault fall is when a horse and rider pair impact a solid fence and rotate over it, causing the horse to land on its back on the other side. When a rotational horse fall occurs, the rider's chance of being trapped by the horse increases drastically, along with the probability of serious injury. A more comprehensive history of the sport and the current safety challenges is outlined in Chapter Two, Literature Review.

1.1 Goals and Objectives

The sport of Eventing has recently initiated a number of efforts with the goal to improve safety. Among these, the United States Equestrian Federation (USEF) and the United States Equestrian Association (USEA) is sponsoring a research project at the University of Kentucky to evaluate frangible and deformable technologies and safety fence designs. The University of Kentucky Research Team consists of Dr. Suzanne Weaver Smith (lead project advisor), Dean Grulke (project advisor), Michelle Tucker (bio-systems and agricultural engineering undergraduate student), Isaac Scherrer (mechanical engineering undergraduate student), and Chad Burgin (mechanical engineering undergraduate student). Two senior design teams were also associated with the overall project. While the team worked together on the same overarching project goals, each member had specific responsibilities and areas of study. Michelle Tucker focused on analysis of horse impact data and video provided from British researchers. She also helped evaluate the use of the instrumented sledge hammer as a suitable horse impact tester. Isaac Scherrer and Chad Burgin worked together to evaluate and expand the Prolog® safety design. They also developed, built, and tested wood foam composite fence rails. The two senior design teams each focused on the development and preliminary evaluation of a new safety fence design.

My contributions as a member of the UK research team are documented in this thesis. The overall objective of this effort is to develop a process for evaluation of eventing safety designs. Several sub objectives comprised the effort of this thesis:

1) to survey the current state of research and available safety designs within the sport
2) to create a safety design evaluation and validation process
3) to apply the evaluation process to existing designs
4) to determine the process's applicability to the wide range of safety designs within the sport

The multi-disciplinary nature of sports safety in general and eventing safety in particular necessitate a collaborative research effort. Any areas that were contributed by or assisted by another researcher are identified here in the introduction or within each chapter.

During the course of this project the UK team has networked with experts in the field including the President of the USEF, David O'Connor, as well as, the Chief Executive of British Eventing, Mike Etherington-Smith. The team has also met with course builders and course designers on multiple occasions. In addition, members of the team spent a week in England coordinating with British Eventing sponsored researchers at the University of Bristol and at the Transportation Research Laboratory. The project has involved communication with other safety device designers both nationally and internationally. These many discussions have helped to provide background about the sport's history, culture, and future directions.

1.2 Thesis Outline

Chapter Two of this thesis includes a summary of the history and rules of eventing and specifically the cross country portion. Also, the current safety challenges and the steps being taken within the sport to decrease risk to both horse and rider are outlined. The literature review includes an overview of studies and research that have been conducted on the properties of a horse's body and the motion of jumping.

As reference for what frangible and deformable fence designs are currently available, Chapter Three summarizes the key attributes of the known safety fence technology and devices.

Chapter Four introduces relevant testing methods and capabilities from other fields as well as testing methods used for representing horse impacts. The chapter also discusses the process of design evaluation including computer modeling, prototyping, laboratory and field testing, and implementing designs.

The design concept studied in Chapter Five was first suggested by the David O'Connor. The chapter provides a description of this particular safety fence design, the hinged gate. The hinged gate's background and use is explained, before outlining the application of the aforementioned process of design evaluation. During the course of the design evaluation, I constructed a full size model of the hinged gate for field testing at two locations (a private farm and the Kentucky Horse Park).

Chapter Six presents the need within the sport for safety fence designs for additional types of fences. During this work, I developed a collapsible table safety fence design and constructed a scaled prototype of the design for preliminary evaluation. This section of the thesis presents the design goals and challenges, along with results.

Chapter Seven closes the thesis with a summary, conclusions and recommendations for future work.

Additionally, Appendices A and B provide a summary of the construction supplies and cost for both the hinged gate and collapsible table fence built for this Thesis. Appendix C provides a list of the fences included in the cross country portion of the 2009 Rolex as well as pictures of a selection of the fences. Appendix D outlines the process to install one of the current frangible devices, the frangible pin system. Throughout the thesis English units are used (with metric in parenthesis for reference where useful).

Chapter 2: Literature Review

2.0 Introduction to Eventing

The sport of Eventing was initially created as a test for military horses and riders. Originally, only active Army officers and active military horses were permitted to compete in the sport in the Olympic Games. The three phases were designed from fundamental, crucial duties of a military officer and horse team including obedience, stamina, and courage when entering a battle, jumping new obstacles, dealing with rough terrain, and covering long distances when traveling to new locations for battle or delivering messages. Having the competition spread out over three days helped to test the overall fitness and soundness of the horse and rider, since military duties were also not limited to one day of intense activity.

Since 2004, the current “short format” has been used in the sport consisting of dressage, cross country, and stadium jumping; one each day for three days. The change was made for the 2004 Olympics as a result of the International Olympic Committee threatening to remove the sport from the Olympics. Essentially, the format of the second day went from three sub-sections and approximately 16 miles to a single sub-section covering approximately 3.75 miles [15]. The original three field requirements consisted of steeplechasing, “roads and tracks”, and cross country. The “short format” now only has cross country on the second day. Eventing is often referred to as a “Three-Day Event” or “combined training” since the competition generally occurs over three days and requires many different skills to be competitive. The sport is somewhat unique in that men and women compete against one another on equal footing [26].

Competitions are identified by their category and level of difficulty. Categories include National Three Day Events (CCN), International Three Day Events (CCI), International One Day Events (CIC), and Championships (CH). The level of difficulty is identified with a star rating where higher difficulty coincides with a higher number of stars. CCI events include 1* up to 4* events and CIC events range from 1* up to 3* [62]. The only 4* CCI event held in the United States is the Rolex Three-Day Event held every year at the Kentucky Horse Park in Lexington, Kentucky. To win the Grand Slam of Eventing a competitor must win the Rolex at the Kentucky Horse Park as well as the two CCI 4* events held in England, Badminton and Burghley Horse Trials [57].

2.1 Focus on Cross Country

The second day of the competition, the cross country test, consists of a horse and rider team attempting a course of a maximum number of 29 to 45 jumping efforts (depending on the competition level and identification), while traveling across rough terrain and open fields in an optimum time. Penalties are applied to the competitor's score if the optimum time is exceeded or as a result of fence refusals [62]. The rider is permitted to walk the cross country course on foot before the competition begins, but the horse is not permitted to ride near or jump the fences before entering the cross country phase.

The sport rules are continuously updated as new frangible and deformable safety devices are introduced. The 2010 Rules specify that a rider is given 25 penalties (at the discretion of the ground jury) if a frangible device is broken [62]. The qualifications to compete and the specific rules of the competition are specified by FEI for international competitions. The complete set of rules can be found on the FEI website [62].

The fences in the past have typically been solid, stationary, wood fences. At the CCI 4* level ("four-star" level), fences can be almost 4' tall with a 6' spread from front to back. Appendix C includes a list of the fences that were included in the cross country phase of the 2009 Rolex [49]. The allowed dimensions of fences are specified in the FEI Eventing Rules [62].

2.2 Safety Concerns

In the five year period starting in 2002 and ending in 2006, the Equestrian Federation of Australia (EFA) helped organize a national data collection system in an effort to gather accurate data that could be used to make the sport of eventing safer. In the three years leading up to 2000, over 12 riders died in eventing competitions held in the United Kingdom, Ireland, and Australia. In the United Kingdom, four out of the five rider deaths occurred in rotational falls where the horse hit a solid fence, flipped, and landed on the rider. All five deaths occurred in one four month period in 1999. According to FEI data and other research, the greatest risk of serious injury within the sport is when a rotational horse fall occurs. This Australian report titled "Safety for Horses and Riders in Eventing" found that between May 1997 and September 2007, 25 riders died in eventing competitions worldwide. Out of these 25 deaths 18 rider deaths were tied to rotational horse falls [39].

These statistics do not include the risk of serious injury or death for the horse. In the United States, between November 2006 and May 2008, at least 6 horses died in the cross country phase of eventing competitions. Causes of horse deaths within the sport include broken bones or internal injuries from rotational falls and "cardiopulmonary hemorrhage" during competition [16]. Denny Emerson, who is a past president of the

United States Eventing Association (USEA) and a member of the Gold Medal Team in the eventing 1974 World Championship, summed up the situation the sport is currently facing, ‘you cannot have a sport where the price of a mistake, even a stupid mistake, is flipping and possible serious injury or death’ [15].

2.3 Increasing Awareness and Safety Discussions

As a result of the increased occurrence of serious injury and deaths within the sport, top eventing riders and leaders have been discussing reasons behind the increased accidents. Although the sport of eventing has always had risk associated with it, a significant number of serious injuries and rotational falls have only been occurring recently. One of the first widely publicized rider deaths due to a rotational fall happened in 1999 at Burghley in England, even though the sport has been around since the early 1900’s [59]. An Eventing Safety Summit was held on June 7 and 8th, 2008 in Lexington, KY. The event was organized by the United States Equestrian Federation (USEF) and USEA “as a response to an uncharacteristically tragic Eventing season” [46].

The safety summit had over 250 attendees, including fans, coaches, riders, trainers, course designers, and veterinarians. The overall goal was to come up with “five to seven potential solutions that were both feasible and effective.” The summit was subdivided into four different areas including veterinary/medical, course design, education, and qualifications. In order to start the discussion, the USEF President and eventing competitor, David O’ Conner, and the USEF CEO, John Long, summarized the challenge with statements. Mr. Long admitted ‘our sport is in trouble [but] by showing up here we’re collectively acknowledging that things need to change.’ David O’Conner, a past Rolex winner himself, encouraged focusing on ‘reducing horse falls,’ instead of specifically focusing on just reducing rider falls in order to improve overall safety [40, 46]. After all, Mr. O'Conner explained, 'there is an assumed risk in our sport. We can't stop people falling off all the time' [46]. At the summit several issues and topics were raised, including the following:

- increasing use of frangible/deformable fence technology,
- monitoring speed of competitors on course,
- discussing the appropriate level of technicality in courses,
- considering issues that may affect the overall health of the horse (fitness, horse age, training, safety equipment, etc.),
- considering rules associated with required rider qualifications,
- determining whether instructors should be required to be certified/licensed,
- creating a watch list for dangerous riders, and
- considering what data collection could add to the safety of the sport.

In September 2007, a Safety Task Force, created by the USEF in further response to "several tragic injuries and fatalities" in the US and around the world at the end of 2006 and the beginning of 2007, released a report with recommendations on safety within the sport. Their recommendations included instituting rules to increase accident preparedness at USEF-licensed eventing competitions, creating a uniform way of collecting data and reporting serious accidents, and determining feasibility of tracking rider falls, injuries, and notices of dangerous riding [19]. The FEI has also set up a Safety Committee, which was lead by David O'Conner and had a meeting in Copenhagen in January 2008, with representatives from 22 nations [18].

2.4 Risk Factors

The committees and discussions in the US and internationally seem to address with a fundamental theme – What has changed in the sport to cause these problems and how can the sport adapt to face these challenges? Mike Etherington-Smith, the Director of Sport for British Eventing, summarized the situation saying "We need to ask ourselves what, if anything, has changed in recent years that could be causing the accidents." He suggests that it is likely a mixture of many contributing factors [20].

One factor is the major change made in 2004 from the "long format" to the "short format" consisting of only the cross country portion instead of including the roads and tracks and steeplechase portions as well. Some argue that as a result of this change, the cross country questions or fences have increased significantly in technicality and difficulty for horse and rider. Denny Emerson argues that this change now "demands flawless pace and timing", which is more like show jumping [15]. Another well known eventing competitor, Jim Wofford, states that in his estimation almost half of the cross country fences will now be "some form of narrow, angle, corner, or accuracy question—what some observers have referred to as 'show jumping at speed'" [59]. Unlike show jumping, these fences are set in the field with uneven terrain and often over hills or possibly hidden around turns, leaving horses little time to prepare for each jump. Mr. Emerson pointed this out stating, "these jumps come up on a horse before he has a chance to see it." He also said the increased difficulty has pushed some competitors to the limits of their abilities, suggesting that while rider's skill and ability are very high at the upper levels of competition "the questions are too technical for most horses" [15]. The sport of eventing tests the partnership between horse and rider; therefore, both the horse and rider must be capable. An upper level eventing rider and trainer, Danny Warrington, lost his wife to an eventing accident. He was quoted as saying that the horse his wife was riding when she died ‘did not want to be an advanced horse. But we kept trying to make him [one] because she wanted to go to the Olympics’ [16].

Also, some claim that the culture of the sport has changed over time, thus the ability and training of competitors has also changed. Denny Emerson discussed the necessity of horse and rider competing at the “appropriate level.” In his opinion, the competitive nature of many eventers results in them trying to move up to the next level before they or their horse is ready. Mr. Emerson suggests that many coaches won’t risk losing their student by telling them that they are not ready to compete at the next level [59]. A classic sentiment in the horse world is that a horse and rider pair should not change competition levels until the horse and rider are bored at the current level [16]. Even if qualification standards are increased, a competitor must still analyze their own situation. Just because they may meet the standards doesn’t necessarily mean the horse and rider pair are ready to change levels. However, as suggested in the safety summits and safety groups, increasing rider qualifications, especially for the top events may help improve safety. Denny Emerson commented on the significant difference in riding quality between the top 20 and bottom 20 riders at the Rolex competition in Lexington, KY [15].

Part of the culture change seems to be in the way riders learn to ride. Many riders today board their horses in eventing barns and constantly ride with a coach specifically directing their training. Riders today may not be as prepared for unexpected situations, rough terrain, and difficult jumping situations because as Denny Emerson explains “they don’t grow up galloping bareback up and down hills.” For those who almost grew up on the back of a horse they “just learned how to get it done,” they learned “how to survive bad footing, [and] vertical jumps” [16].

These cultural changes may now be contributing to the increased disrespect that some riders are showing the jumps. Some experts in the field argue that young riders today are approaching jumps with too much speed and not enough balance for the horse to properly and safely take fences in the field. Mike Etherington-Smith pointed out that in recent years fence profiles have been softened with the intent of making it easier for a horse to recover if a rider makes a mistake. However, a possible unintended consequence is that riders may now approach the fences faster, instead of giving the fences the same respect that was seen in the past [20]. The new trend towards frangible and deformable fences may help save horse and rider pairs if they get into trouble, but it has some people wondering if it will also make riders even more likely to run faster and harder at fences that they think will get out of the way if something happens. John Williams, an Olympic rider, discussed his view of this challenge saying ‘the disrespect riders show to the act of running cross country over obstacles is growing faster than the safety of the sport is growing’ [16].

The cross country phase of eventing is not the only portion of the competition that has changed over time; the dressage section of the event has also grown more technical. Jim Wofford argues that in recent years cross country has not changed as much as the show jumping and dressage portions have. He claims that research into other equestrian sports (like steeplechasing) shows that the type of fences horses are being asked to jump and the speeds they are being asked to jump them are reasonable and are not that different than challenges presented in other equestrian sports for as many as twenty years. However, in recent years the requirements of dressage have increased to include “collection” of the horse. This dressage requirement causes the horse to “begin to surrender his body to his rider and he begins to surrender his initiative as well.” If a horse is trained too much in collection some field experts argue that horse will never be the same again. The horse becomes too reliant on the rider, losing his own initiative to take ownership of approaching and taking off at fences. The horse begins to rely almost completely on the rider to direct when and where to take off for a cross country fence. Training under controlled circumstances further teaches the horse to rely on the rider and trust that the rider knows when and where to take off. This can set the partnership up for disaster when the rider inevitably does make a mistake during competition, when the surroundings are unfamiliar and pressure is high. Mr. Wofford sums it up as “more collection, less initiative—less initiative, more falls” [59].

Other slight and seemingly unconnected changes within the sport may also be contributing to the current challenges, for example changes in the current saddles. According to Mike Etherington-Smith, it is possible that modern saddle designs may keep the rider in the saddle longer than older saddle designs. Since riders don’t want to fall off, the shift toward saddle designs that may aide the rider in staying in the saddle at first seem like a good idea. However, when a rotational fall occurs, if the rider stays in the saddle even a fraction of a second longer this may increase the risk of the rider falling under the horse when they do at last fall out of the saddle, instead of falling off away from the horse at the beginning of the fall [20]. Consequently, when addressing the current safety challenges, all factors and aspects of the sport must be considered from many perspectives.

2.5 Data Collection

In addition to the safety summits and safety teams created to understand the current challenges, recent work gathered data on typical competitors' experiences as well as documented accidents as they occur. In 2000, an International Eventing Safety Committee strongly encouraged the creation of an international database organized by FEI to track accidents during competitions, including injuries incurred and specific details about the fence and circumstances surrounding the accidents [4].

In 2001, British Eventing began a database of fall data. The database system was created and is analyzed annually by Transport Research Laboratory (TRL) at Wokingham. TRL has been around for over 70 years and is known for its expertise in motor vehicle safety in which similar database approaches are useful. TRL works on projects ranging from helmets for race car drivers to seat belts for passenger vehicles. The British database holds data including fence, fall, and medical/injury details. Annually, TRL releases a report of the data before the next eventing season begins. This allows the data to be reviewed and changes to be implemented based on trends found in the data [50].

Using the 2007-2008 data from British Eventing, risk factors were calculated for common types of falls. If a rider is unseated and falls but the horse does not fall the rider has a 2% "risk of a serious/fatal outcome"; if a non-somersault horse fall occurs there is a 7% "risk of a serious/fatal outcome"; finally, if a somersault horse fall occurs there is a 30% "risk of a serious/fatal outcome" [11]. While these statistics vary from year to year and from country to country, it is clear from this and other research that the risk of serious and/or fatal injury drastically increases when a horse somersaults or rotates over a fence. Therefore, improving eventing safety is focused on decreasing horse falls, and specifically on reducing rotational horse falls.

The US now also has similar data collection in place, organized by USEA and USEF, to track accident information. FEI, the international equestrian body also has overall annual reports on gathered course and accident information. FEI gathers information on the number of overall competitors, falls, and injury information [22]. These databases allow the international and national bodies to monitor types of fences and situations and justify fence removals or rule changes. Overall risk statistics are calculated annually which allow the sport governing bodies to monitor the trend of accidents and serious injury year to year to determine if injury rates are increasing or decreasing on average. As trends are identified new rules or course changes can be implemented in an attempt to improve safety. The 2008 report from the USEF Eventing Safety Officer documented several specific changes that were implemented in the US. These changes included elimination of a competitor from a competition after a fall during cross country, more specific qualification requirements, and specification of dangerous riding penalties [21].

2.6 Available Research

According to David O’ Connor, one significant factor in improving safety is “rider education, rider responsibility, and rider respect” for the courses [18]. However, another major factor is looking for ways to make the cross country courses safer for both horse and rider. Research on the accident data is used to determine types of fences and conditions that may increase risk of injury. In England, Jane Murray completed a PHD research project on factors that may increase the risk of injury to horse and rider. Her findings showed two factors that negatively influenced risk were fences that required the horse to land in water and the combined influence of fence angle and fence width. Other factors that were found to increase risk included the footing in front of the fence, if the riders knew they were in the lead or toward the top of the competition standings, and also if the jump was approached too quickly or too slowly [36].

Research done on safety devices created frangible fences to replace the originally stationary jumps, but until recently there was predominately only one design available. British Eventing sponsored the development of a frangible pin system that consists of two scored aluminum pins that support a horizontal log. If the critical vertical force is applied to the logs during a horse impact then the pins are designed to break, moving the log out of the path of the horse and rider and thus interrupting possible rotational falls (See Chapter Three). In 2008, a group of leaders in the sport including Mark Phillips and Mike Etherington-Smith were quoted as saying “the frangible pin [which is used in Britain and America] is the only thing which has been scientifically tested, and is therefore the only tool we have to prevent the rotational fall without changing the nature of the sport” [18]. The frangible pin system is a device that is only applicable to a selection of the cross country fences in use around the world. Therefore there is still a need for the development of additional frangible or deformable safety devices.

This thesis is part of an effort at the University of Kentucky to explore new safety designs with two goals in mind (prevent rotational falls and don’t drastically change the nature of the sport. Chapter Three, Overview of Cross Country Eventing Safety Designs, explores the safety devices that are currently available, the ones that have been recently developed, and the ones that may be on the horizon. Chapter Four of this thesis, Testing & Validation Methods Capabilities, further explains some currently-available testing and evaluation methods used in eventing and other related fields.

Research is available on the kinematics of horses in general and the motion of horses while jumping. Equestrian riding has been cited as having the “highest mortality [rate] of all sports.” Part of this risk is likely due to the significant size and power of horses. Some horses have a mass of as much as 34 slugs, are capable of moving at approximately 40 mph, can kick with approximately 2,000 lb, and support riders approximately 9.5 ft in the air [3]. Note that in this thesis the English system of units was used. In some cases, research is presented in metric units if the relevant research in that area is also in metric. The English units are provided in parenthesis for reference.

Seven reports [35, 44, 45, 8, 9, 17, 31] provide examples of the research papers published on center of mass and related factors that contribute to the motion and power of these massive creatures. A 1995 study video recorded 68 horses during a cross country competition. Using the footage, the researchers studied several factors including the horse’s leads at takeoff and landing and the horse’s airborne time over the fence. The study concluded that “15% of approach strides, 31% of jump strides, and 43% of departure strides were disunited.” These findings were unexpectedly high since a disunited stride is assumed to be “less balanced and less efficient” [35]. This study is particularly interesting in light of the debate about whether riders are approaching jumps with increasingly less balance and whether this may be a contributing factor to increased incidents on course. The paper also concluded that horses ranked higher in the competition were in the air shorter periods of time over the fences. It has been found that the airborne phase of the jump takes the longest period of time in the jumping sequence, which suggests that a horse that is able to shorten this phase may be able to shorten their overall cross country time and thus be more competitive than a horse that is airborne longer [35].

Another example of a research study that qualitatively analyzed the jumping motion of a horse was conducted in 1999. It divided the jumping sequence into 5 different parts: the approach, take off, suspension, landing, and departure. All five sections were then studied for influential factors including speed, body angles, body position of horse and rider, center of gravity, and height over the fences [45].

Many studies have analyzed factors involved in the motion of horses. However, in 2000 a study used common factors to classify 31 “untrained” horses as either “good” or “bad” jumping horses. The researchers concluded that the “good” group of jumping horses, on average, cleared the fence easily, and had greater flexion (proper bending and lengthening) in their forelimbs. Conversely, the “bad” group of jumping horses was considered to consistently knock or hit the fence, had a noticeably higher mean velocity over the fence, had a smaller angle of landing, and landed farther from the fence. Several of these factors are interrelated. A horse with a higher mean velocity and a smaller angle of landing is likely to be landing farther from the jump, which will decrease the distance the horse has to set up for the next obstacle. This may also contribute to a flatter jump, which in turn may make it easier to knock the fence [44]. Another study considered the power and energy necessary in a horse’s hind legs to jump an obstacle [17].

Another factor that is discussed when considering cross country fence safety is the influence the rider's motion and mass has on the horse while jumping. A 2005 study analyzed the repeatability of certain factors of 141 different horses jumping with and without riders. The study included 28 different riders and considered factors including take off and landing distances, different heights of limbs over the fence, and the angle of the horse's head. The repeatability of the parameters was found to be higher when the horses were jumping with riders [31].

Other studies have explored the inertial properties of horses, which can be useful information when attempting to develop mathematical models. One study determined the 3-dimensional inertial properties of horses including the mass, density, center of mass, and inertial tensor. This was done by dividing 6 deceased frozen Dutch warmblood horses each into 26 segments. The data from the frozen segments were then used in a linear regression model to estimate the behavior of living horses. The horses had masses ranging from 470 kg to 620 kg. While this is helpful for estimating live horse motion, the usefulness of the data is greatly diminished if it is not applied to living horses of around the same mass, breed, and body shape as those that were studied [8].

High speed video was used to analyze the body center of mass of 12 live horses while standing, walking, and trotting. These test subjects were warmblood horses with masses ranging from 450kg to 670kg. Horses can be complicated to estimate since living horses are not rigid body systems. This study also showed that horses are in general efficient movers. While the external view of the horse shows significant motion, the study concluded that the body center of mass showed "smooth, small" motion, which conserves energy [9]. Understanding kinematics and inertial properties of horses in general and in reaction to a jump can be used to make mathematical models to assist in developing new designs.

2.7 New Designs and Ideas From Related Fields

When developing new designs it helps to gather ideas from other applications and other fields of study. Due to the flighty nature of horses, many horse-friendly devices have quick releases or breakaway features. For example, breakaway halters have many of the same considerations as a deformable or frangible fence. It must be able to withstand every day “use” or contact, be able to withstand the elements, breakaway safely and quickly in an emergency (i.e. the critical force load is applied), be easily replaceable, and be affordable. Some horse halters are designed with a thin piece of leather strapped to the rest of the nylon halter, because leather breaks at a lower force than nylon. After the leather piece fails, just that piece can be replaced for minimal cost so the halter is ready for use again. Other designs use Velcro release systems, but have problems with releasing at too low a force [27]. While these designs may seem unrelated, they highlight how simple, inexpensive solutions can be implemented in creative ways to design an efficient, reliable, and affordable safety device.

On the other end of the spectrum, frangible devices are in use in the NASA space shuttle program. The space shuttle assembly is attached to the mobile launch platform with a system including frangible nuts. When launch is initiated, explosives known as pyrotechnics are used to release the frangible nuts, disconnecting the space shuttle assembly from the platform. While pyrotechnics are not suitable for cross country obstacles, the NASA system shows that frangible technology is a reliable and relatively efficient choice for releasing systems [54]. For further discussion on how frangible and breakaway technology is being used within the sport of cross country eventing, the next chapter, Chapter Three, presents general safety designs.

Chapter 3: Overview of Cross Country Eventing Safety Designs

3.0 Introduction

One objective of this effort is to unify, validate, and distribute safety device information nationally and internationally. While there are a number of safety devices currently being developed or in production, there is a lack of communication within the sport about what devices are available. Furthermore, the stage of development, extent of field testing, and effectiveness are also largely unknown to the sport as a whole. One contributing factor is that almost every cross country jump is slightly different, whether simply the way it is placed in the terrain or the way it is decorated. Appendix C provides the list of jumps that were used at the 2009 Rolex Four Star Three-Day Event at the Kentucky Horse Park. This list of the 2009 cross country fences, gives an example of how many different fence types exist in just one course. This chapter summarizes the safety designs currently being explored within the sport, possible future concepts, methods for increasing communication within the sport, and key considerations for equestrian eventing and sports safety in general.

3.1 Current Designs

Designs and ideas for improved safety of fences have recently emerged within the sport of eventing. However, the variation in courses means differences in design complexity, and challenges for testing effectiveness. Attributes of current designs from various sources throughout the world are summarized in the following sections. This list doesn’t endorse any design as safe (or unsafe) for use in a course installation. The list is a 2010 snapshot of types of devices that are currently being explored by researchers and developers internationally. Every attempt has been made to be thorough, but other designs may exist that are not included.

3.1.1 British Eventing Frangible Pin

The Transportation Research Laboratory (TRL) in Wokingham, England began their research into frangible devices by gathering data about falls during competitions in 2000 [34]. TRL developed the specifications for the frangible pin under sponsorship of British Eventing. Since that time British Eventing has continued to sponsor work by TRL and the University of Bristol to delve deeper into the frangible pin system. While TRL suggested the possible use of a “frangible element” in several different jump types (Post & Rail, Square Spread, Ascending Spread, and Corner), the frangible pin system is most widely used in the post and rail setup [7]. Figures 3.1 (a) and 3.1 (b) show the frangible pin in action and how it prevents rotational falls. Device installation is described in detail in Appendix D. The system includes a rail supported on either end by a frangible pin which breaks if the vertical load reaches the critical design load. TRL found that a horse is most likely to experience a rotational fall if they impact an obstacle above the knee but below the elbow [28, 34]. The frangible pins are designed to break and interrupt the fixed point rotation, which is intended to keep the horse and rider safe.

(a) (b)

Figure 3.1 Frangible Pins Preventing Rotational Fall [6]

British Eventing is currently sponsoring work to create a 2nd generation of the frangible pin made out of a more brittle material to enable improved failure reliability in the field [5].

3.1.2 Expanded Polystyrene Logs: Prologs® By Safer Building Materials

The prolog is an expanded polystyrene log which is designed to break at the critical design force to prevent a rotational fall. These logs are produced by Safer Building Materials, run by Olympic eventing competitors Mike Winter (based in England) and Kyle Carter (based in the US) [58]. These logs are designed to resemble traditional wood logs in size and are painted and carved to preserve the current look of the sport. Figures 3.2 and 3.3 provide examples of the logs in use in a 2009 Young Rider's competition at the Kentucky Horse Park.

Figure 3.2 Example of Square Safer Building Materials' Prolog® [56, 58]

Figure 3.3 Example of Round Safer Building Materials' Prolog® [56, 58]

The Prologs® are starting to see more widespread use, having been used in CCI*, CCI**, and CCI*** events and have been included in courses designed by the President of the United States Equestrian Federation, David O'Connor [58]. Further research into the breaking load of these logs in different shapes and sizes has been conducted at the University of Kentucky resulting in a wider range of available sizes and shapes.

3.1.3 Collapsible Table Jump

Doug Payne, an eventing competitor and mechanical engineer, created a collapsible table jump design. The prototype was built by Eric Bull and was used in the Plantation Fields Horse Trials in Unionville, PA in June 2009 [47]. The fence is essentially a wooden jump supported by a metal track with a wooden pin, as seen in Figures 3.4 (a) and 3.4 (b).

Figure 3.4 Doug Payne’s Collapsible Table Jump [42]

When sufficient load is applied to the fence, the pin breaks allowing the jump to collapse to about half of its original height and into essentially a coop shape.

3.1.4 MIM Construction Frangible Devices

The NewEra System from Mim Construction was conceived and developed by Mats Björnetun and Anders Flögard of Sweden. Mim Construction is a company that sells crash safety nets for use in automotive applications. However, the company’s capabilities expanded to developing and testing safety devices for cross country eventing. The designs are centered on the use of a frangible device or clasp that is designed to be connected between two bolts or two straps as seen in Figure 3.5 [24, 55].

Figure 3.5 Example of Mim Clasps [29]

The frangible clasp has a stress concentration circle that fractures at the critical load and separates the clasp from the bolt or strap on one side allowing the fence to collapse. The operation of the device is shown in Figure 3.6 as a series of frames from high speed video.

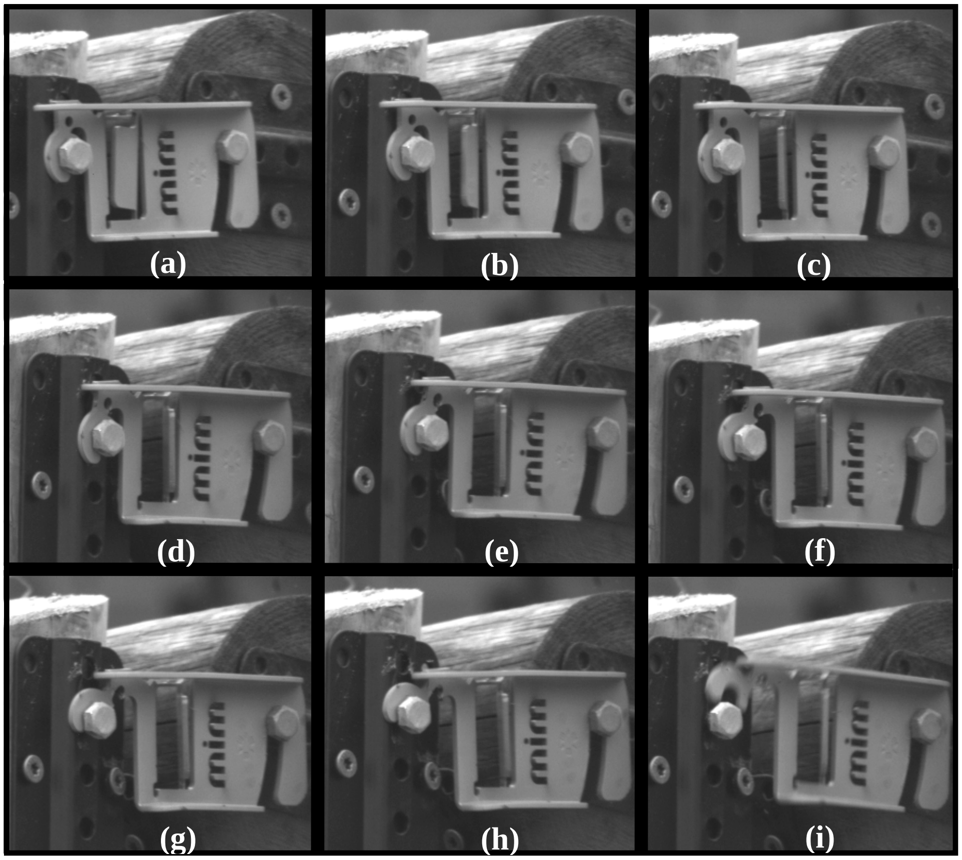


Figure 3.6 Frames from High Speed Video of Mim Clasp In Operation [29]

The device is equipped with an indicator flag which lies flat before it has been triggered (Figure 3.6 (a)). However, as the device is weakened in Figure 3.6 (b) through (d), the flag raises indicating that the device should be replaced before the next competitor. In frames (g) – (i) the frangible area breaks, releasing the clasp.

The design has proven to be versatile with application to various jump types including post and rail, table fences, hinged gate, and corners. The fence designs have been tested by Mim Construction using a crane to create a pendulum tester and a load cell on the fence itself to record the impact as seen in Figure 3.7 [24]. Current work is being done by the company to develop a more sophisticated pendulum tester for more widespread testing.

(a) (b)

Figure 3.7 Post and Rail Setup and Preliminary Method of Pendulum Impact Testing [24]

(a) (b)

Figure 3.8 Collapsible Table Jump Setup [24]

(a) (b)

Figure 3.9 Hinged Gate Setup [24]

Several of the fence designs have been implemented into actual competitions.

3.1.5 Concept Designs

In this thesis, concept designs for a hinged gate with a frangible pin and for a collapsible table with resettable springs, are discussed in Chapters Five and Six respectively. Other concepts are also currently being developed in the University of Kentucky Mechanical Engineering Department. Early in the project David O'Connor suggested a reverse post and rail situation with a releasing strap as a way to expand the implementation of post and rail jumps with safety devices. A team of senior design students explored the feasibility of developing an energy absorbing strap (Figure 3.10).

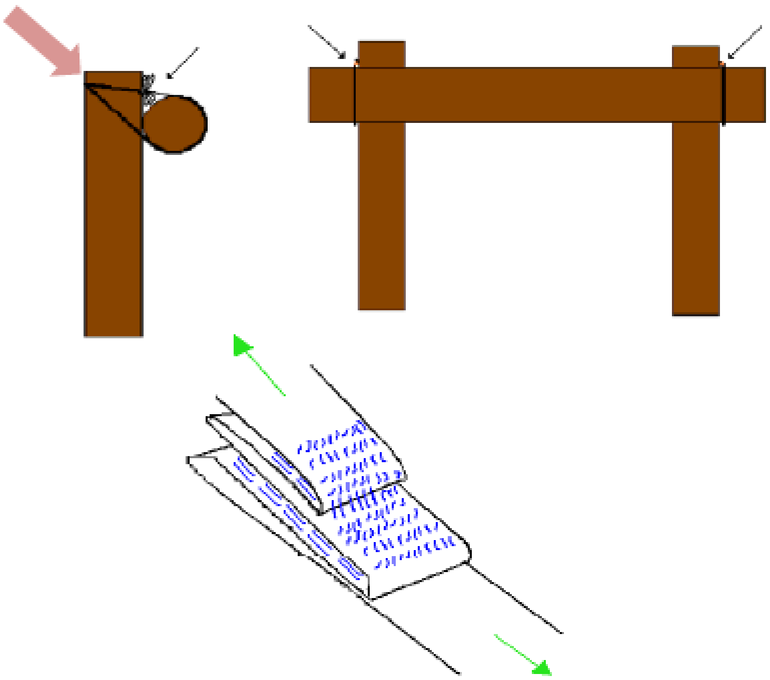


Figure 3.10 Snap and Strap Future Concept [56]

The system is designed to support the rail with a strap that is folded and stitched in one area. The stitching rips when the critical design force is reached, which allows additional length of the strap to extend. This enables the log to drop, removing the pivot point of the impacting horse and rider pair. The concept is still in the preliminary stages of lab prototypes.

Another senior design team at the University of Kentucky developed a collapsible table fence design that used frangible pins and a pivot arm to move the fence out of the way in case of a serious impact. Also, a spring system was used to help collapse the fence faster than it would if relying on the force of gravity alone.

3.2 Methods of Demonstrating, Unifying Designs

One hindrance to the development and widespread use of designs is the lack of communication within the sport between device designers, course designers, course builders, and competitors. Therefore, as a result of this research two approaches were pursued to increase awareness of devices currently available and those being developed. Fundamental to all safety efforts is that course designers and builders must understand devices that are available so that they can decide which designs will work for specific applications in the field. A design chart was developed with the goal of quantitatively identifying aspects of safety designs, along with their stage of development. Figure 3.11 shows the preliminary version of the chart, which documents key aspects of available designs and concepts. The red box identifies the aspects being identified for each design. The blue box identifies the names and pictures of the available designs and concepts. Finally, the green box identifies the area where the information is filled in for each design.

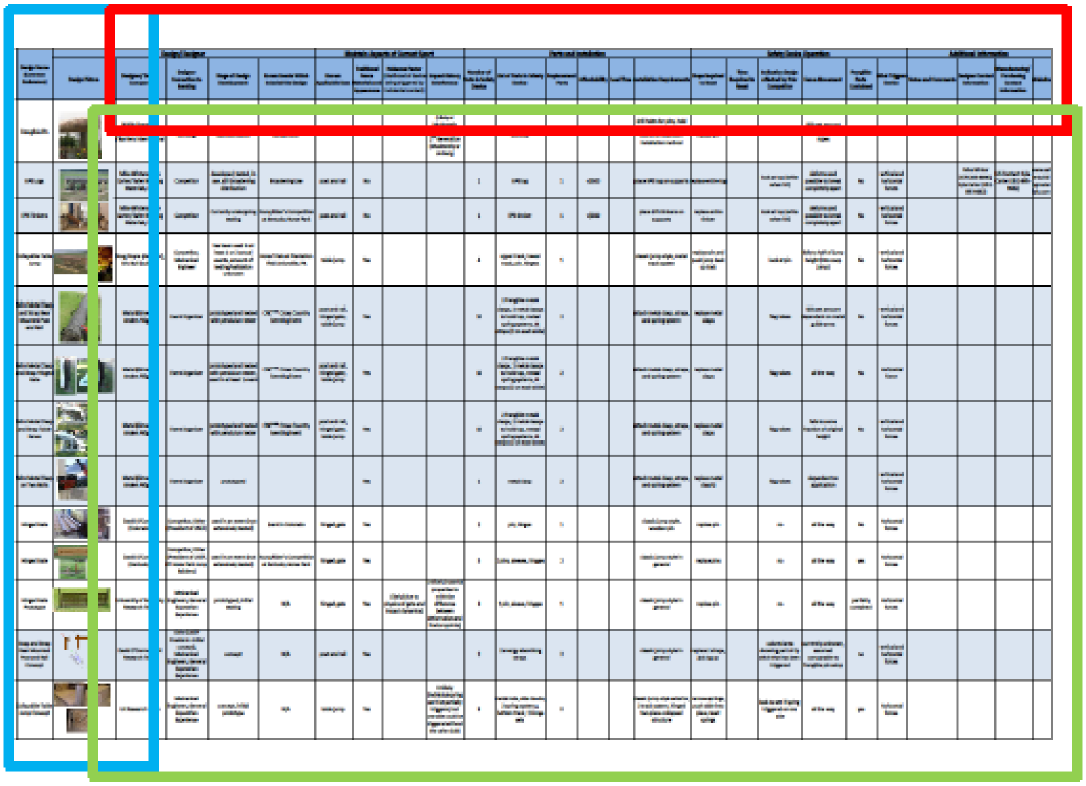


Figure 3.11 Preliminary Chart Documenting Aspects of Available Designs

This information is not ready to be released to the public so the detailed information for each design is not provided here. However, Tables 3.1 and 3.2 identify the chart headings from the red box in Figure 3.11.

Table 3.1 Design Chart Breakdown—Part I

Headings	**Corresponding Required Input Information**
Design Name (Common Reference)	User Input
Section 1: Design/ Designer	
Design Picture	Upload Picture
Designer/ Design Company	User Input
Designer Connection to Eventing	Competitor, Event Organizer, Engineer, General Equestrian Experience, None, Other (User Input)
Stage of Design Development	Concept, Prototype, Initial Testing, Extensive Testing, Used in Events, Widespread Use and Distribution, Other (user input)
Known Events Which Included the Design	User Input
Section 2: Maintain Aspects of Current Sport	
Known Applicable Users	Post and rail, table jump, hinged gate, corner, other (user input)
Traditional Fence Materials and Appearance	Yes or No
Nuisance Factor (Likelihood of device being triggered by incidental contact)	Likely, Moderately Likely, Unlikely
Impact History Interference	Likely, Moderately Likely, Unlikely
Number of Parts in Safety Device	Enter Number
Section 3: Parts and Installation	
List of Parts in Safety Device	User Input
Replacement Parts	Enter Number
Affordability	<\$100, <\$500, >\$500
Lead Time	User Input (or maybe provide reasonable ranges)
Installation Requirements	User Input

Table 3.2 Design Chart Breakdown—Part II

Headings	**Corresponding Required Input Information**
Section 4: Safety Device Operation	
Steps Required to Reset	User Input
Time Required to Reset	User Input (or maybe provide reasonable ranges)
Indication Design Affected by Prior Competitor	Yes (and User Description) or No
Fence Movement	User Input (or maybe provide reasonable ranges)
Frangible Parts Contained	Yes or No
What Triggers Device	Vertical Force, Horizontal Force, and/ or Other (user input)
Section 5: Additional Information	
Notes and Comments	User Input
Designer Contact Information	User Input
Manufacturing/ Purchasing Contact Information	User Input
Website	User Input

Eventually, the idea of this approach is to make the chart available via a safety device website where new concepts and designs could be uploaded for consideration by safety device designers.

Another approach to increasing awareness of current safety efforts are hands-on demonstrations of devices. In October 2009, the University of Kentucky research was presented to equestrian organization leadership and course builders, among others (Figure 3.12). The demonstration meeting provided an opportunity for the many groups to discuss current ideas, possible changes, and future work (Figure 3.13). It also provided the chance to view and try out the devices themselves (Figure 3.14). A second demonstration was prepared for the April 2010 Rolex Event, but was interrupted and discontinued by a severe thunderstorm.

(a) (b)

Figure 3.12 Design Demonstration

(a) (b)

Figure 3.13 Design Demonstration

Figure 3.14 Instrumented Sledge Hammer Demonstration

In order for devices to be safely used and accepted into mainstream eventing competitions, course designers, builders and riders will need to be familiar and comfortable with new designs. It is crucial to the safety of the sport that designs be extensively validated before use in the field, properly applied by course designers, properly installed by course builders, and clearly understood by riders. Hopefully, increasing communication within the sport and increasing access to new devices will make a significant contribution towards reaching those goals.

3.3 General Requirements For Jump Designs

From review of existing devices, discussions with eventing leaders, course designers, and participants, general cross country safety fence guidelines were developed and are as follows:

General Parameters/Considerations for Cross Country Eventing Fences

- Maintain Aspects of Current Sport
    - Verify device capable of replicating current fence dimensions and sizes
    - Maintain current fence appearance (e.g., similar materials, same look to horses, incorporate various shapes and decorations)

  - Achieve quick device reset time (e.g., prevent necessity of holding horses on course)
  - Determine applicability to courses (e.g., what percentage of jumps could incorporate the design)
  - Determine applicability of design for different levels of competition and different jump sizes
- Safety Device Operation
  - Do no harm, Do not increase risk! (Most important reminder to search for unforeseen dangers)
  - Evaluate reliability of failure at critical design force
  - Consider possible interaction between horse, rider, and fence if partially or fully triggered (verify no possible source of increased risk)
  - Evaluate frequency of device triggering in a competition
  - Determine method of identifying that the device has been partially triggered and must be replaced
  - Minimize impact history interference (prevent a hit from weakening the device and then have a later light hit trigger the device)
  - Asses ability to withstand outdoor elements (reliability and behavior after prolonged exposure to the outdoor elements)
- Parts and Installation
  - Ensure design affordability (acquisition, maintenance, cost of replacement parts)
  - Simplify materials and tools needed to construct and reset
  - Simplify required technical knowledge to construct fence and to reset after being triggered
  - Simplify method for jump judges to verify the device is set up correctly or that the device is damaged and must be replaced
  - Determine feasibility to mass produce and implement (how easy to machine items and construct)
  - Encourage design simplicity (minimize number of original and replacement parts)

- Design/Designer
  - Consider jump designer qualifications (ex: eventing competitor, engineer, etc.)
  - Evaluate stage of development of the design (ex: concept level, tested, implemented, etc.)
  - Test/validate device for safety effectiveness

Also, several factors were considered during the course of this project that are applicable to safety research in other sports:

Top Sport Safety Take Aways

- No matter what don't increase the risk in any way!
- Benchmark safety research from other applications or sports (even if doesn't seem to directly apply)
- Talk to a VARIETY of experts in the field both new and old to the sport to get a feel for the sport culture and the kind of things the sport is likely to accept vs. what is likely to be dismissed off hand (ex: maintain integrity of sport, keep seemingly the same to spectators)
- View the sport in action. Important to understand the rules and the technicalities behind how it is played and how the players will be interacting with whatever is being designed
- Determine what safety issues are considered important by each constituency
- Create a baseline for what forces, impacts, sounds, motion (etc. whatever is being analyzed) are normal and within safe ranges for competitors and/or spectators
- Institute a method to gather data about accidents when they occur (ex: environment, possible causes, any possible relevant factors)
- Consider summarizing available designs and opening lines of communication within the sport (often scattering of ideas and partial concepts that don't progress because not widely known about)
- Consider creating specifications not designs

- Designs may be accepted easier if they come from within the sport rather than from outsiders
- Create inexpensive, portable, accessible methods to test/validate safety improvement specifications
- Be aware of the potential for implied endorsement by labeling a design as a “safety device” or by being known to study it.
- Determine customer’s preferred method of viewing research findings (ex: full report, 1 page takeaways, posters, video, etc.)

One of the most important steps in the initial phase of a project is to study reports, experiments, standards, and testing guidelines from your field and any related fields. This helps to prevent researchers from duplicating work unnecessarily and provides direction for any new studies. Also, especially at the beginning of a project, it is easy to have an overload of opinions and pressures from different sources within the sport. Therefore, it is important to focus your efforts and clearly define your project objective at the beginning.

3.4 Conclusion

This summary of currently available designs and approaches for communicating them to the sport is one contribution of this thesis. Ideas about improving safety within cross country eventing are currently being and have been looked at from many different independent sources. One important step forward, is to convey the concepts of different designers to the larger eventing organizations so that designs can be validated for safe use in competition through a standard means of testing. Overall understanding and exposure can be gained through use of a safety device website and in more local arenas through field demonstrations of devices as they are being developed and when they become available for general use. Most importantly however, standardized fence specifications and standard testing methods are needed in order to gain effective widespread use of safety devices.

Chapter 4: Testing and Validation Methods

4.0 Introduction

Requirements have not been defined for safety device operation for the equestrian sport of cross country eventing. Consequently, no standard testing method has been widely accepted in the sport. It is therefore useful to understand what testing equipment exists in other industries and its applicability to verifying eventing fence safety designs. The large impact forces and suddenness of falls encourages a comparison to automotive safety testing.

4.1 Automotive Safety Testing

The safety of vehicles has been greatly enhanced by the thorough, consistent, and "well-established testing program" used for vehicles in the United States. The Federal Motor Vehicle Safety Standards (FMVSS) provide a consistent safety standard that all car manufacturers must adhere to [38]. The National Highway Traffic Safety Administration (NHTSA) also organizes efforts to improve highway safety [37]. One high profile area of crash testing is in the use of crash test dummies for certifying safety of vehicles. Crash test dummies are built as a representation of the actual weight, size, and structure of the average human. They are made from "materials that mimic the physiology of the human body" and include accelerometers, load sensors, and motion sensors to gather data during impacts. At several key body points on the crash test dummy accelerometers determine how quickly the speed changes, load sensors record forces, and motion sensors record the amount of deflection. Paint is placed on key areas of the crash dummy so that after the impact the paint spots within the car identify which part of the dummy impacted specific points inside the vehicle [38].

At the Transportation Research Lab (TRL) in England, a large pendulum (shown in Figure 4.1) is also used for impact testing to represent crash situations. Different crushable materials attached to the pendulum extend the impact duration to make accelerations representative of real situations.

Figure 4.1 Pendulum Tester at TRL in England [53]

4.2 Background of Eventing Safety Testing

Vehicle crash testing procedures are long established and therefore have understood and accepted detail and complexity. So, while the sport of equestrian cross country eventing may not have the infrastructure necessary to immediately support the cost and complexity of the vehicle testing process, certain aspects can be adapted to jump design and testing.

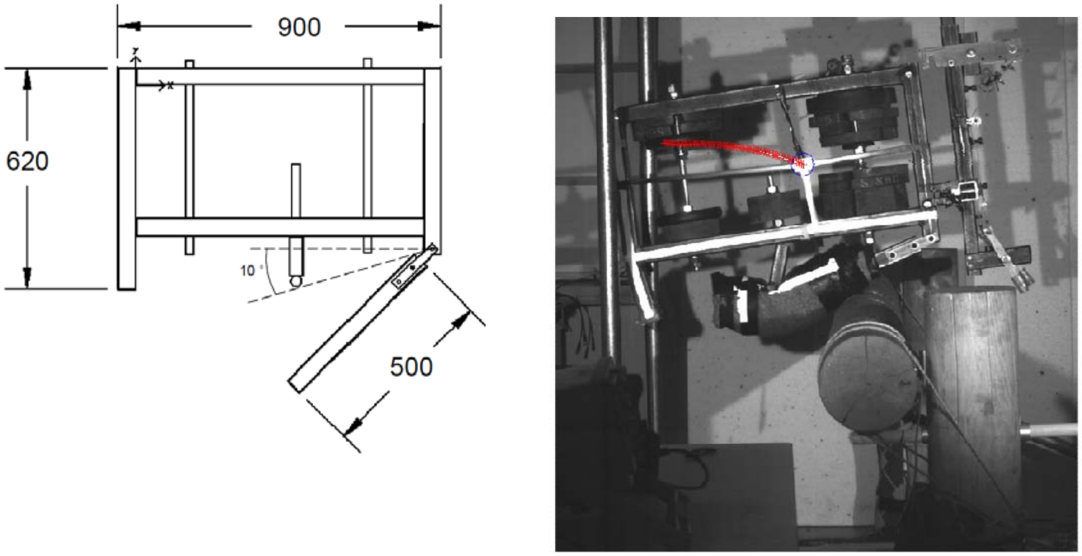
4.2.1 Horse Simulators

British Eventing sponsored design and construction of horse simulator impact testers. One of these testers was created by the Transportation Research Laboratory as a full size representation of a horse and was labeled the New Equestrian Dummy (NED) (shown below in Figure 4.2) in 2000 [1]. This tester weighed 475 kg and was constructed out of springs and metal masses in an attempt to simulate a horse impact. The tester mainly represented the body and front legs of the horse. The model was deployed by running it down a cable towards a post and rail jump at approximately 6m/s at a specified angle, such that the impact consistently occurred at "150mm below the elbow joint on the model" [1].

Figure 4.2 TRL Horse Impact Simulator NED [1]

This model was used to develop and test the first frangible pins that subsequently gained widespread international use on post-and-rail jumps.

In 2007, British Eventing sponsored a student team from the University of Bristol to conduct studies to better understand the forces involved when a horse impacts a fence. The team developed a scaled horse simulator in the lab. The Bristol Equine Safety Subject (BESS) was 1/3 the mass of the estimated full size horse mass. Figure 4.3 (a) provides a University of Bristol team drawing of BESS and Figure 4.3 (b) shows BESS during a lab impact test [1].



(a) (b)

Figure 4.3 The University of Bristol Testing Mechanism, the BESS [1]

The scale model was launched at several different fence setups and through the use of force readings and high speed video each set up was viewed to better understand the impact forces and their connection with rotational falls. The team also developed a full size fence with force readers to record impact forces during actual competitions. A system of force load cells was attached to the fence to measure both the horizontal and vertical forces during impact. The study found that force load cells could be reliably used in the field to gather data from competitions. Also, from the in-lab testing their findings suggested that reducing the frictional force between the fence and the horse’s leg may help to reduce the amount of rotation of the horse during impact [1]. This research was expanded on by another University of Bristol team in 2008, where the scaled model was used again to study a variety of fence designs and the associated forces and rotation of the model. The findings concluded that using a rail in the fence that was allowed to rotate or spin would reduce the friction between the horse and the fence but was not found to be easily applied to a full size model for implementation [28].

4.2.2 Frangible Pins

TRL continued to research frangible pins periodically for approximately the last ten years. As part of their work, they created a frangible pin specification to prevent a rotational fall and recommended methods of testing the fence-installed pins. The specification stated that each frangible pin should fail under a “brittle failure load of 6.0kN-7.5kN with an energy of less than 70J” [43]. In other words, there are two parts to the specification, that the pins have a desired maximum breaking force of 7.5kN and secondly, have a maximum suggested amount of energy that should be required to fracture the pins (70J) [43].

Cases were reported that the current British eventing frangible pins did not always behave as expected [5]. In 2009, a student group at the University of Bristol in England performed a fracture mechanics study on two different pin materials to determine if the TRL specifications were being properly met. A pendulum test setup based on the IZOD impact test was used. Three different methods were used to determine the peak force and energy absorbed in impact. The difference between the potential energy of the pendulum at its release point and the point where it swung to on the other side represented the absorbed energy during impact. The second absorbed energy method used a high speed video of the impact to calculate the work performed to break the pin. The pin deflection seen from the video times the force applied yielded the work (absorbed energy). Thirdly, the work (energy) was calculated as the area under the Force Displacement curve taken from a slow bend test of the specimen. The peak loads were recorded using load sensors.

The University of Bristol team concluded that the frangible pin material was breaking at around the specified peak load but was requiring too much energy in order to break the pins. Peak force alone is not sufficient to guarantee proper fracture of the pins. The proper peak force is required to reach the material's ultimate strength where fracture begins, but a certain amount of energy is required in order to propagate that crack through the pin. Many factors contribute to material fracture mechanics including material properties, diameter size, and notch shape. The university of Bristol team concluded that the peak breaking force was largely determined by the smallest diameter of the pin using equation 4.1,

$$F = \frac{\sigma}{A} \tag{4.1}$$

in which F= force, σ= Stress, and A= cross sectional area [5].

The energy required to propagate the crack depends on if it is a ductile or brittle break. With a ductile break more energy is required for the plastic deformation that occurs, while less energy is required for the brittle break that happens along the grain lines. Specific for the current frangible pin application, the University of Bristol team found that another material, LM15 Cast Aluminum, was closer to meeting the desired energy and peak breaking force specifications outlined by TRL [5].

4.2.3 Field Testing

In order for safety within the sport of cross country eventing to extend to wider implementation, a portable tester with the ability for widespread application is necessary. When testing cross country courses it is necessary that the testing mechanism be able to be moved both from course to course but also easily from jump to jump within each course. While having a representation of the actual motion and structure of a horse is useful for research, a tester meant simply for verifying the operation of a device in the field may not need to be as complicated as an instrumented horse simulator dummy. The necessary operations of the tester will be dependent on each specific safety device and how it releases the fence. For example, devices may include components such as frangible devices, spring systems, or resistant straps. However, previous research concluded that both the peak force and amount of energy imparted are crucial to successful testing [5]. Findings from TRL and the University of Bristol suggest that energy plays a fundamental roll in breaking the frangible pins [5, 33]. Part of TRL's specification required that the post and rail system with the frangible pins installed be tested to ensure it fails with 200J of energy. The suggested field testing approach used a falling weight between 50 and 150kg. The height the weight is dropped (from 0.39 to 0.14m) is defined such that the desired 200J is achieved [33]. However, this particular field testing method is only applicable for vertically triggered designs.

In many testing situations pendulum testers are often effective. In laboratory testing, Charpy or Izod impact tests often use a pendulum setup to determine the amount of energy required to break a sample.

One application of a field pendulum tester to the sport of eventing is shown in Figure 4.4. Mats Björnetun and Anders Flogård from Sweden devised a pendulum impact tester out of a crane, bale of silage, and a load sensor mounted on the fence being impacted.

Figure 4.4 Mim Construction Pendulum Impact Test [25]

To increase the accuracy, efficiency, and versatility of testing, these researchers are currently developing a pendulum tester specifically designed for use on testing cross country fences.

While the above mentioned testing methods can be useful, they are expensive and difficult to move and quickly set up at any course. Therefore, the University of Kentucky Research Team evaluated a testing approach that would be simple and easily portable so that it could be accessible for course builders across the country. Instrumented sledge hammers have historically been widely used in civil engineering to create excitation impacts when studying the dynamic vibration response in structures ranging from bridges to railways [41, 61]. Many of the current proposed designs are contact force triggered devices. The feasibility of using an instrumented sledge hammer to apply the critical impact force on the proposed fence designs was evaluated. Use of hammers became popular in civil engineering partly due to their “low cost, simplicity and speed of execution,” three characteristics that are also important for successful implementation within the sport of eventing [41]. However, the use of instrumented sledge hammers in testing requires analysis of the experiment’s repeatability and accuracy due to the human operator. The repeatability and consistency of the impact force, location, and speed warrants consideration. Also, methods of determining the energy expended during hammer impacts have not been determined for this application.

4.2.4 Force Measurements During Competitions

However, testing the operation of proposed designs is only half of the challenge. In order to know at what force the devices should trigger, the forces of horse impacts must also be understood. Therefore, British Eventing sponsored Competitive Measure to build and implement an instrumented cross country fence to record horse impacts during competition. The company developed two different instrumented fences, one for the 2008 season and one for the 2009 season. Figure 4.5 (a) shows the 2008 instrumented fence, sponsored by Good Year. Figure 4.5 (b) shows the second version (2009 model) of the instrumented jump. The first fence has a sloped front and a single rail at the peak of the jump. The 2009 fence, on the other hand, is a table fence with a front and back rail; the back rail is slightly higher to define the depth of the fence for the horse. The two fences have different designs, were used in different competitions, were set at different locations in courses, and were used over two separate eventing seasons. They therefore yielded broad sets of impact data for analysis.

(a) 2008 Model [12]

(b) 2009 Model [13]

Figure 4.5 2008 and 2009 Competitive Measure Instrumented Jumps

The 2009 jump was designed to allow the height to be changed quickly so that it could be used in a wider range of competitions. Figure 4.6 shows the support structure of the jump which was shortened and lowered into the ground for use in a lower level competition.

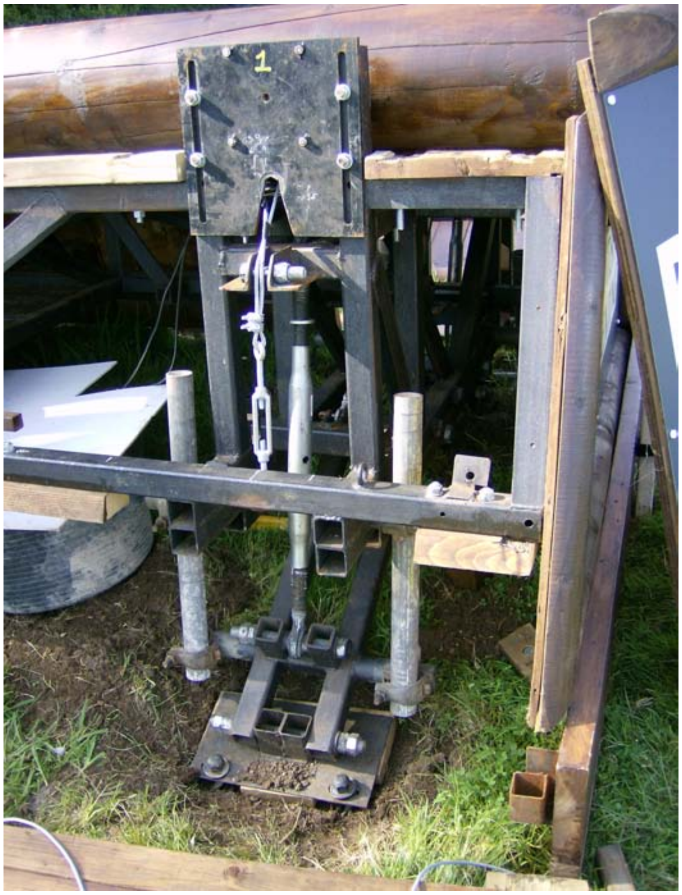


Figure 4.6 Competitive Measure Instrumented Jump Support [13]

Competitive Measure, run by Tim Deans and Martin Herbert, designed the fence to record the force versus time while also recording a high speed video of horse impacts. This overall experimental setup is shown in Figure 4.7.

Figure 4.7 Competitive Measure Equipment Setup [13]

The goal of the fence was to use the recorded data to better understand at what force ranges serious injuries are more likely to occur. No serious rotational falls were recorded during the use of the instrumented fence, but the recorded data served to bound the range of non-serious impacts. The 125 frame-per-second high speed videos have also been used to study the role of horse and rider motion and position during impacts [12].

4.3 Fence Design Testing Process

After researching the available testing and design validation techniques, a guideline for design development and evaluation was developed. The University of Kentucky cross country fence safety development approach includes several elements:

- Design requirements and constraints for safety fences in general
- Equations to represent and understand the motion of the device and fence
- Identification of design requirements and constraints for the specific jump type
- Identification of key variables, value ranges, and distributions

- Determination of design critical forces (and distributions)
- Use of computer modeling for better understanding of safety device/ fence system
- Field testing for validation.

All of these elements were combined to create a 5-step approach for safety device development: (1) Theoretical and Computer Modeling; (2) Prototyping; (3) Laboratory and Field Testing; (4) Limited Test Implementation; (5) Redesign and Full Implementation. The application of these steps and their development are discussed in the following sections.

4.3.1 Theory, Equations, and Computer Modeling

Since a competition includes large variations in rider mass, horse size, riding style, jumping power, and take off angle, understanding of this variability in a jumping accident is obviously important to the pursuit of decreasing risk of injury. Having a general awareness of what variables drive the safety mechanism or an idea of the effects of variable interactions may prevent problems during the fence construction phase.

Mathematical models can initially represent the motion involved to determine expected behavior either by hand or using a computer mathematical simulation program like MATLAB.   CAD and finite element programs, such as ProEngineer and ANSYS, can also be used to develop 3D models of a design component to get an idea of the expected stresses and deflections due to specified parameters such as forces, impact direction, etc.

4.3.1.1 Computer Modeling Example: Monte Carlo Simulations

One method of understanding the variable interaction in a design is the use of Monte Carlo methods. Monte Carlo simulation is a method of random sampling which allows the variability representing 100’s or 1000’s of possible scenarios to be separately computed, then examined to understand the probability distribution of results. As a general illustration of methodology, the approach is described here before being applied in following chapters. Figure 4.8 shows a legend with three separate markers. The marker used to represent a sample result is dependent on the physics representation programmed into the Monte Carlo code (implemented here with MATLAB random variables).

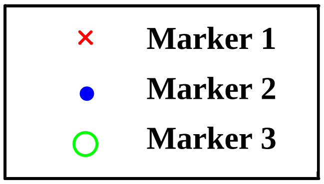
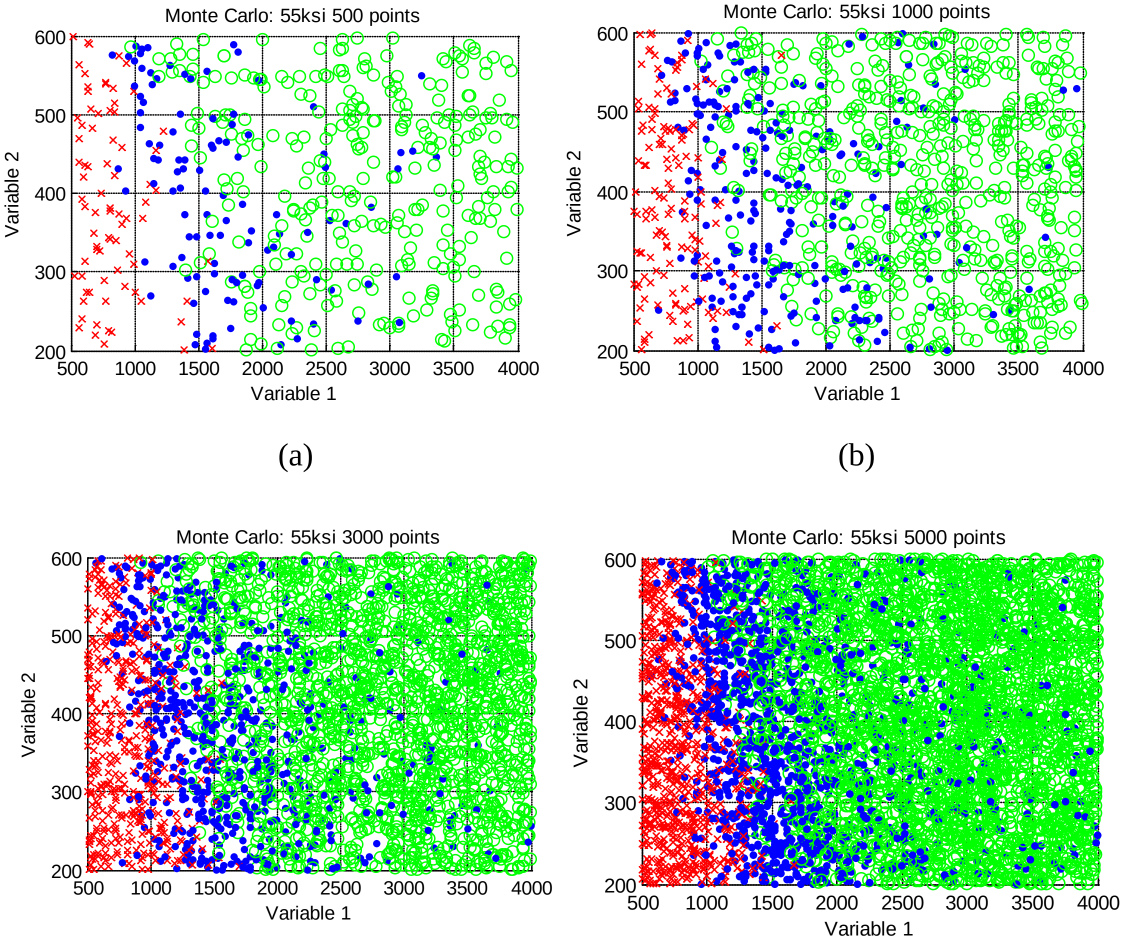


Figure 4.8 Monte Carlo Example Legend

The number of samples is arbitrary, but in most situations, accuracy increases with the number of samples. Here, it is necessary to have enough points that the general trends, or overall design behaviors, are clearly defined. As a representative example, Figure 4.9 shows four typical results plots with increasingly more samples ranging from 500 points to 5000 points.



(a) (b)

(c) (d)

Figure 4.9 Monte Carlo Number of Points Example

Theoretical equations representing the forces and motion of the design are plotted based on the dependent variables. The following description is for one application of Monte Carlo, the analysis of a frangible device. However, the same general process could be used with different equations and comparisons for other types of devices. Variable ranges were programmed within Matlab as uniform distributions or as normal distributions, depending on the variable. The command “normrnd” (Eq. 4.2) returns random numbers within a normal distribution when the user inputs the mean and standard deviation [32].

Variable3=normrnd(mean,standard deviation,1,1) (4.2)

The command “rand” (Eq. 4.3) returns random numbers in a uniform distribution between specified end points [32].

Variable1=startpt +(endpt-startpt).*rand(1) (4.3)

For Figures 4.10 to 4.12 Variables 1 and 2 are uniformly distributed and Variable 3 is a normal distribution. The variable ranges were then sampled dependent on the corresponding mathematical equations. The programmed code created a plot of a user-defined number of points, with each point representing a different combination (or sample) of variable values. Using an if-loop calculated maximum normal stress, which was then compared to the allowable normal stress and the yield stress for the material considered. If the calculated stress was lower than the material yield stress then that point was plotted as a red X (marker 1) representing an unchanged frangible device, if the calculated stress was larger than the yield stress but lower than the maximum stress then that point was plotted as a blue dot (marker 2) representing a deformed frangible device, and finally if the calculated stress was greater than the maximum material stress then that point was plotted as a green circle (marker 3) representing a broken frangible device. However, this example only illustrates the behavior since the actual level of device fracture is also dependent on the amount of energy absorbed during impact. Reaching the critical load only suggests that the typical specimen of that material would have a fracture within the cross section but not necessarily enough energy to propagate the fracture throughout.

The Monte Carlo plots are a visual way to represent the mathematical equations specific to the dynamics of the design to determine general trends. Since plots are constrained to 2 or 3 dimensions, multiple plots must be viewed to determine the overall trend of key parameters. While all of the determined variables were allowed to vary, the most efficient method of analyzing trends was to view 2D plots of the data or histograms. Here 2-D plots are used. Figure 4.10 shows a 3D plot that simultaneously represents the trends in a three variable comparison. However, the 3D point distribution cloud can be crowded. Trends were often more clearly seen by looking at 2D plots. Figure 4.11 shows the three 2D plots that correspond to the single 3D plot.

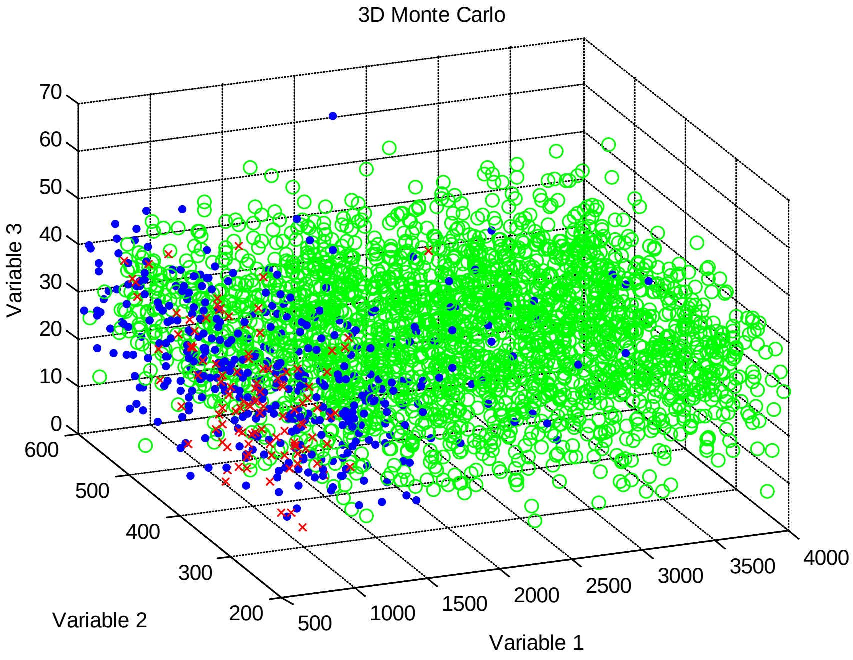
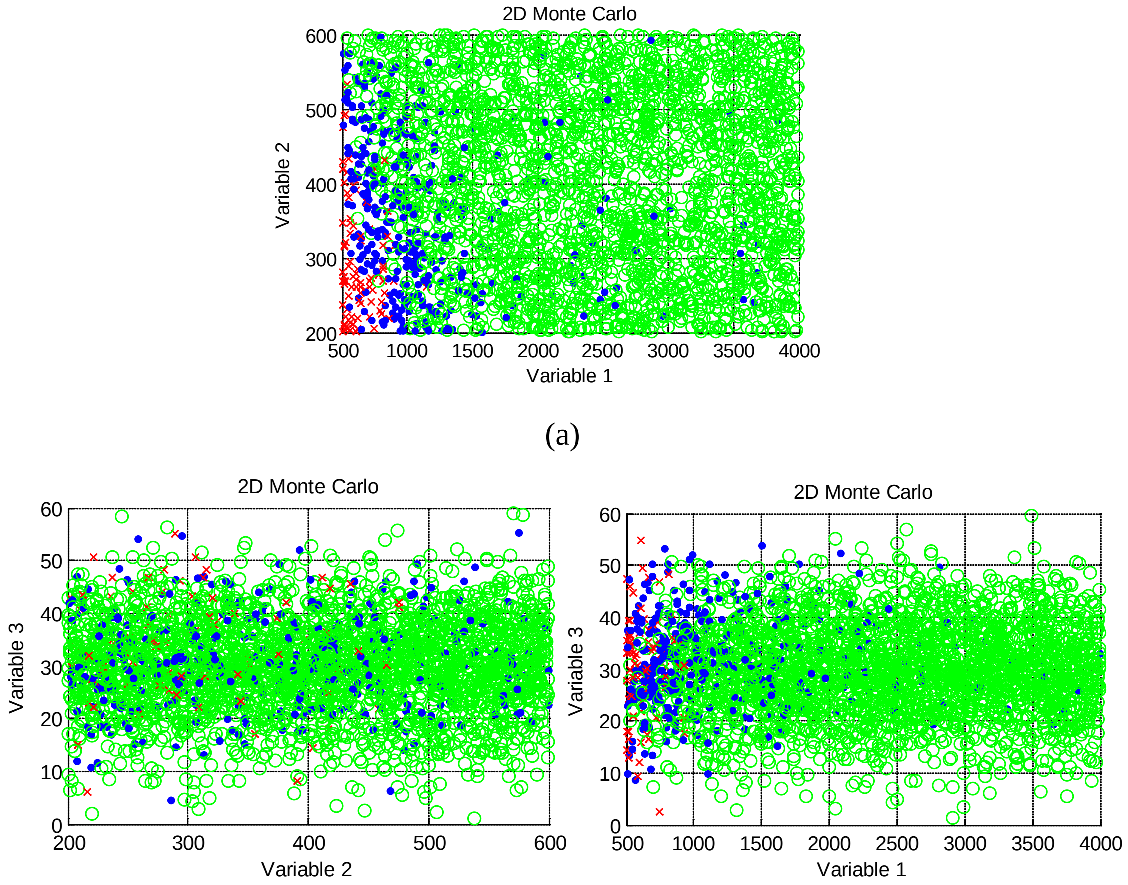


Figure 4.10 3D Monte Carlo Plot



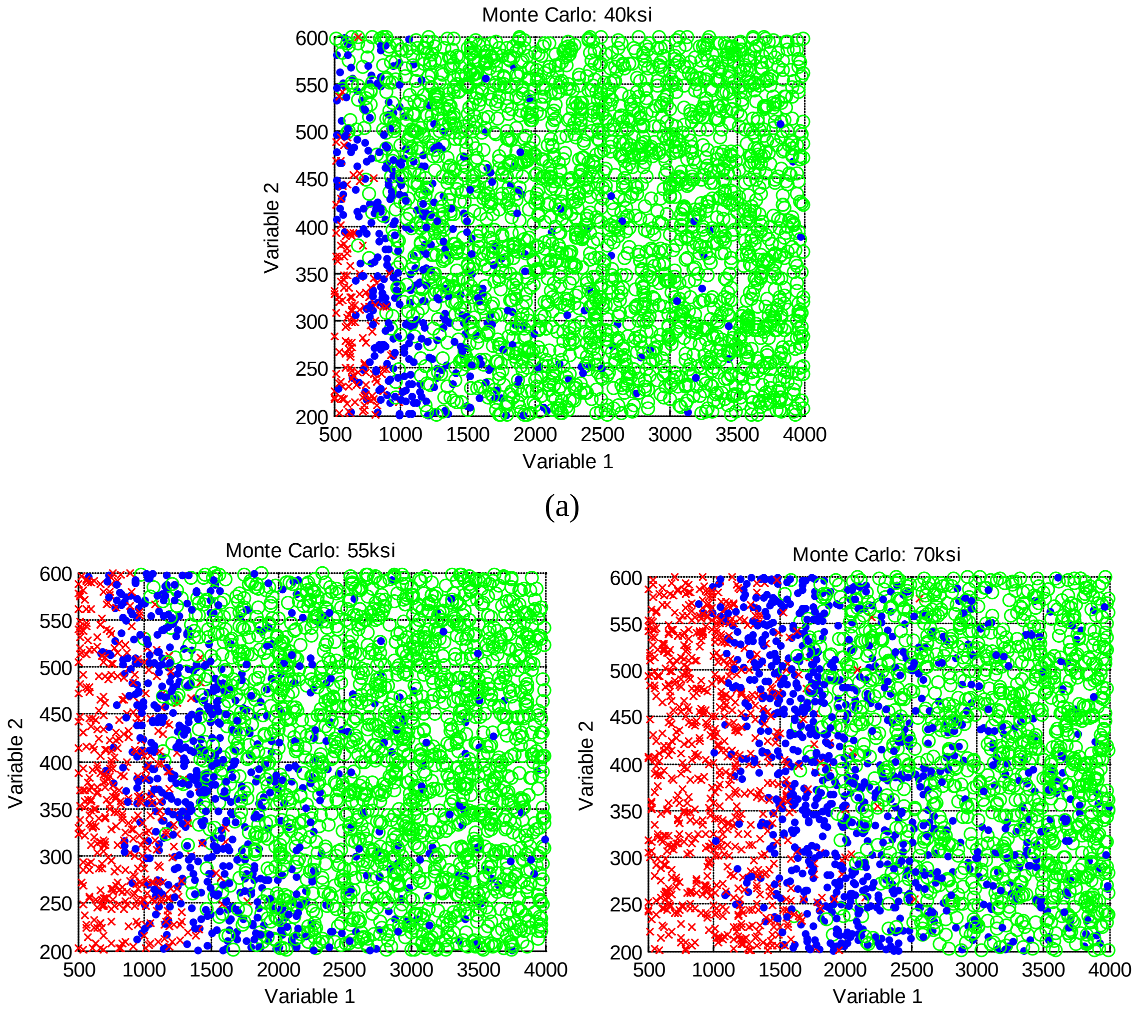
(a)

(b) (c)

Figure 4.11 Corresponding 2D Monte Carlo Plots

Only two variables are directly quantified in each plot even though all of the variables contributed to determine the location of each individual point. This explains the mixing behavior of the broken, deformed, and unchanged results. The Monte Carlo plotting method helps to identify this complicated variable interaction. The mathematical equations and the programming for the plots could often be verified by plotting situations which had well understood behavior to see if the results matched the expected behavior. When the material that was being considered was changed, the trends were basically shifted according to if the material was increased or decreased in strength. Figure 4.12

shows how the three overall condition regions are shifted to the right as the material strength was increased from 40ksi to 70ksi.



(a)

(b)

(c)

Figure 4.12 Shift in Monte Carlo Trend Regions

That way if the frangible device was desired to be in a certain range of breaking or triggering, the material could be chosen based on how much the plots need to be shifted to reach the desired region.

If a design is in the initial stages of development, using computer modeling software such as AutoCAD or ProEngineer may be helpful to mapping out the construction of the design. Also if project appropriate, ProEngineer Mechanica or ANSYS are stress analysis programs that could be used to analyze 3D models for stress and deflection. Since the model results are only as good as the given forces, variables, and defined 3D model this option is only helpful if the variable information is well known and an operator experienced in this type of software is available. Even then, it is likely that extensive field testing will be required to confirm results. Therefore, the in the initial stages of this research theoretical equations were used to gain initial understanding related to the design construction, but field testing was heavily relied on to draw conclusions.

4.3.2 Prototyping of Jumps/Fences

Due to the immense size of equestrian cross country eventing fences, scaled prototypes can be useful in studying a design in a more manageable size for an indoor lab. The Cordwood fence, for example, was from the Rolex 2009 CCI Cross Country 4* Event (shown in Figure 4.13) [49, 56].

Figure 4.13 Example of Cross Country Fence at 2009 Rolex [56]

This obstacle had a height of 3’11" and a spread of 5’3" [49]. The fences also are often over 12’ long. Therefore, it may be unmanageable to initially test a full size model of a cross country fence. If a prototype is created in half the dimensions (1/8 the volume), the design may be easier to change and tweak in the initial design and development stage. If the fence has previously been developed, a scaled prototype still may be useful if the motion or construction of the fence is questionable. Otherwise, a full sized model may be necessary for a complete analysis. When using a prototype to analyze conditions such as the dynamic motion or energy lost through the fence, attention should be given to the materials and construction method used in order to represent the real design as much as possible. Any deviation from the intended full size design is one more variable that must be considered when reviewing the results of any study. As an example, Chapter Six outlines the development process and preliminary testing of a scaled prototype of a collapsible table fence (Figure 4.14).

Figure 4.14 ½ Geometric Scale Collapsible Table Prototype

4.3.3 Laboratory and Field Testing

In order to gain understanding of a designs behavior under controlled conditions, often full-scale laboratory testing is performed before using a design in the field. One example of laboratory testing done at the University of Kentucky, was the use of an overhead crane to measure the force and deflection at failure of a expanded polystyrene (EPS) logs and timbers (Figure 4.15).

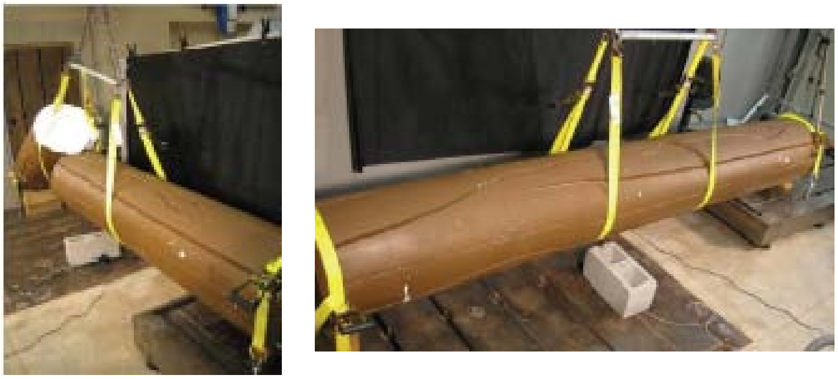


Figure 4.15 Example of Laboratory Testing With a Crane [52]

Field testing can provide more information about the design's interaction with its designed environment. Depending on the maturity of the design, initial field testing can be done on a scaled prototype before testing a full size model. An initial concept may be further developed through the aid of preliminary testing in a lab situation. However, in the end, the design ideally would be placed in a terrain situation similar to that of a competition. In order to decrease the chance of hidden variable interactions testing the fence in its designed use atmosphere helps to identify issues from lay of the land, stiffness of fence footing, outside moisture, etc. The primary goal of the field testing is to simulate the impact of a horse and rider above, at, and below the critical design specifications to determine if the safety fence reacts in desired and expected ways.

Above all else, it is imperative that nothing in the design increases the risk of injury to horse or rider.

The field testing for this research primarily relied on the use of an instrumented sledge hammer for impact testing and the use of a high speed camera to study overall motion. As mentioned previously, a crash test dummy analyzes the acceleration, deflection, and force load during an impact [38]. Since most of the designs studied during this project were triggered by contact force, a testing method with force-measurement capabilities was an important factor. However, this method did not provide an easy method of recording the amount of energy absorbed during impacts. As shown by the previously mentioned University of Bristol study on frangible pins, the amount of energy absorbed during impact is fundamental to determining if a pin will fail or not. Therefore, ideally field testing equipment should also have energy measurement capabilities.

As the safety designs continue to be developed testing methods will also need to be adapted. While the analysis process and methods explored herein should still be applicable at least in part to understanding other designs, a larger more consistent tester would be necessary for widespread course testing. A pendulum tester capable of handling significantly larger masses, built to be folded into a portable form may be appropriate. Work is currently underway in Sweden to develop a pendulum tester for cross country eventing field testing.

4.3.3.1 Field Testing Example: Instrumented Sledge Hammer Analysis

University of Kentucky field testing evaluated using an instrumented sledge hammer as an approximation of a horse impact. In order to determine if the instrumented sledge hammer was an acceptable representation of a horse impact, several areas were explored:

- Hammer specifications and capabilities
- Impact variation due to different hammer tips
- Impact variation due to different impact surfaces (different type of woods, foams, springs, etc.)
- Comparison of impact magnitude to known horse impact data
- Comparison of impact duration to known horse impact data
- Comparison of impulse and calculated for hammer and horse impacts

For the research study a PCB Piezotronics Impulse Force Hammer Model Number 086B50 was used. The hammer was approximately 12 lb and had a sensitivity of 0.82 mV/lb. The hammer was originally purchased and calibrated September 26, 1989 and as part of this effort was sent in for re-calibration June 3rd 2009. The hammer calibration certificate states a measurement uncertainty of ±3.8% [48]. The hammer was supplied with four different tips of varying stiffness. A fifth tip was constructed by undergraduate researcher, Michelle Tucker, out of a softball. The foam interior and leather exterior roughly imitated the stiffness and material of a horse's leg. An Iotech 2009 Wavebook/516E data acquisition system (DAQ) with Waveview software was used to gather impact data. The testing was conducted at a sampling rate of 10,000 Hz and the hammer's operating range is between 0 and 5000 lb [48].

In order to determine the impact duration and impact magnitude of the instrumented sledge hammer on different surfaces, two different hammer tips and two different experimental setups were used. A gray tip of medium hardness (supplied with the hammer) and the slightly softer softball tip were used for both tests. Five different types of wood used to make cross country jumps were impacted on site at the Kentucky Horse Park.

Figure 4.16 Wood Impact Testing at Kentucky Horse Park

Figures 4.17 and 4.18 indicate the force time plots for both hammer tips respectively.

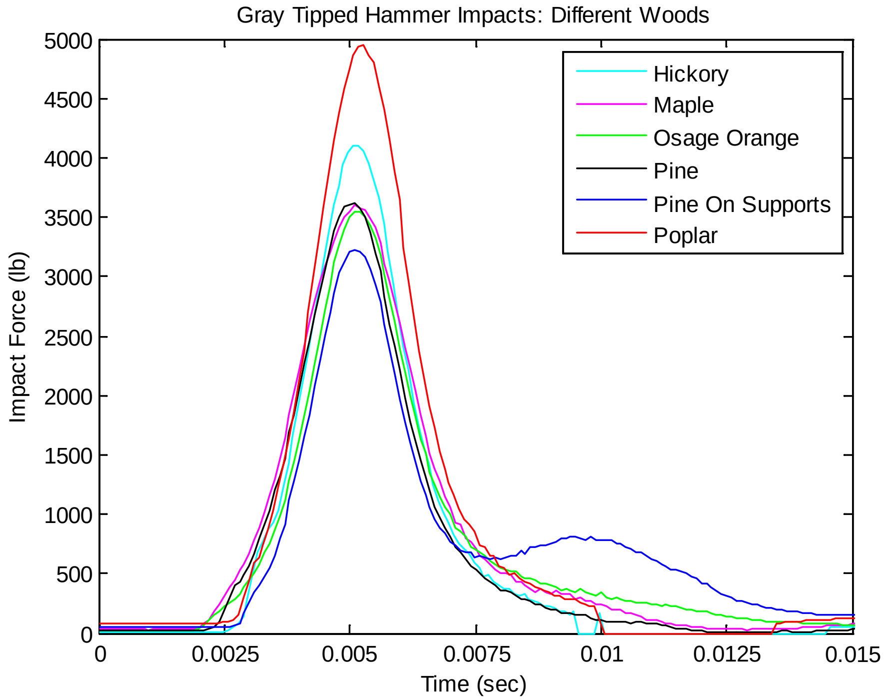


Figure 4.17 Gray Tip Impact Plots

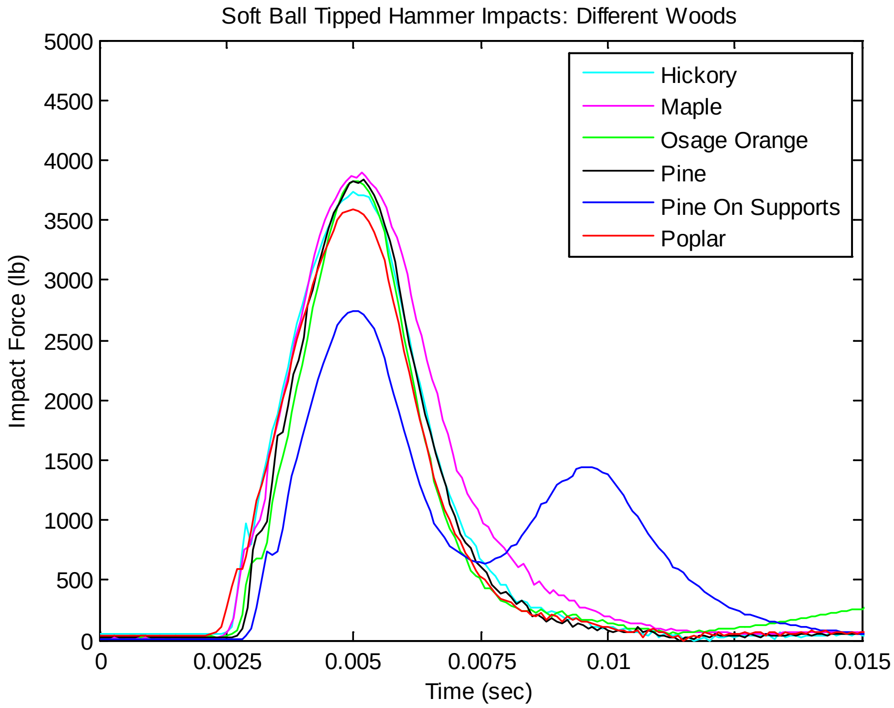


Figure 4.18 Soft Ball Tip Impact Plots

In the lab, both hammer tips (gray tip and softball hammer tip) were used to test the impact results of six different material setups. While most of these materials are not currently in widespread use on cross country fences, these materials were tested to see how they each affected the time duration and magnitude of the hammer impacts. Figure 4.19 shows the instrumented sledge hammer with the softball hammer tip in place and the gray tip next to it. The tested materials wood (plywood board), thin foam (one layer of gray foam), thin EPS foam (small white foam block), thick EPS foam (large white foam block), and thick foam (two layers of gray foam) are shown from left to right in the figure below.

Figure 4.19 Surfaces Tested in Lab Impact Test

The impact results are shown in Figures 4.20 and 4.21. Notice in Figure 4.20 the materials are listed in the legend in descending order of hardness, and as the hardness decreases the impact peak also decreases, while the time of the impact duration increases. The EPS thin and thick foam sections both have almost the same impact profile. This is likely due to the fact that even the thin EPS foam block was thick enough to absorb the hammer impact without fully compressing the material. Therefore, adding further foam thickness in the EPS thick specimen didn't change the results. Similar behavior can be seen in the impact profiles for the same materials using the softball tip (Figure 4.21). However, the behavior is not as clearly defined as in Figure 4.20, likely due to human operator variability.

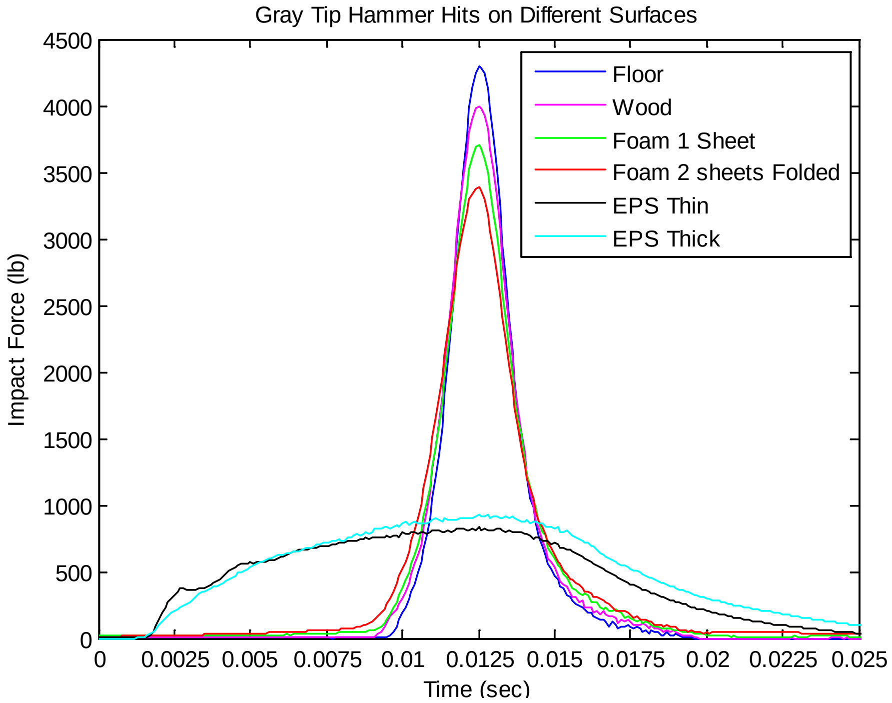


Figure 4.20 Gray Tip Different Surface Impact Plots

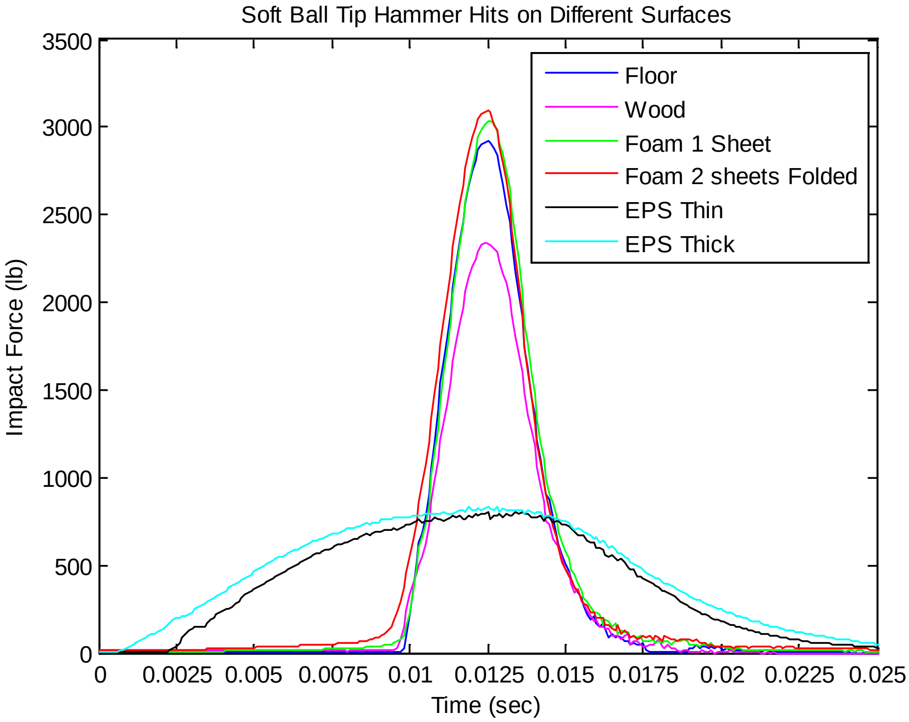


Figure 4.21 Soft Ball Tip Different Surface Impact Plots

As seen in the above figures, the impact hammer duration time was on average less than 0.01 seconds and has a capability of reading up to 5000 lb [48]. Michelle Tucker summarized results from the 2008 Top 20 Impacts Competitive Measure data [13]. From this work the average time duration of the main part of the horse impact was approximately 0.05 seconds and had an approximate peak force average of 2032 lb [13]. Therefore, the instrumented sledge hammer is capable of duplicating the same force range of a horse impact, but has a significantly smaller impact time duration.

As mentioned previously, TRL suggests the method of dropping weights onto the post and rail system to ensure it fails at the desired 200J of energy [33]. If the weight of the hammer (approximately 12 lb or 5.44kg) was just being dropped from a set height, it would have to be dropped 3.75m or 12.3ft in order to reach the desired 200J of energy.

$$
\begin{gathered}
mgh = energy \\
h = \frac{e}{mg} \\
h = \frac{200J}{(5.44kg)*(9.81\frac{m}{s^2})} \\
h = 3.75m \approx 12.3ft
\end{gathered}
\tag{4.4}
$$

Also, another way of analyzing the capabilities of the hammer in comparison to an actual horse impact was to compare the impulses (or area under the impact force vs. time curves). Michelle Tucker conducted analysis on the Competitive Measure Horse Impact data to determine the impulse of the Top 20 Impacts using the “trapz” command in Matlab [13, 32]. Based on her results the impact impulse median was approximately 28 lb*S (126N*S) with an average impulse of approximately 49 lb*S (217N*s) [13]. For comparison, the approximate impulses for three hammer hits were calculated. The light impact yielded 6 lb*s (27N*s), the medium impact yielded 9 lb*s (40N*s), and the hard impact yielded 11 lb*s (51N*s). While the hammer is able to reach the same magnitude range as a horse impact, it is not capable of reliably duplicating the same energy or impulses.

However, the instrumented sledge hammer can still be useful for preliminary field testing. The sledge hammer was used extensively for the University of Kentucky research on the performance of the hinged gate. The forces and energies being studied in this system were much less than those expected to be associated with a rotational fall and were therefore more easily handled by the hammer. Even though the hammer doesn’t provide an easy method for recording impact energies, the same hammer operator was typically used during tests and relatively consistent type, size, and speed of swings were used. Therefore, the results obtained during the field testing should be comparative between tests since the kinetic energy right before impact should have been relatively consistent.

Overall, the instrumented sledge hammer can be useful for some types of preliminary field testing. Specifically for replicating the impact force of horse impacts, but not the same impulse, energy, or time duration of horse impacts.

4.3.3.2 Field Testing Example: High Speed Video Analysis

As an added analysis tool, a high speed video camera was used to study the overall motion of horse and rider and the motion of possible fence designs. The high speed video helped to explore concepts including:

- Motion and time duration when triggering possible fence designs
- Motion and time duration of horse and rider impacting obstacles
- Motion and time duration of horse and rider successfully clearing obstacles

The capabilities of the high speed camera system provides the opportunity to look at each possible jump design up close, in great detail and also estimate the time required for the frangible device to be triggered and fully deployed. Michelle Tucker used Competitive Measure video of actual competitors impacting obstacles and compared this to the associated Competitive Measure impact data plot to better bound actual impact time durations and magnitudes [13]. Figure 4.22 shows shots taken from high speed video of a horse and rider successfully clearing an obstacle at a Young Rider's Competition at the Kentucky Horse Park [56].

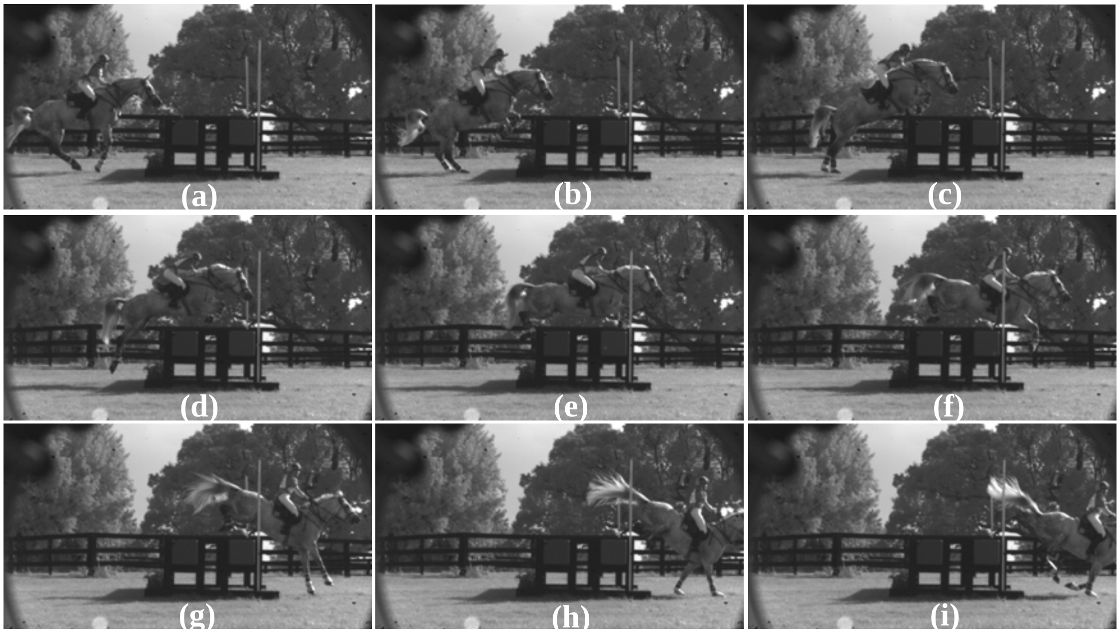


Figure 4.22 Snapshots from High Speed Video From Young Rider's Competition [56]

Viewing videos of successful jumps builds understanding of how a horse and rider's motion work together to correctly and safely clear obstacles. It is important that any possible fence design not interfere with this natural jumping approach, form, or landing.

4.3.4 Limited Test Implementation: Initial Use of Design in Competition

Once the design has been understood as clearly as possible under lab created scenarios, it is possible to have the safety designs introduced into competition practice areas and into lower and intermediate level cross country events. For further research a high speed camera could be used to monitor the fence during competition. The video footage would indicate how the horse approaches and leaves the obstacle and if the device is triggered how quickly the device triggers compared to how quickly the horse exits the fence area. Initial implementation would have to be carefully controlled to ensure that there is no increased risk to horse and rider. However, if frangible devices are added to a competition, plans would have to be put in place to deal with resetting triggered fences with minimal disturbance to the flow of the competition. Even after extensive testing of possible designs, use in actual competitions could introduce new challenges or new design improvements.

4.3.5 Redesign and Widespread Implementation

Any possible safety design must be tested and validated in order for it to be introduced into mainstream competition. The possible challenges or design improvements that may come to light during the limited design implementation could be fixed in a redesign of the fence before widespread implementation of the fence in more competitions. This cycle of use and design improvement is common to the field of engineering and efficiently improves designs overtime. Discussions with international course designers and sport enthusiasts indicates that course designers will either want to test the designs out themselves or see them tested before implementing them into their own course designs. Therefore, implementing the fence in a limited arena first allows time for course designers to voice their suggestions and concerns, implement these changes, and then implement the design in a wider arena with more support from within the sport. All of the above mentioned steps may not be useful for every design, but going through the general guideline helps to outline a starting point for analysis.

Now that a process has been defined for safety fence design and evaluation, the next chapter implements appropriate elements of this process for a hinged gate with a frangible pin release mechanism.

Chapter 5: Hinged Gate Study

5.0 Introduction

USEF and USEA funded the University of Kentucky research on a simple ditch and jump design case study. The project objectives included evaluating frangible and deformable fence designs, exploring feasibility of laboratory and field testing methods, and further understanding design testing challenges unique to cross country fences. The United States Equestrian Federation (USEF) president, David O’Conner, developed this fence design for a ditch and gate jump, also known within the sport as a Weldon’s Wall. The obstacle is a water-filled ditch in front of a 3.5ft wall topped with brush. If impacted at the critical design force, a frangible pin would break allowing the 3.5ft fence to fold down on hinges away from the horse. A schematic of the design is shown in Figure 5.1.

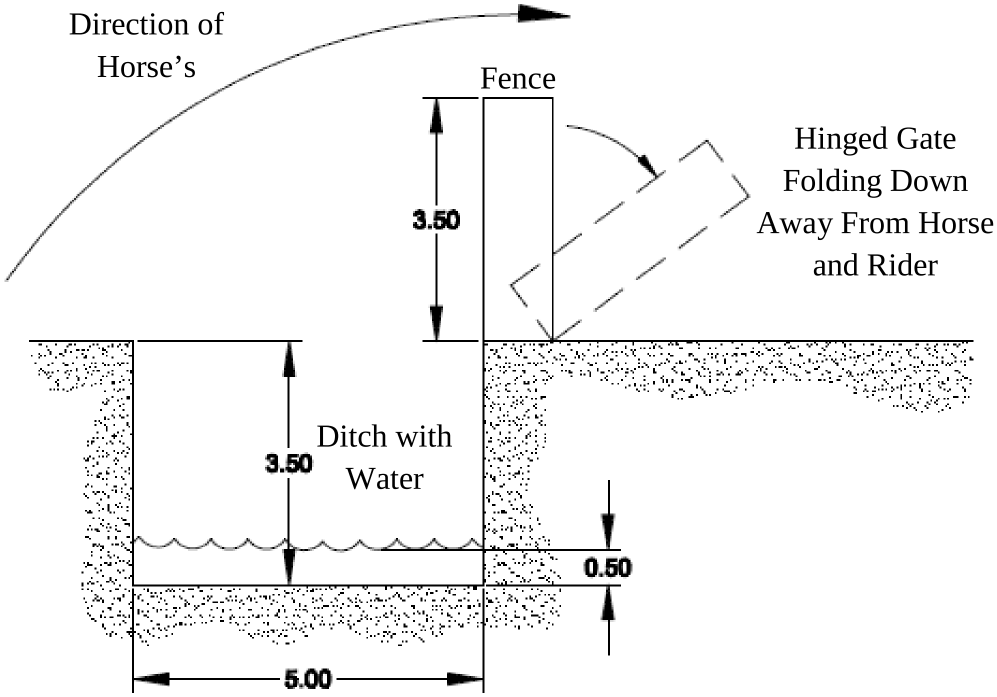


Figure 5.1 Schematic of Hinged Gate System

The below figure shows an example of this type of jump, which was built by the course builders at the Kentucky Horse Park in July 2009 for the Young Rider's competition. The fence incorporated two of the current British Eventing frangible pins, equipped with deeper stress concentration cuts. They were located at either end of the gate at the very top of the gate height. This particular fence would be jumped going from left to right and the portion of the wood fence above the ground level would fold down away from the horse and rider (to the right in Figure 5.2).

(a) (b)

Figure 5.2 Sample Jump at Kentucky Horse Park

Another example of this type of design was built out in Colorado prior to the start of the University of Kentucky research on this project. A wooden broom handle was used as the frangible device and two or three grown men were used to test the breaking force (shown below in Figure 5.3).

(a) (b)

Figure 5.3 Sample Jump In Colorado

These two versions of the design were constructed by course builders and members of USEF partially as a way of determining the initial feasibility of the design. However, little testing was done to determine the optimum construction and strength of the frangible device in the hinged gate. Therefore, goals of this particular study included determining the required number, the optimum location, and a specification for the frangible device. Also, a possible approach to analyzing and validating future safety designs was explored in the study of the hinged gate. This chapter includes the evaluation of the design through consideration of the following points:

- Determination design variables through equations and computer modeling
- Construction of a full size fence model for field testing
- Determination of design specifications
  - Number of frangible devices required
  - Design force

    - Location of pin
    - Pin material
- Consideration of design specific challenges

The general outline of the approach and testing methods involved were discussed in Chapter Four Testing & Validation Methods.

5.1 Theory and Monte Carlo

In order to understand the intended dynamic behavior of the design, basic mathematical equations were developed as a model of how the force is transmitted through the gate and to identify all necessary variables. The following diagram (Figure 5.4) and equations helped to identify the relationship between horse impact height, pin height, and pin breaking force. For simplification at this stage, the hinges were assumed to absorb any energy that would cause the gate to twist, so only force components going into and out of the page were considered here.

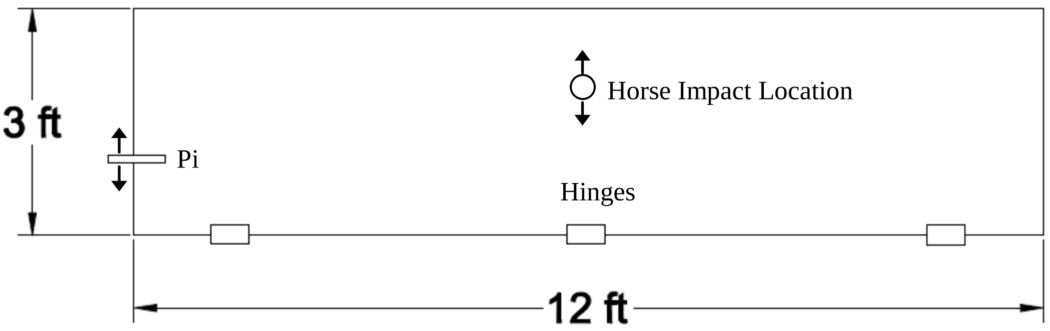


Figure 5.4 Hinged Gate Diagram

When the fence is in static equilibrium the following is true,

$$\sum M = 0 \tag{5.1}$$

Therefore, the reaction force at the pin can be determined through relating the moments caused by the horse impact force and the pin reaction force as

$$F_{reaction} = \frac{F * (H)}{P} \tag{5.2}$$

where, $F_{reaction}$=Reaction Force at Pin Location, F=Force of Horse Impact (component into and out of the page), H=Vertical Distance of Horse Impact From the Hinge, and P=Vertical Distance of Pin From the Hinge. This equation can now be used to determine the relationship between the height of the horse impact and the reaction force at the pin. When the horse impact occurs at the top of the fence (36” from the hinge) the equation is written as

$$F_{reaction} = \frac{F * (36'')}{1''} = 36 * F \tag{5.3}$$

When the pin is located at the bottom of the fence (1” from the hinge), and is written as

$$F_{reaction} = \frac{F * (36'')}{36''} = F \tag{5.4}$$

when the pin is located at the top of the fence (36” from the hinge). When the horse impact occurs at the bottom of the fence (1” from the hinge), the reaction force is represented as

$$F_{reaction} = \frac{F * (1'')}{36''} = \left(\frac{1}{36}\right) * F \tag{5.5}$$

when the pin is located at the top of the fence (36” from the hinge), and is represented as

$$F_{reaction} = \frac{F * (1'')}{1''} = F \tag{5.6}$$

when the pin is located at the bottom of the fence (1” from the hinge).

These equations imply the higher the impact force is above the pin in general the easier the pin will break due to a higher reaction force at the pin. However, since the horse impact location is likely to vary with competitors, horse size, land layout, etc., the optimum location of the pin must be determined within the scope of all of the variables involved in the design.

In order to gain a better understanding of the general interaction between the many variables, the method of Monte Carlo simulation (mentioned in Chapter Four) was applied. The first step was to determine the key design variables.

Hinged Gate Direct Design Variables (independent variables):

- Horse Impact Force
- Height of Horse Impact
- Pin Height
- Preload Moment Value
- Length gate load applied along pin
- Point of interest distance from the post
- Distance from post to start of load
- Pin big diameter
- Pin little diameter
- Radius of cut

Hinged Gate Indirect Design Variables (dependent variables):

- Length of overall pin
- Type of material (strength, hardness)
- Type of KT (strength of KT and type)

- Sleeve or no sleeve to hold pin in place (if pin moves around harder to break cleanly)

These variables are identified in the schematic of the pin held in the post and against the gate shown in Figure 5.5.

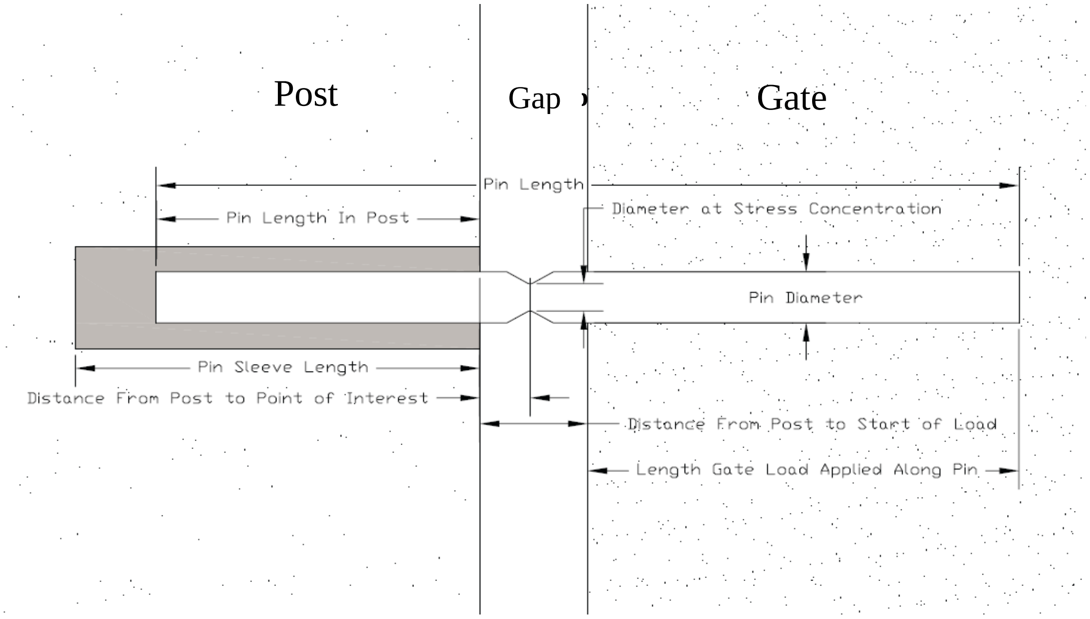


Figure 5.5 Hinged Gate Pin Variables Schematic

The intent of using the Monte Carlo method was to gain a general understanding of the design behavior. Consequently, only rough estimates of appropriate ranges for the listed variables were programmed into Matlab. Due to the inherent variability, the exact variable ranges and material strengths used are not as important as the general trends seen in the plots.

In order to represent the plots for the hinged gate with the frangible pin, the moment at the point of expected break was calculated.

The moment equation can be written as

$$M = W_o * DA * X_1 - W_o * DA * \left(X_2 + \frac{DA}{2} \right) \tag{5.9}$$

where, M= Moment at stress concentration (point of expected break), W_o=Applied Pressure (lb/in), DA=Distance pressure is applied along pin (in)—contact between gate and pin, X_1=Distance point of expected break is from "wall" or post (in), and X_2=Distance from "wall" or post to where applied pressure begins (in). The moment value can then be used to find the normal bending stress using the equation

$$Normal\quad Bending\quad Stress = \frac{M * y}{I} \tag{5.10}$$

and more specifically for a circular diameter using the equation

$$SigmaNorm = \frac{32 * M}{\pi * (d^3)} \tag{5.11}$$

where, SigmaNorm=Normal Stress at point of expected break, M=Moment, and d=pin diameter at stress concentration. To guarantee that the pin will break at the desired point and critical load, a groove is cut into the pin located in the gap between the post and the hinged gate. The stress concentration factor (kt) indicates how much the stress is amplified by this groove in the pin. With the stress concentration factor applied, the maximum stress is written as

$$\text{SigmaMax=kt*SigmaNorm} \tag{5.12}$$

where, kt=stress concentration factor. When a metal rod is subjected to bending stress, transverse shear stress is also present. Shear stress is maximum at the center of the pin and zero at the outer edge, while normal stress is the opposite of this [10]. The transverse shear stress can be written as

$$Transverse\quad Shear\quad Stress = \frac{V * Q}{I * b} \tag{5.13}$$

Where, V= shear force, Q= top or bottom portion of cross sectional area times the distance to the centroid of that area, I= the second moment of area, and b= width.

Typically, transverse shear stress is small enough compared to normal stress that it can be neglected. Therefore, for this problem the assumption is being made that only normal stress is present.

Figures 5.7-5.10 were created considering a material with an ultimate or maximum strength of 99ksi and a yield strength of 95ksi. Since these plots were useful in gaining understanding in the initial stages of analysis, the material strength was not specific to a certain material but was simply used to get overall trends. The following plots focused on the key parameters including impact height, horse impact force, and pin height. However, as discussed in Chapter Four, the plots are based on the entire variable interaction. Figure 5.6 indicates the symbols and colors used to identify each of three scenarios, the pin broke, the pin deformed, or the pin was unchanged (didn't break or bend).

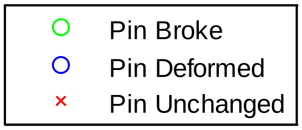
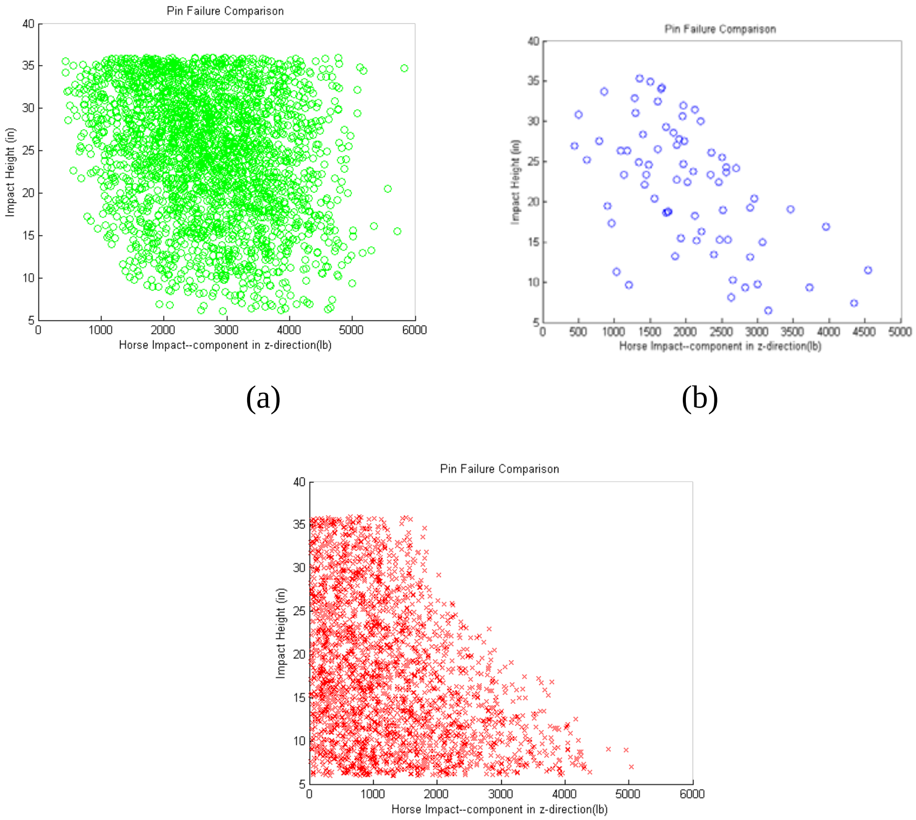


Figure 5.6 Monte Carlo Plots Legend

Figure 5.8 plots the relationship between horse impact force and impact height and includes all three possible situations (broken pin, deformed pin, and unchanged pin). When all of these points are included on one plot it is somewhat difficult to see the complete range of each of the three possibilities. Figures 5.7 (a), (b), and (c) plot the same variable comparison as Figure 5.8, but each show only one of the possible situations at a time. As seen in Figure 5.7 (a), the pin breaks easier as the impact height increases. The centered nature to the scatter plot is due to the way the variables were defined. Some variables, as discussed in Chapter Four, were plotted as a uniform distribution within a range and other variables were defined with a normal distribution. Figure 5.7 (b) shows the points representing a deformed pin, notice these points occur in generally the middle region, between where most of the broken pins and unchanged pins occur. Figure 5.7 (c) plots all of the points that represent unchanged pins. These points form a triangle covering the low impact force and low impact height regions. When all three possible situations are superimposed onto one plot the overall behavior is shown (Figure 5.8).



(a) (b)

(c)

Figure 5.7 Impact Force and Impact Height:
(a) Broken Pins, (b) Deformed Pins, (c) Unchanged Pins

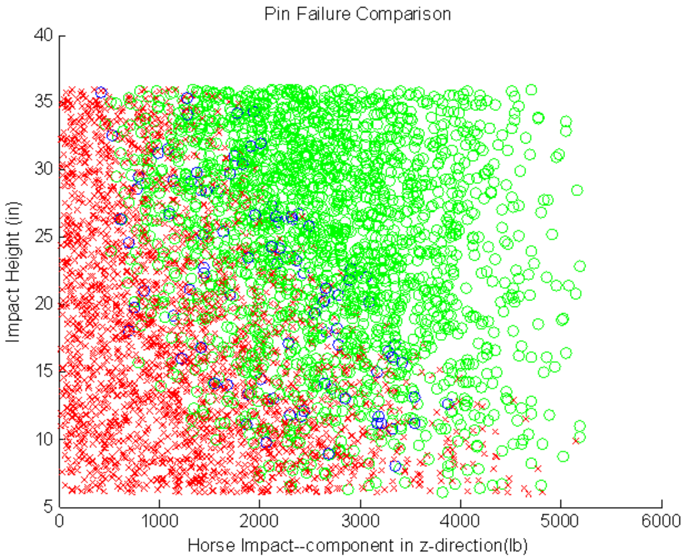


Figure 5.8 Monte Carlo Plot Comparing Horse Impact Force to Impact Height

Figure 5.8 is a Monte Carlo plot looking at the relationship between the horse impact force and the height of the impact. The plot displays the general trend that as the horse impact force increases the pin breaks more reliably as shown by the increased number of green points. Note that when the impact height gets low enough (to about 6 inches) the pin generally doesn't break despite increasing the impact force. This can be seen in the line of red x's plotted horizontally at a height of approximately 6 inches even all of the way up to almost 5000 lb. The relationship between the impact height and horse impact seems to be an exponential curve rather than a linear relationship. When designing the optimum pin for the hinged gate, it may be preferred to have the expected design breaking force fall in the green region instead of the overlapping region. This means that the pin may be deformed or broken occasionally at lower forces than necessary, but the design should trigger reliably when a dangerous force level is reached.

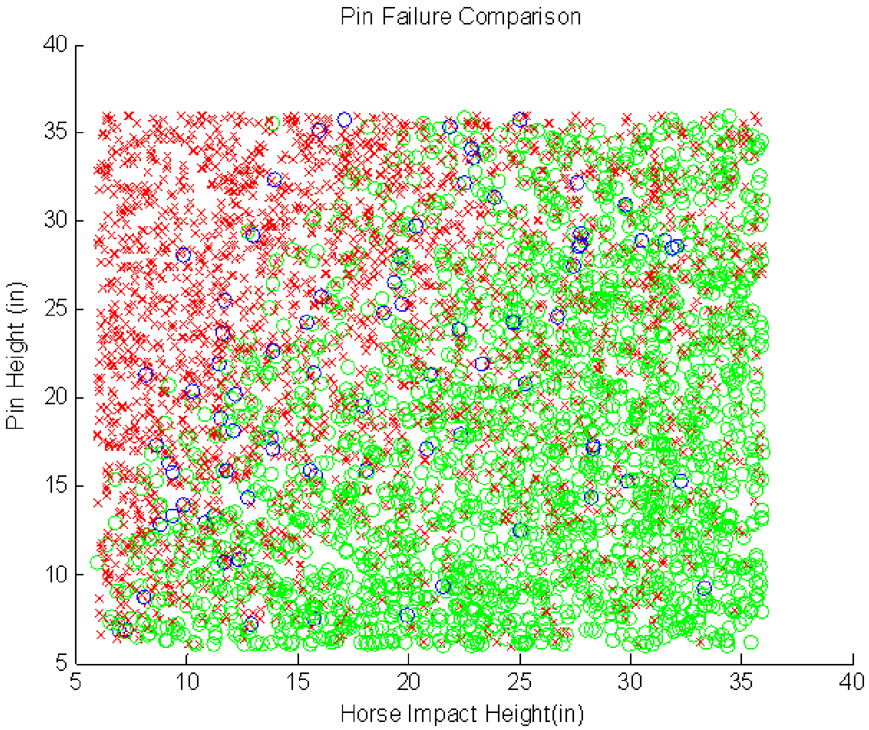


Figure 5.9 Monte Carlo Plot Comparing Impact Height to Pin Location

In Figure 5.9, there seems to be a generally linear overlap relationship between pin height and impact height, such that as the pin height decreases and the horse impact height increases the pin breaks more often. However, this plot is a good example of how the other variables in the code that are not directly shown on this plot, affect the result of the pin status as seen in the diverse mixture of unchanged pins and deformed pins (red and blue points respectively). Thus, the relationship between pin height and horse impact height has some influence, but is not the ultimate determinator of the pin status.

Figure 5.10 shows a more defined trend between horse impact force and impact height because the red and green regions are not mixed throughout the entire plot. There is an overlap between the two regions, but there is also a distinctive pin breaking region and an unchanged pin region.

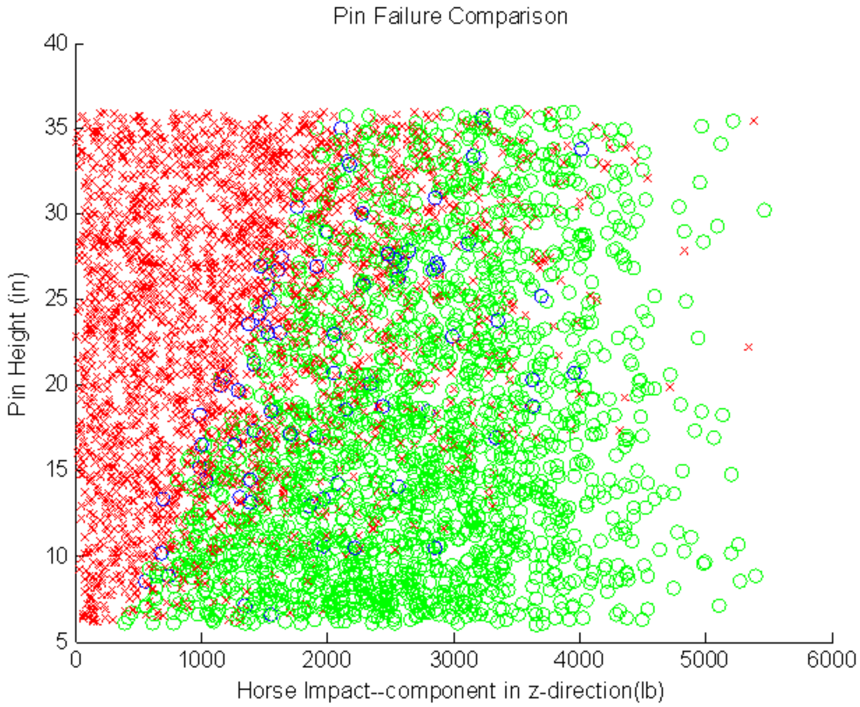
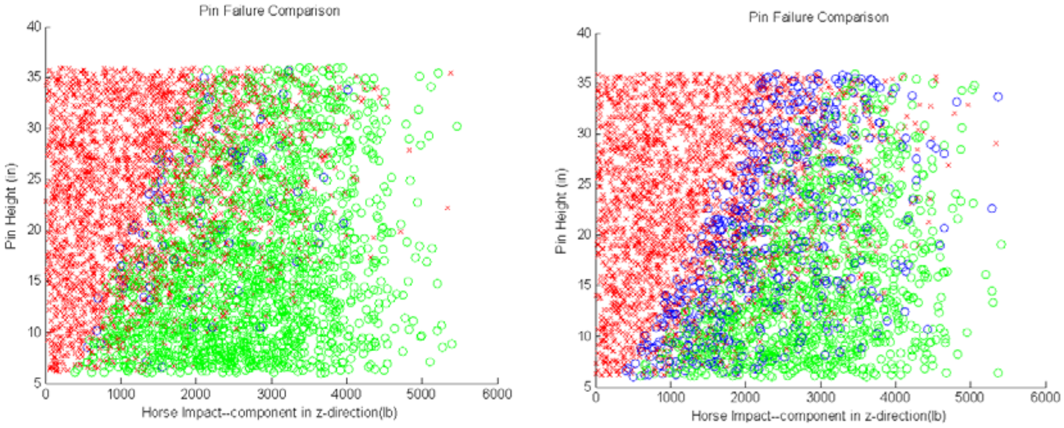


Figure 5.10 Monte Carlo Plot Comparing Impact Force and Pin Location

Figure 5.10 reiterates the trend that the pin breaks more readily as the pin height decreases and the horse impact force increases. Figure 5.10 was plotted using an ultimate strength of 99ksi and a yield strength of 95ksi (shown in Figure 5.11 (a)). The same figure has been replotted (Figure 5.11 (b)) with an ultimate strength of 150ksi and a yield strength of 110ksi to represent how the Monte Carlo results change for different material properties.



(a) (b)

Figure 5.11 Comparison of Different Material Properties:
Ultimate Strength-- (a) 99ksi (b) 150 ksi; Yield Strength-- (a) 95ksi (b) 110ksi

Specific to the hinged gate, the above plots clearly show that as the difference between the yield strength and ultimate strength increases the probability of having a deformed pin instead of having a pin that cleanly breaks increases. This is evident in the increased region of blue circles, representing situations where the pin deformed. For use in the hinged gate a deformed pin is never desired. This means the pin may deform at a lower force then desired and then trigger unexpectedly later with a light impact, or that the pin may deform instead of breaking away when desired leaving the gate unmoved during a critical impact. A tentative conclusion drawn from the Monte Carlo analysis is the necessity for the pin material used to have as minimal a difference between the yield and ultimate strength as possible. Also, the pin should be located at half the height of the hinged gate or below. However, it is important to note that these plots are based on theoretical equations gained through making some assumptions. For example, energy loss through the wood of the gate and the hinges has not been included. For that reason, while some helpful trends can be identified more detailed theoretical analysis or field testing of a full model is necessary for more conclusive observations.

5.2 Full Size Hinged Gate Field Model

To understand implications of aspects that were not previously modeled and energy loss, a full size model was constructed of the hinged gate. The hinged gate was a relatively simple design to construct and analyze (even though force and material complexities still existed). The design served as a suitable starting point for understanding key forces and dynamics involved in safety devices while a prototype approach was analyzed. A version of the hinged gate was built without the hedge and without the ditch since these two components were not critical to the analysis of the safety device's behavior. The model is shown in Figures 5.12 (a) and (b).

(a) Model Constructed at Private Farm

(b) Model Moved to Testing Site at the Kentucky Horse Park

Figure 5.12 Full Size Hinged Gate Field Testing Model at Two Locations

Figure 5.13 Field Testing Hammer, Pin, Hinged Gate Model

The model was initially constructed and tested at a privately owned farm and was later moved and tested at the Kentucky Horse Park. The construction supplies and estimated cost are provided in Appendix A. The same model was used at both locations, but different posts were used to secure the base to the ground. Both test sites were relatively flat open areas. Therefore, there was not any significant difference in the model setup between the two locations. The model was 12ft by 3ft and had less than 3 inches between each slat to prevent a horse's leg from getting stuck between the boards. The gate itself was supported by a board running along the base of the jump with three hinges. The posts on either side were used to anchor the base and the safety device (frangible pin) was placed in drilled holes and sleeves at various heights for testing. Concerning the design specifications, there were three main questions: what design force should avoid neck injury, where should the breakable pin be located, and what material should be used for pin construction.

5.2.1 What Design Force?

FEI has not developed a specification for cross country fences identifying the critical design forces to prevent a serious injury or a rotational fall. This section summarizes the available information on force levels.

The mathematical equations and the variables of the featured design were identified, listed, and initially bounded with the Monte Carlo simulations. However, more detailed force information and variable ranges were needed for accurate field testing. Throughout the project the University of Kentucky effort was coordinated with research supported by British Eventing and conducted by Competitive Measure, to avoid duplication of work. More information on the work conducted by Competitive Measure was provided in Chapter Four Testing & Validation Methods. Competitive Measure's data on real horse impacts served as a source to estimate the variable ranges for this design. However, no rotational falls and few serious falls were recorded in the data used. The type of jump and terrain used to gather the data were also much different than the situation of this particular hinged gate since on typical jumps the most common serious falls are from rotational falls rather than neck injuries from straight on impact. Michelle Tucker worked with Competitive Measure's data to plot information including average impact angles and forces to aide in bounding the variability values. The data analysis aided the Monte Carlo plot work and aided in bounding the size and material needed for the pins used in the field testing. However, due to the uncertainties in Competitive Measure's data in application to the hinged gate, further biological research was done by Michelle Tucker.

A horse's neck could be broken from a straight on head impact into the gate, resulting in an inward force on the nose and head, creating a tension force on the top side of the neck and compression on the bottom side of the neck bones. (Note: the following research data and relevant comparison research was originally done in the metric system so it is shown here in the metric system, but English conversions are also provided for reference.) Biological journal articles indicated that 2,014-1,671N (453-376 lb) was required to break the neck of a dairy cow compared to 3156 +/- 1586 N (710+/-356 lb) for a pig [2, 30]. A study of an intact human head and neck showed damage at an approximate tensile force of 3373 +/- 464 N (758+/-104 lb) [60]. In this study the ligaments and muscles were still intact, but since a cadaver was used the results still may differ from a living creature that still had full use of the attached muscles. Based on the combined research a biomechanics force number was estimated at 2000N (450 lb) [2, 30]. Taking into account that these results were performed on smaller deceased animals where the muscles were not able to assist in protecting the neck from impact, the biological suggested force was increased by a factor of 2. A force of 4000N (900 lb) was therefore used as a rational estimate for a neck injury load.

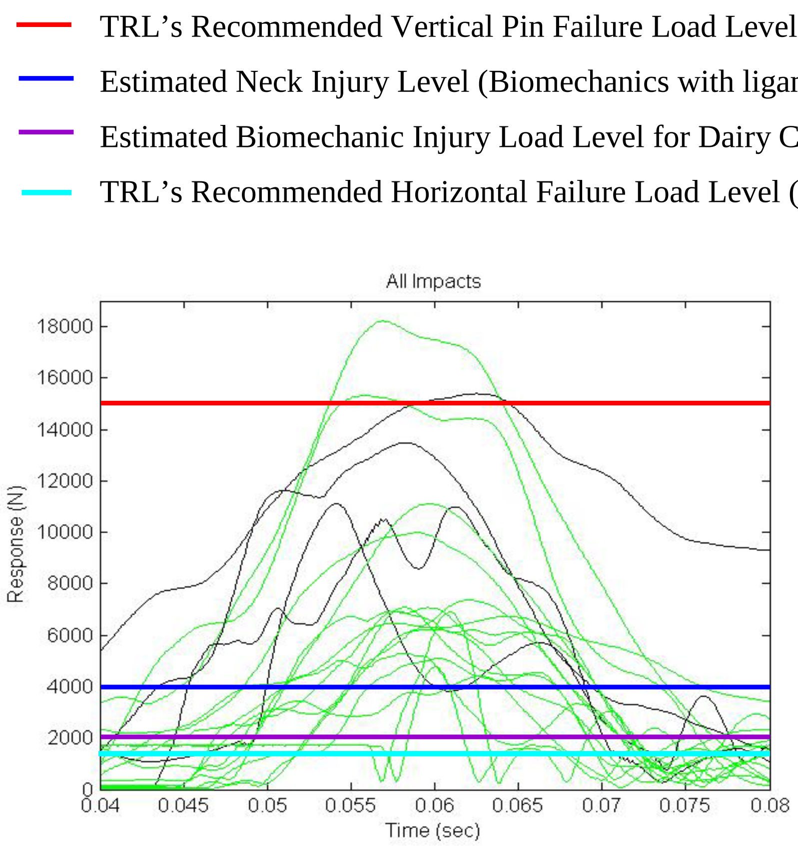


Figure 5.14 Design Forces and Data from Top 20 Impacts (citation needed)

Figure 5.14 plots three key forces on top of data from Top 20 Impacts from Competitive Measure's Instrumented Jump data [14]. The black lines indicate contacts classified as body hits and the green lines represent hoof strikes. With the estimated neck injury force so low and considering amplitude only, numerous hoof strikes have sufficient amplitude to trigger a safety device.

5.2.2 Where to Locate Pin?

Paramount to the reliable operation of a design is how many safety devices will be used and where those safety devices will be located. While this may seem like a simple question, the location of the safety device(s), in this case the frangible pin, affects the necessary strength and size of the device and is closely tied to parameters including the location of the horse impact and how much energy is lost through the gate.

From the Monte Carlo computer simulations discussed earlier (Figures 5.9 and 5.10), the necessary pin placement was determined to be around a quarter of the way up the height of the gate. The lower the pin is located the easier it will break. However, there is a tradeoff between making the pin easy enough to break that all critical impacts trigger the device, but not so easy to break that the device has to be reset for every light impact.

Experimental field testing was conducted using the full size hinged gate model and the instrumented sledge hammer to record impact force histories. Numerous pins were created from one material batch, were machined to a single specification, and were located at the same height (approximately half the height of the gate) in the hinged gate test model. The pins were placed at approximately half the height of the gate instead of a quarter of the way up the fence so that hitting the pin directly could be directly compared to impacting the gate at the location of the pin. The design of the hinged gate has three boards that run horizontally along the gate. Therefore, matching those three heights to the three impact heights along the fence simplified testing. Each pin was placed inside of a metal sleeve in a hole drilled in the post to ensure the same location was used for each test and that the pins did not move around during impact. Part of this study considered whether one or two pins (one on each side) would be the most effective design. The study began by analyzing a single pin design.

Three pins were initially placed inside the sleeve and hit directly with the instrumented sledge hammer one by one to obtain an average direct breaking force. The pins were then placed into the post one by one and the gate was impacted at nine different locations with the instrumented sledge hammer to determine how much the pin breaking force varied throughout the gate. Figure 5.15 depicts the average breaking forces (as seen by the instrumented sledge hammer) for the pin directly and through the gate at each location. The force to break a pin by hitting it directly is shown on the left of the diagram under the single pin testing setup. The location of the forces in the diagram correspond to the location where the hammer was hit against the fence when that breaking force was recorded. A significantly higher force is required to break a pin when impacting the gate compared to the force required to break it if the pin is hit directly. The difference in the force levels across the gate and compared to hitting the pin directly are explored further in Figure 5.16.

Figure 5.16 translates the forces in figure 5.15 into force factors relative to breaking the pin directly. The differences in the forces levels across the gate can be easily compared through the use of these force factors. The breaking force of hitting a pin directly (100 lb) represents a factor of 1. The forces to break the pin through the gate are scaled from that basis. Therefore, it requires 7 times more force to break a pin by hitting the pin through the gate (at the exact location where the pin touches the gate) instead of hitting the pin directly, due to energy loss through the gate. The maximum breaking force is found at the center bottom location, with the force being generally larger all along the bottom. This is likely due to the hinges absorbing much of the energy, instead of having a large moment arm to help rotate the fence around the hinge which explains the lower force factors at the top of the fence. Also, the force factors are large at the center and symmetrical lesser towards the sides of the fence. Therefore, the pin specification could be determined using the center force factor, assuming the horse is unlikely to impact the fence at the base. Furthermore, the force factors decrease upward and to the sides from the center point, ensuring that if a critical impact was enough to break the pin at the center they would also break at the other points around the fence (other than at the very bottom).

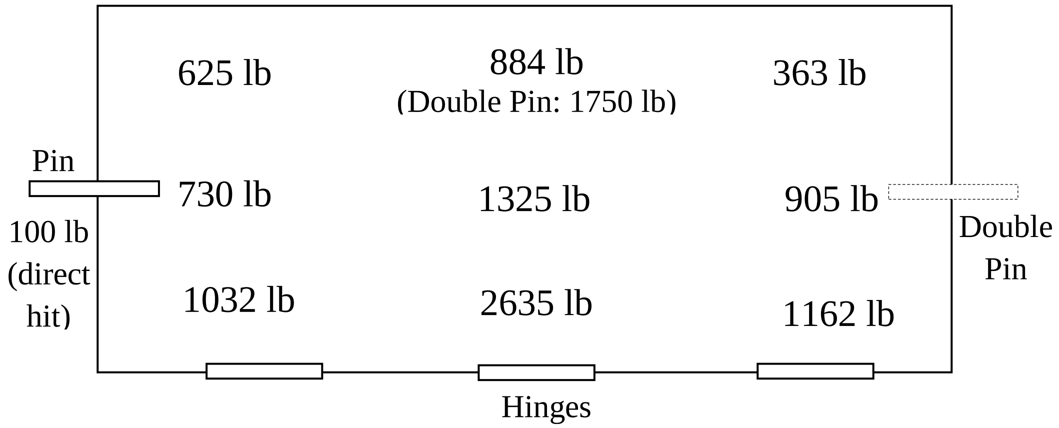


Figure 5.15 Forces at Different Location Along Hinged Gate

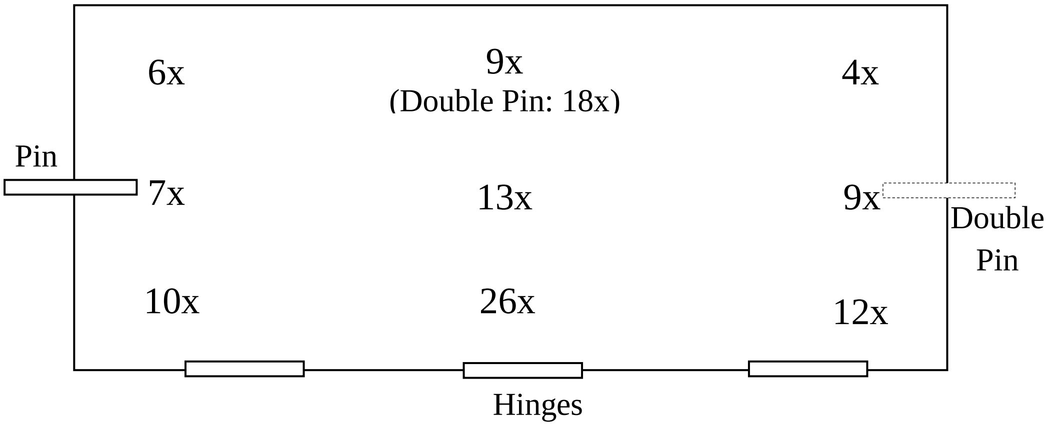


Figure 5.16 Force Factors at Different Locations Along Hinged Gate

Both Figure 5.15 and 5.16 also represent the required breaking force for when two pins were placed in the hinged gate (one pin placed on each side of the gate at half the height of the hinged gate). Figure 5.17 shows the double pin testing setup. A pin of the same size and specifications were located on both sides of the hinged gate.

Figure 5.17 Pin and Impact Locations Identified

Only one location is shown as reference (in Figures 5.15 and 5.16), the top row center location. When the hinged gate was impacted directly in the middle of the top board both of the pins broke. However, the force required to break the double pin setup was twice as much as the force required to break the pin in the single pin setup (as would be expected). Therefore, it follows that the force differential between breaking a single pin directly and breaking two pins through the gate would be significant, complicating the pin specification. Also, if the impact occurred off center (which is likely in a real life jumping situation) only one pin broke leaving the hinged gate in place. Therefore, with the two pin setup if a critical impact occurred off-center, the fence may not collapse increasing the risk of serious injury.

These exact force numbers are specific to the construction and materials of this prototype. If another jump was made out of different materials or had more mass, the results would vary. It is also important to note there is a significant error present here due to the fact that these are not necessarily the minimum forces required to break the pin at that point. The hammer was hit incrementally harder against the fence, but the required breaking force is actually between the highest “didn’t break” force and the lowest “did break” force because the gate resists motion and yields higher forces when you hit the hammer against it harder even if the pin broke both times. The plot in Figure 5.19 helps to bound the error by indicating this region between the known “no pin change” and the known “pin breaking” point. Figure 5.18 provides labels for the nine tested locations. Location F in Figure 5.19 represents a point where the pin failure load has been tightly bounded. The “no pin change” and “pin breaking” points are almost on top of each other. Point E, however, shows a situation where the breaking force and the no pin change force are far apart and it is unknown where the actual breaking force is closer to the upper point (1325 lb) or the lower point (789 lb). Therefore, the pin breaking force at this location is less certain. This error combined with material variability creates large variability ranges. The average value of breaking the same pin design directly was 100 lb with a standard deviation of 15 lb, showing the variation in the results.

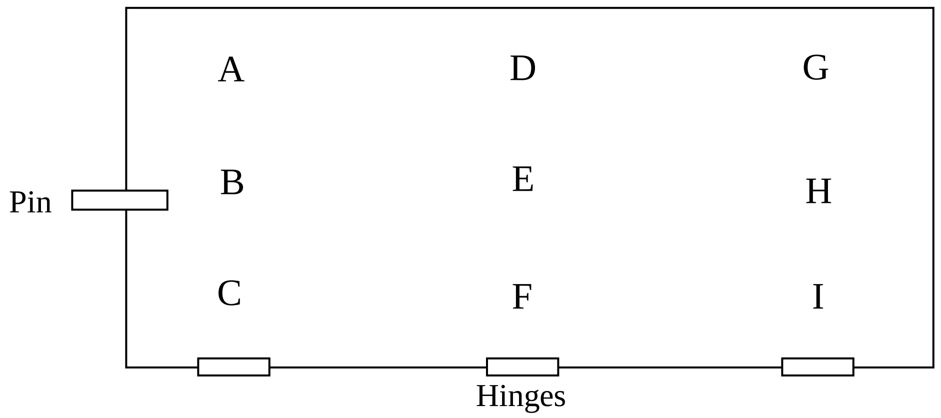


Figure 5.18 Legend for Different Locations Along Hinged Gate

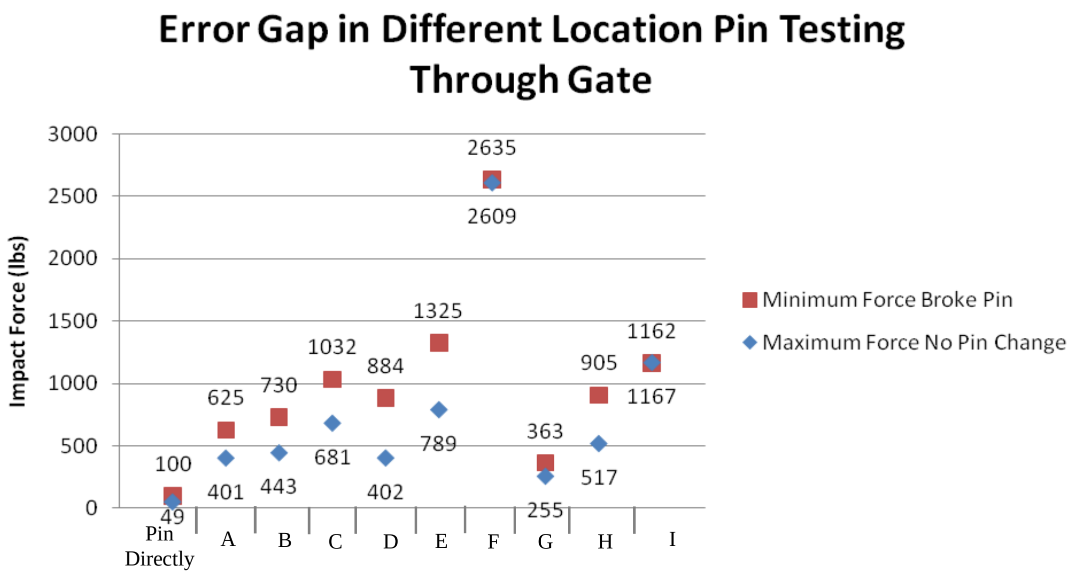


Figure 5.19 Error Gap in Testing Different Locations

In conclusion, as seen in the large force factors given in Figure 5.16, there is a significant difference between the amount of force that the horse or rider feels and imparts on the jump during impact compared to the amount of force actually applied on the frangible pin. The estimated critical design force of 900 lb that the biological research suggested means that the force the horse and rider feels during the impact would need to be below this force to escape serious neck injury. Due to the energy lost in the gate, the pin would need to be designed to break at an order of magnitude lower force than that 900 lb. When looking at Figures 5.15 and 5.16 to determine at how much lower of a force the pin would need to fail, it is important to determine which region of the gate a horse and rider are likely to impact during an accident. Since there is a ditch in front of the jump it may be difficult for the horse and rider to forcibly impact the bottom third of the gate however the top two thirds of the hinged gate along its full width should be considered. The largest factor in this region is approximately 13x the pin breaking force when the gate is impacted directly in the middle. Therefore, the pin would need to fail at a force 13 times smaller than the critical design value of 900 lb. Also, due to the afore mentioned material, horse, and riding variability a factor of safety should also be added to this breaking force. A typical engineering factor of safety (FS) of 2 would halve the critical design value of 900 lb to 450 lb, and the pin force down from approximately 70 lb to 35 lb.

However, during our work with the competitive measure data we found that the force amplitudes resulting from a common hoof strike can often be as high as a body strike, but of a shorter impact duration. Since the estimated neck impact injury force is much lower in magnitude than many of these body and hoof strikes, this particular design suggests that there may be many false triggers. Meaning, the jump will likely be triggered often by impacts that are not critical impacts disrupting the flow of the event.

However, this low of a force is believed to be necessary in order to protect the horse from possible neck injury impact. The solution to these unwanted safety device triggers may lie in exploring other types of safety devices other than force level triggered devices, which will be briefly discussed in Chapter Three Overview of Cross Country Eventing Safety Designs.

Due to this study, it was determined that only one frangible pin should be used in the device. Using two pins decreases the efficiency and safety of the design due to:

- Increased chance that only one pin will break during a critical impact increasing risk to horse and rider
- Increased required material and expense
- Increased design complexity (more pieces to check and maintain)
- Decreased reliability of safety device (possibility of defects in two pins instead of one)

For the design tested, the field testing results suggest that using a single pin located at about half way up the hinged gate provides a balance between desired operation and design complexity.

5.2.3 What pin material to use?

The choice of material and geometry for a frangible device has proven to be far more difficult than one would expect at first consideration. Outdoor use and consistent results dictate the use of materials that are not affected by exposure to weather conditions. On one of the hinged gate prototypes that David O'Conner had built, a wooden pin was used. However, wood is not used here since the material properties can often be unpredictable and can change when exposed to rain and humidity in the field.

In order to gain a firm understanding of the different material behaviors, the field testing of the hinged gate and pin system included over 200 recorded impacts, over 60 pin designs, 4 different materials (aluminum alloy 6061,6063,7068,7075), 5 different pin diameters (1”,3/4”,1/2”,3/8”,5/16”), 3 different stress concentration cut shapes (v cut, half vcut, u cut), and a range of cut depths.

Initial testing was conducted in the lab to understand the issues, to evaluate the behavior of Aluminum Alloy 6063, and to test the behavior of different stress concentration cut shapes. Figure 5.20 indicates three different stress concentration shapes that were used. Figure 5.21 (a) depicts the preliminary lab test setup, which was a statically-loaded cantilevered pin. Pins after testing are seen in Figure 5.21 (b).

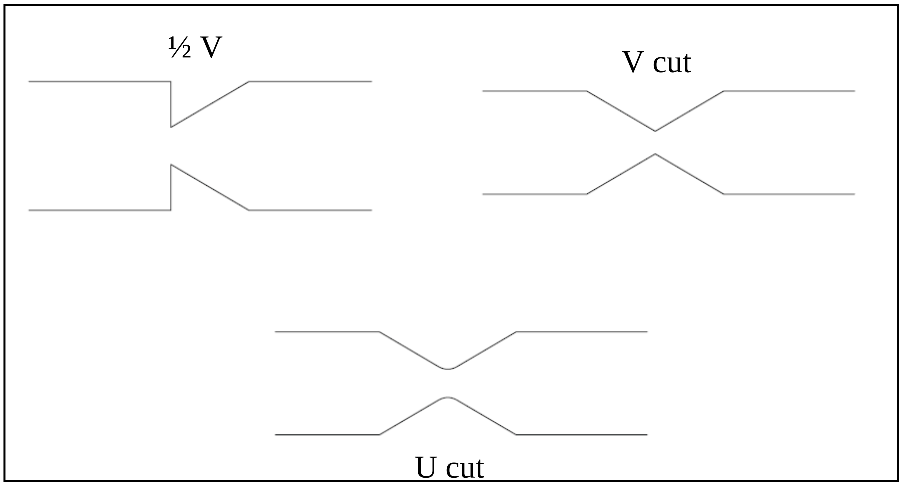


Figure 5.20 Stress Concentration Cut Shapes

(a) (b)

Figure 5.21 Preliminary Pin Testing in Lab

The aluminum alloy 6063 was found to be too ductile for the desired purposes. In order for the gate to move out of the way of the horse and rider, it is important for the pin to break free cleanly in a short time and within a small force range. Figure 5.21 (b) shows that this particular material generally started to bend early and continued to bend instead of break as further weight was added. Also, while the half-v cut shape often failed more easily than the v-cut, both shapes adequately fulfilled the purposes of including a stress concentration. A u-shaped cut was found to be more easily and repeatedly machined than the v-cuts. This stress concentration cut was used for the remainder of the tests since all of the shapes adequately defined the point where the pin should break.

The other three materials (aluminum alloy 6061, 7068, 7075) were tested in the full size hinged gate model. The field testing measurement involved an instrumented sledge hammer and a high speed camera. Figure 5.22 (a) shows a typical set up of the high speed camera capturing the behavior of a breaking pin at the private farm used for testing. Figure 5.22 (b) shows the set up of the instrumented sledge hammer and data acquisition system at the Kentucky Horse Park.

(a) (b)

Figure 5.22 Field Testing Setup

Figure 5.23 shows the instrumented sledge hammer, one of the larger pins tested, and the metal u-brackets used to restrain the pin after breaking.

Figure 5.23 Field Testing Setup and U-bracket Constraints

Figure 5.24 indicates the dimensions of the most common pin testing setup. Tables 5.1-5.3 summarize the tested pin designs and results.

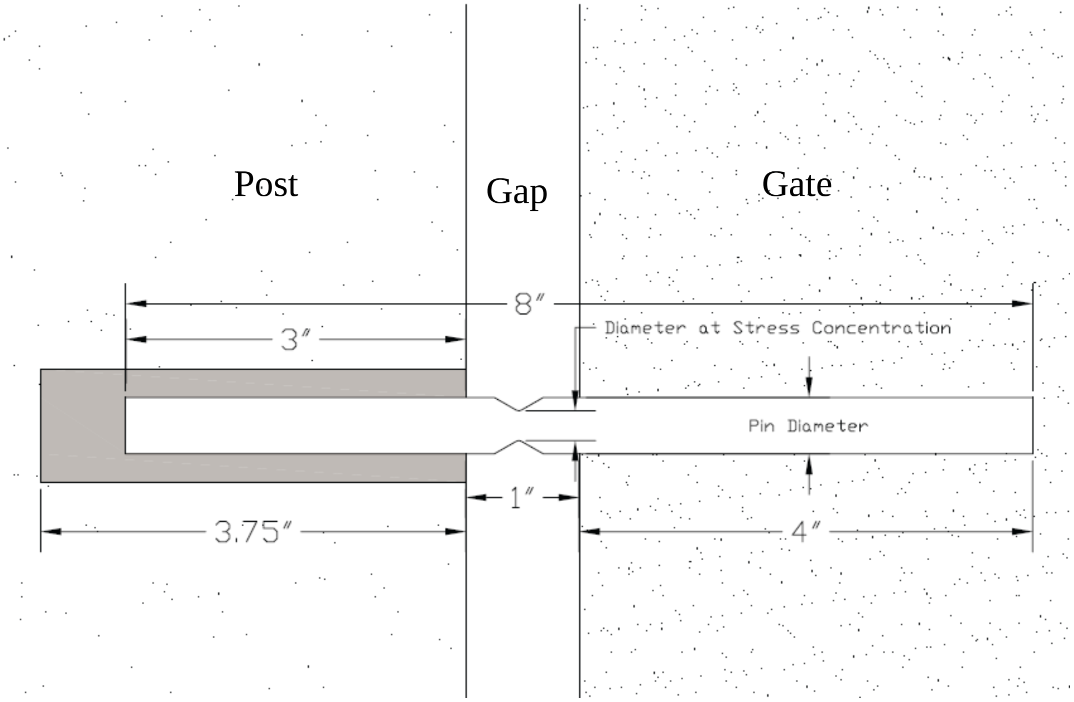


Figure 5.24 Sample Test Pin Dimensions and Setup

Figure 5.25 indicates a series of shots captured from the high speed camera video of a pin breaking cleanly away as desired. Figure 5.26 shows a pin that was made from Aluminum Alloy 6063 which was too ductile and bent instead of breaking, which delayed the collapse of the hinged gate.

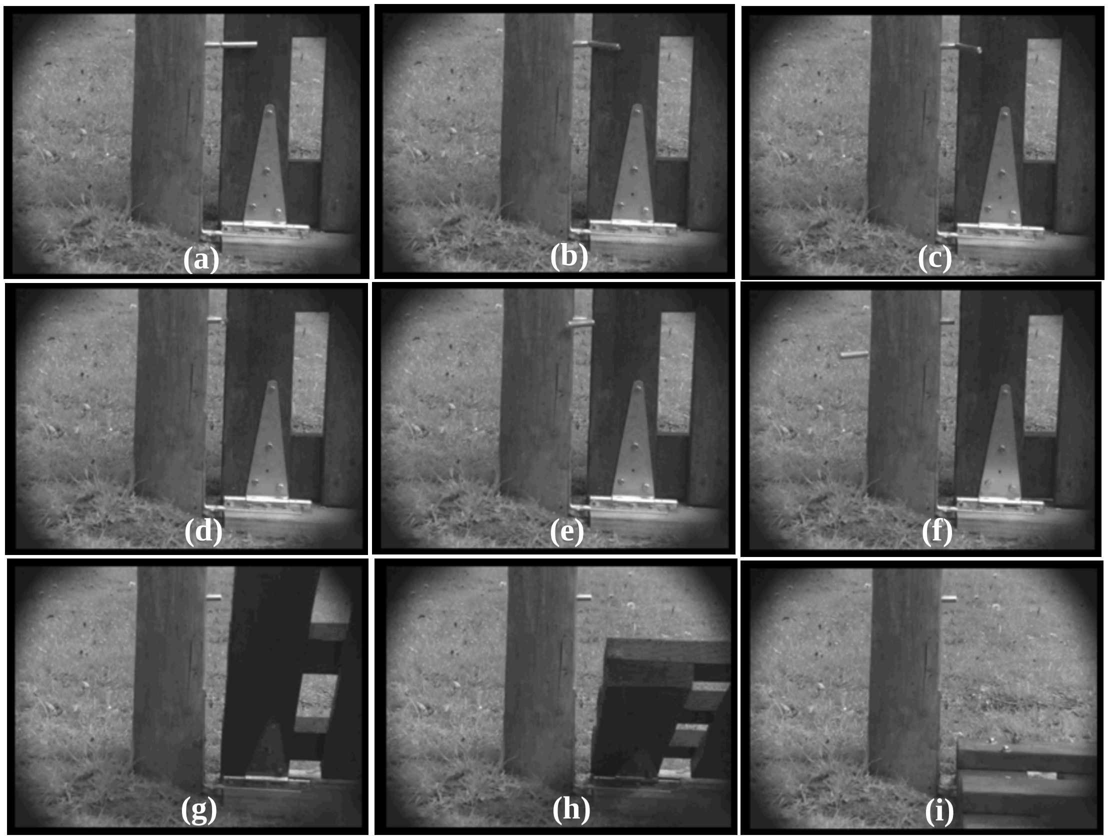


Figure 5.25 Series of Photos From High Speed Video of Breaking Pin

Figure 5.26 Too Ductile To Break Properly When Gate Triggered

The pins, which were tested in the full size hinged gate, ranged in material and size. Figure 5.27 and 5.28 display some of the pins tested with their change in outer diameter and size of stress concentration cuts. The interlocking sleeves used to secure the pins in the posts are also shown.

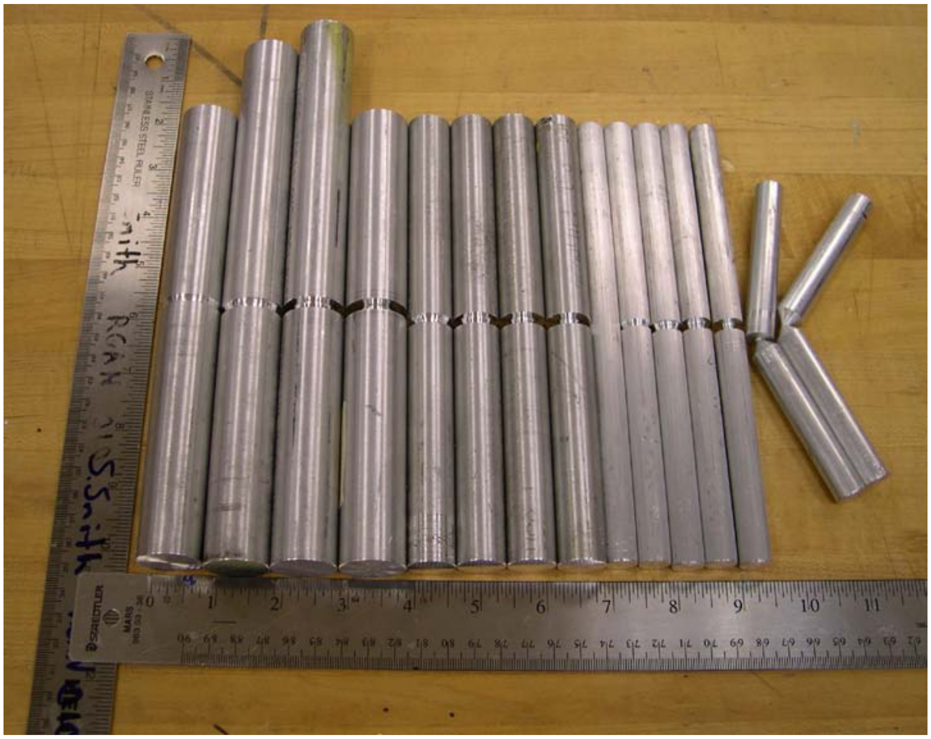


Figure 5.27 Test Pins for Hinged Gate

Figure 5.28 Test Pins and Sleeves

During the course of testing the various pins the desired material behavior was determined. Figure 5.29 shows examples of the pins that were tested. When a pin was broken the two corresponding pieces were taped together and labeled for future reference. The pins on the left hand of the picture were Aluminum Alloy 6061. If the stress concentration factor was large enough the pins were successfully broken, but with smaller stress concentrations the pins would only deform instead of breaking. The pins in the middle and on the right were Aluminum Alloy 7068 which broke cleanly with minimal deformation. However, as the pins got larger the required breaking force well exceeded the force range for the hinged gate system and eventually exceeded the operating region of the instrumented sledge hammer for the largest sizes.

Figure 5.29 Broken Pins

Figure 5.30 Close Up of Broken Pins

Figure 5.30 shows a close up view of the fracture of the pins of Aluminum Alloy 7068. Even though this material fit the desired requirements of breaking at a desired force level with minimal deformation, the fracture surface indicates that this material failure is a ductile process, with most or all displaying the thin lip around the outer edge of the breaking surface. The clear “cup-and-cone” look of the specimens show that overall these were ductile breaks. Yet, there was evidence of brittle failure in the swirling and rough ridges in the aluminum alloy 7068 specimens. Note that the behavior seen in these specimens may also be connected to the cross section size of each pin. The 7068 aluminum is overall classified as a ductile material, but within the aluminum group it appears to act closer to the range of brittle behavior [51]. Thus, aluminum alloy 7068 was selected for the final pins due to its fracture toughness, hardness, and material strength because it will behave more like a brittle material than aluminum alloys 6061 or 6063.

Tables 5.1-5.3 include a summary of representative results of the pin testing on Aluminum Alloys 6061, 7068, and 7075 respectively.

Table 5.1 Aluminum Alloy 6061 Pins

Aluminum Alloy 6061					
	Outer Diameter	Inner Diameter	Max Force With No Change	Bending Force Range	Broken Minimum Force
Direct on pin	0.5	0.5	--	545-668	--
through gate			--	1,604-2,033	--
Direct on pin	0.5	0.45	--	545-870	--
through gate			--	1,694-2,215	--
Direct on pin	0.5	0.4	--	335	122**
through gate			--	1,300-2,394	--
Direct on pin	0.5	0.3	--	--	--
through gate			--	1,800-2,420	--
Direct on pin	0.5	0.2	--	--	--
through gate			--	--	1,960

**The Bent or Broken force is lower than the force at the previous level (“no change” or “bent” categories)

Table 5.2 Aluminum Alloy 7068 Pins

Aluminum Alloy 7068					
	Outer Diameter	Inner Diameter	No Change Max Force	Bending Force Range	Broken Minimum Force
Direct on pin	1	0.9	1,587	--	--
through gate			1,828	--	--
Direct on pin	1	0.8	--	--	--
through gate			2,596	--	--
Direct on pin	1	0.65	1,408	1,163**	--
through gate			1,828	--	--
Direct on pin	1	0.5	--	--	1,138
through gate			1,672	--	--
Direct on pin	0.75	0.65	2,537	--	2,481**
through gate			2,058	--	--
Direct on pin	0.75	0.5	--	--	968
through gate			2,134	--	--
Direct on pin	0.75	0.4	--	--	380
through gate			2,233	--	--
Direct on pin	0.75	0.3	--	--	--
through gate			--	--	1,854

**The Bent or Broken force is lower than the force at the previous level (“no change” or “bent” categories)

Table 5.3 Aluminum Alloy 7075 Pins

Aluminum Alloy 7075					
	Outer Diameter	Inner Diameter	No Change Max Force	Bending Force Range	Broken Minimum Force
Direct on pin	0.5	0.5	--	517-796	865
through gate			2,172	--	--
Direct on pin	0.5	0.45	590	--	470**
through gate			2,411	--	--
Direct on pin	0.5	0.4		369*	422
through gate			2,309	--	--
Direct on pin	0.5	0.3	--	--	--
through gate			2,108	--	2,297
Direct on pin	0.5	0.2	--	--	--
through gate			--	--	1,588
Direct on pin	0.375	0.375	--	320*	302**
through gate			2,376	--	--
Direct on pin	0.375	0.325	--	--	--
through gate			3,389	3,955*	4,639
Direct on pin	0.375	0.3	--	--	--
through gate			2,594	--	3,617
Direct on pin	0.375	0.25	--	--	--
through gate			807	1,789*	2,022
Direct on pin	0.375	0.2	--	--	--
through gate			--	--	--
Direct on pin	0.3125	0.3125	--	--	319
through gate			--	1,151-4,172	--
Direct on pin	0.3125	0.3	--	--	--
through gate			2,026	2,233-4,134	4,385
Direct on pin	0.3125	0.275	--	--	--
through gate			--	1,696*	2,408
Direct on pin	0.3125	0.25	--	--	--
through gate			1,340	3,296*	3,703
Direct on pin	0.3125	0.2	49	--	100
through gate			443	--	730

*uncertain if bent or still unchanged at this force level

**The Bent or Broken force is lower than the force at the previous level (“no change” or “bent” categories)

Even though each chart represents one specific aluminum alloy and the material was ordered from the same company each time, batch testing must be done to determine accurate and consistent material properties. Batch testing was not done for this analysis, but would be necessary to ensure reliability of metals used to make a key component of a safety device. The data was obtained through impact testing with an instrumented sledge hammer. For the “direct on pin” data results, a metal pin was inserted in a sleeve in the post and directly impacted with the hammer. The results labeled “through gate” meant the gate was held up by the pin inserted in the sleeve in the post and the gate was impacted with the hammer at the pin location. The impacts are incrementally increased until the pin bends or breaks. Therefore, there is added error in the result since there is the possibility of the pin being damaged or weakened by a previous impact without changing to the unaided human eye. This error may cause the data represented with ** in the plot where the higher category (bent or broken) actually has a lower force than the lower category (bent or no change respectively). While there is error, this data still serves to bound the behavior and strength of each material type.

Table 5.1, clearly shows that aluminum alloy 6061 bends over large force regions and rarely breaks free even when large force loads are applied, making it ill-suited for this design. Table 5.2 shows that Aluminum Alloy 7068 rarely bends or deforms, instead it generally has no pin change or it breaks completely. However, due to the large strength capabilities of this material the larger pins were not breaking at all or broke at forces far beyond the force range of the hinged gate design. Since this material was difficult to order in diameters smaller than ¾”, Aluminum Alloy 7075 was chosen as a suitable material choice. As seen in Table 5.3, Aluminum Alloy 7075 has a lower strength capability than 7068, and has slightly more pin deformation than 7068. However, it still adequately fits the desired material properties. Based on the desired performance of the pin the following material parameters were determined:

- Low % elongation at fracture (approximate: under 12%)
- Large Brinell hardness number (approximate: over 100)
- Large ultimate tensile strength (approximate: over 60,000psi)
- Ultimate and Yield strength close together
- Low fracture toughness (closer to brittle, decreases impact history interference)
- Corrosive resistance—good use outdoors
- Affordable cost
- Machinability decent so stress concentration grooves can be added reliably
- Overall statement: Good strength and exhibit brittle-like behavior

These are specifications. One material was found suitable for these specifications, but there may be many materials that would adequately fulfill these requirements.

5.3 Other Areas of Consideration:

After all of the theory based analysis and field testing a list of “do’s/don’ts” and other areas of consideration were compiled.

“Do’s /Don’ts”:

- Use frangible device on one side only (if two are used and one side is triggered other side must be triggered immediately and automatically)
- Frangible device trigger location currently recommended at approximately half the height of jump (tradeoff between gate acting as a lever arm decreasing

required impact force to break and energy loss through impact with fence increasing required impact force to break)

- Metal sleeve in post to hold end of frangible pin to ensure tight fit and limited motion during impact
- Follow recommended material specifications:

Important Considerations:

- Contain breakaway portion of pin to prevent flying metal from impacting horse or rider or later getting under foot of competitors
- Include support system to prevent hinged gate from falling completely parallel to ground to prevent chance of trapping horse or rider under fallen fence
- Test each constructed fence for overall stiffness and bendability causing energy loss from one end of fence to the other (significant energy loss is expected through materials of fence at impact
- Material quality control highly important: each batch of material must be tested for mechanical properties to determine proper size to guarantee desired force required for pin failure
- Mass of gate structure could feasibly be too large to move out of the way quickly enough to keep a horse impact below the critical design force without adding a preload to the system to aide in the movement/folding of the gate

Cursory thought has been given to the other considerations. Since the pin could potentially hit someone or become unwanted litter on the course after the device is triggered, metal U-brackets were used to secure the pin to the gate. To ensure that the pin can't slide out at all, a small rope can be placed through a drilled hole in the pin and tied to the gate if desired.

Figure 5.31 U Bracket Constraints

Also, there is a small possibility of the hinged gate falling on a rider or horse's leg if it is triggered as the horse goes over it. Therefore, a preliminary study was conducted to determine the feasibility of adding supports to the back of the hinged gate to provide a region between the gate and the ground to prevent trapping limbs. Figures 5.32-5.34 provide a rough 2D and 3D sketch of a possible support.

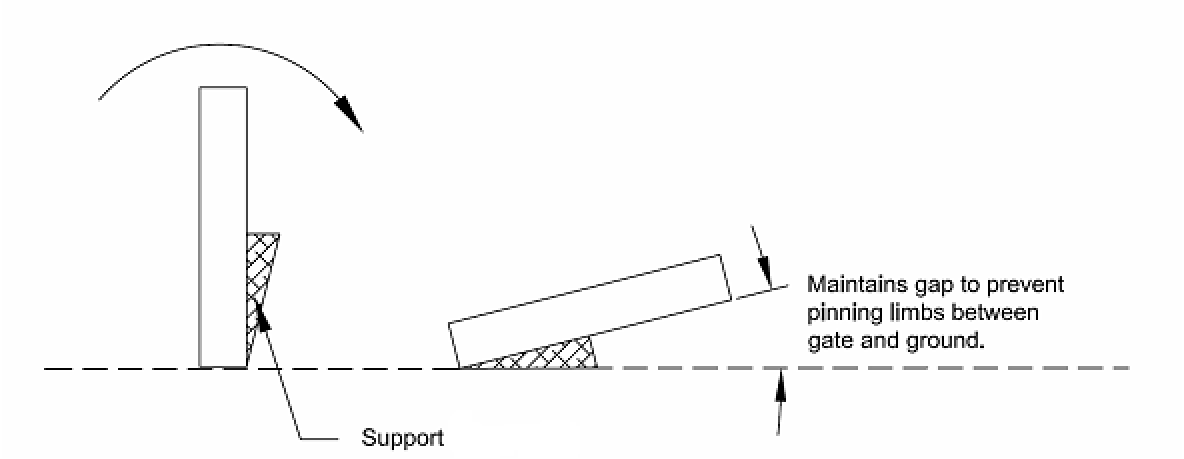
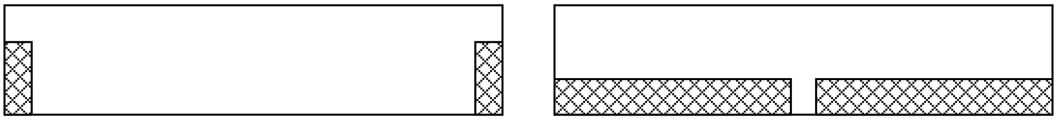
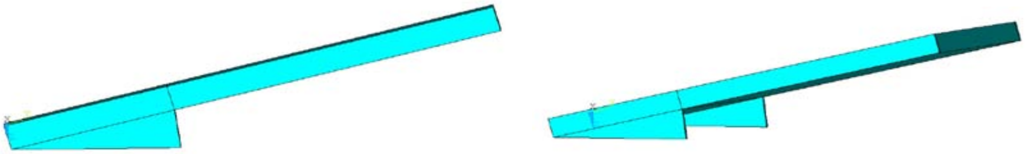


Figure 5.32 Support System



(a) (b)

Figure 5.33 Example Support Types



(a) (b)

Figure 5.34 3D Example of One Support Type

The support could either be tall, thin supports on both ends of the gate (Figure 5.33 (a)) or be a long low support along the bottom (figure 5.33 (b)). Further study would be required to determine the exact size, material, and necessary strength of the overall gate structure and supports.

In addition, the hinged gate design often varies in mass depending on how it is constructed. The University of Kentucky full size model had less mass then the other two hinged gate models that were built previously (Figures 5.2 and 5.3). It is feasible that if the mass of the hinged gate is too large that the mass will not move out of the way fast enough to keep the horse’s impact below 900 lb and avoid the risk of neck injury.

A video of the instrumented sledge hammer impacting the gate, breaking the pin, and then the gate falling was studied to get a rough estimate of how long it takes the hinged gate to get out of the way. The video was taken at 15 frames per second and it took 13 frames to break the pin and for the gate to fall meaning it took roughly 0.87 seconds to get completely out of the way.

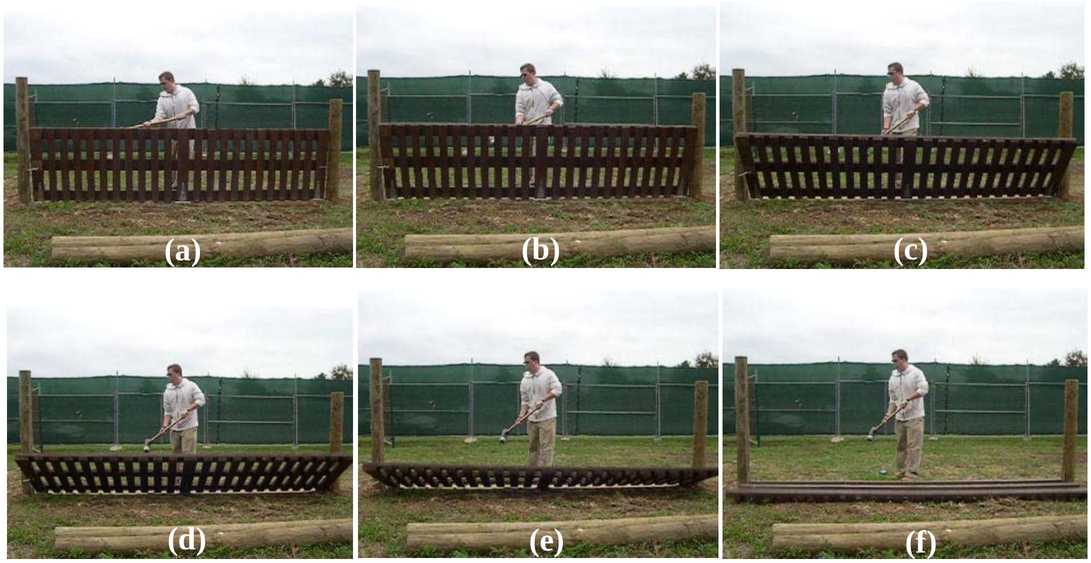


Figure 5.35 Series of Photos of Pin Breaking and Gate Falling

From Michelle Tucker's data analysis on the Competitive Measure Top 20 Data, the estimated average time duration of the critical portion of the horse impact was 0.05 seconds which is only a fraction of the time it takes the gate to get fully out of the way [14].

While the duration of the instrumented sledge hammer is less than the horse impact duration, it can still be used as a useful analysis tool (as discussed in Chapter Four). In Figure 5.36, it is evident that when a pin is hit directly but doesn't break the impact force-time history has a symmetric shape. However, if the pin is hit directly and breaks the contact ceases immediately and the force immediately drops to zero.

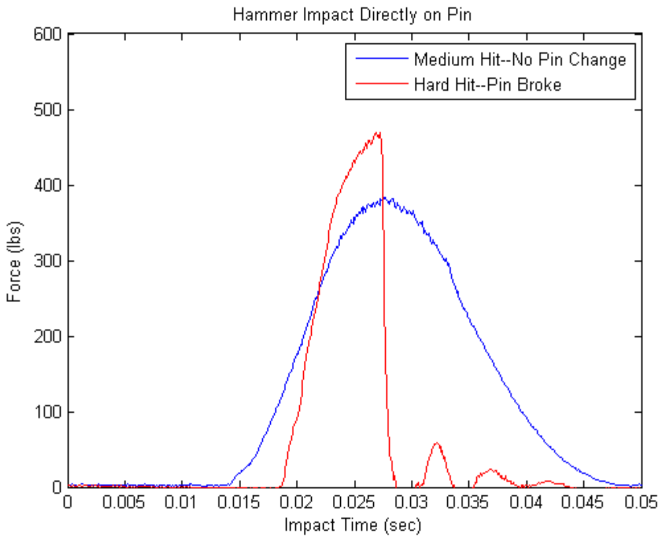


Figure 5.36 Pin Breaking Plot

Figure 5.37 shows a comparison of impact hammer force-time histories when the pin is hit through the gate. When the pin breaks, the force seen by the hammer does not sharply fall to zero, but instead is affected by the moving mass of the gate. The duration of the instrumented sledge hammer impact is less than the time it takes for the hinged gate to get out of the way so the contact is continued for the duration of the impact rather than dropping sharply like in Figure 5.36.

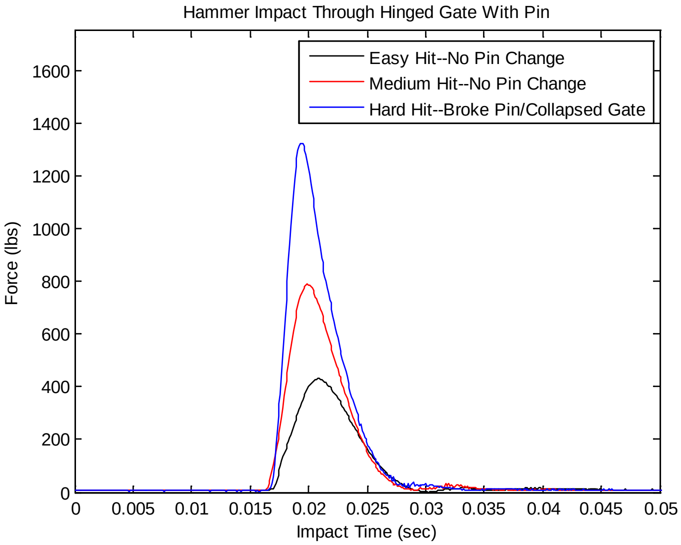


Figure 5.37 Impact Plots

5.4 Conclusion

Further research needs to be conducted to create a testing instrument or method to determine the mass of each specific fence, energy loss through the fence, and how long it takes the fence to move out of the way after triggering. This work is necessary to ensure that the critical design force is avoided when the device triggers.

A general specification was created for a frangible pin for use in the hinged gate system. This research showed that aluminum alloy 7075 is a suitable material for the application, that only one pin should be used, and that the pin should be placed approximately a quarter of the way up the height of the fence. It was found that either a u or v shape stress concentration cut is suitable and the thickness of the pin and depth of the cut is dependent on the mass and stiffness of the gate design and the chosen critical design force.

During the analysis of this particular hinged gate design a preliminary outline of a testing approach was developed that could be applied to studying other safety devices. This testing approach was outlined and discussed in Chapter Four and will be applied to another safety device in Chapter Six Collapsible Table Jump.

Chapter 6: Collapsible Table Jump

6.0 Introduction

A challenge moving forward is how to incorporate safety improvements for table jump designs. According to the FEI 2008 Safety Statistics presentation, a "square spread" type fence had the second highest number of total somersault falls out of 12 types and ranked third for number of rotational falls when scaled for the number of times this type of jump was jumped in courses compared to other fence types [23].

Figure 6.1 Example of Table Fences in Rolex 2009 [29]

Examples of cross country table fence designs can be seen in Appendix C: Chart of Rolex 2009 Jumps. As frangible or deformable designs for table jumps are developed they may need to be tested for different types of table fences and adapted to include other jump types such as corners or ascending spreads. The complexity of table jumps encourages designers to consider a variety of solutions to fit the many applications including considering collapsing sections or moveable sections. In this chapter, the previously outlined testing guidelines were adapted for the development and preliminary discussion of a new collapsible table design. These efforts included the following steps:

- Mathematical Model

    - Consider mathematical model of a rotational fall (initially brief qualitative understanding, future efforts include more detailed mathematical representations)
- Design Development, Goals, Table Top Model
    - Define fence parameters
    - Develop initial concept drawing
    - Develop table top model to determine initial design feasibility
- Prototype Construction
    - Develop half dimension scaled prototype
- Preliminary Lab Testing
    - Conduct preliminary impact tests to determine expected fence behavior
- Design Challenges and Possible Redesign Suggestions
    - Discuss concept design challenges with UK Research Team and field experts
    - Consider possible challenge solutions or redesign
    - Future Work could include: Further redesign (iterative process throughout testing and implementation), field testing, assessment on if a full size model is feasible or if a component of the design would be applicable to another concept, testing of full-size model, implementation stage.

Due to the lack of maturity in the concept design, further research is necessary before a full size model could be created for use in the field.

6.1 Design Development, Goals, and Table Top Model

Design parameters and goals were developed through consultation with experts in the sport and by considering the pathfinder mathematical model of a rotational fall. Based on this information, a collapsible table jump concept was developed, preliminary models were created, and a half-dimension scale prototype was built. Generally, consideration of table jumps has the following objectives:

- Understand dynamics of table fences in general including mass movement, manageability, need within the sport, among others
- Evaluate feasibility of horizontally triggered folding table design
- Evaluate applicability of portions of this design to other fences in the sport
- Determine approximate time of table collapsing
- Determine efficiency of mass movement
- Understand challenges for table design in general

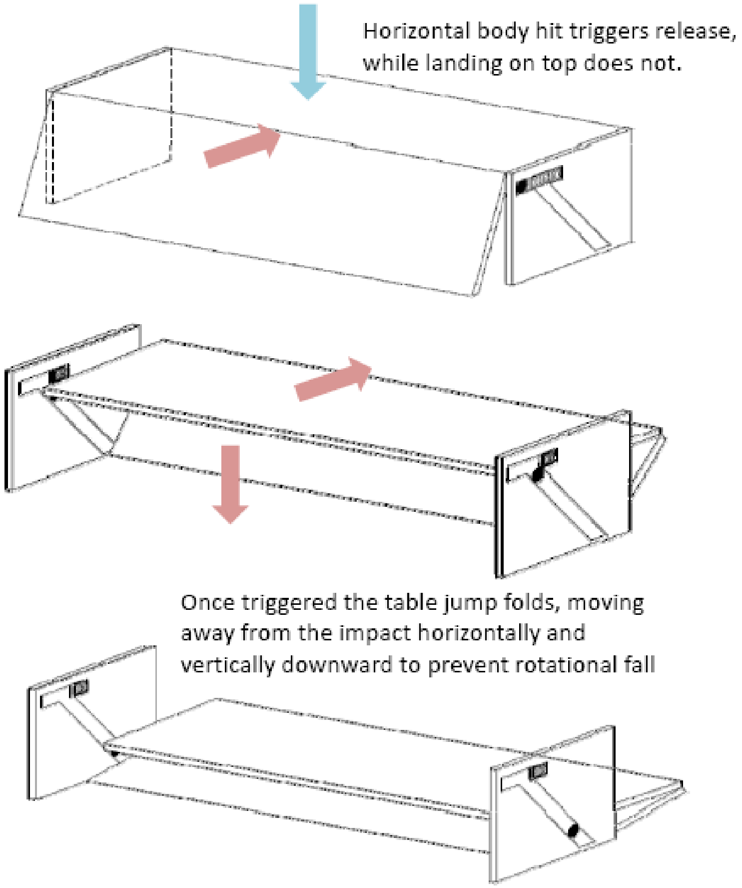
Challenges for table designs include maintaining aesthetics typical of sport, preventing possibility of collapsing on someone, triggering both sides at same time or not at all, understanding being horizontally versus vertically triggered, supporting downward force to allow jumping off top, determining design complications, eliminating areas where horse could be pinched, and identifying amount jump collapses (i.e.: ½ height, ¾ height).

Further consideration led to narrowed goals. Specifically for this table the following requirements were defined:

- Allows horse and rider to land on top of jump and jump off without triggering collapse

- Moves away from impact horizontally and downward vertically to prevent rotational fall (collapses to almost flat horizontally and vertically)
- Spring loaded release system allows table to move away from light contacts, but only collapse for critical design force impacts
- Horizontally triggered (instead of vertically triggered)
- Springs are energy dependent not just force dependent (may help to differentiate between energy of a hoof strike vs. a critical body impact)
- Maintaining low friction in the tracks helps to move the mass of the jump efficiently
- Relatively simple method to reset fence quickly
- Attempts to imitate exterior look of current jumps maintaining general aesthetics and integrity of the sport
- Mechanism or portions of the design may be applicable to other fence types
- Fence is resettable, does not require replacement parts which decreases the maintenance cost of the fence.

Preliminary concept drawings (Figure 6.2) were created to incorporate the general motion and components of the proposed design. Note that the front panel of the jump design is shown in the first picture of the concept drawing, but for ease of viewing is not shown in the second two pictures.

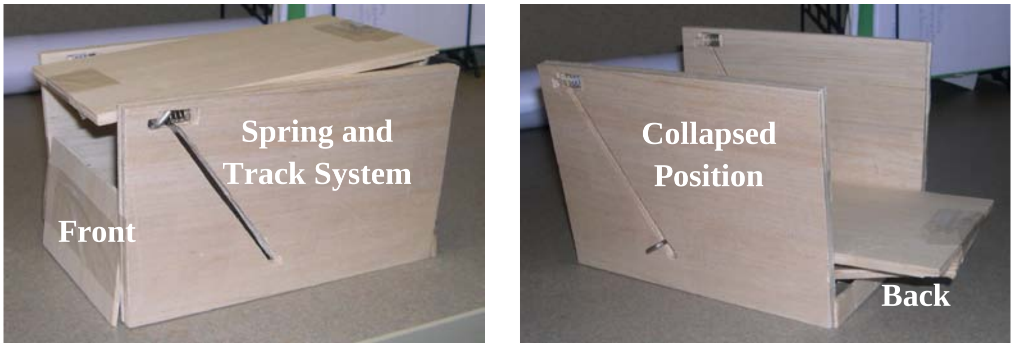


Horizontal body hit triggers release, while landing on top does not.

Once triggered the table jump folds, moving away from the impact horizontally and vertically downward to prevent rotational fall

Figure 6.2 Drawings of Collapsible Table Concept

Since the concept was being developed from scratch, a small functional model was first created to determine if the idea could be transferred from paper to a fundamental 3D working model before tackling a more realistic prototype. Figures 6.3 (a) and (b) show the initial functional model of the collapsible table design.



(a) (b)

Figure 6.3 Initial Functional Collapsible Table Model

The model was constructed out of balsa wood and was roughly 9 inches long by 6 inches tall by 6 inches wide. The model was built to represent the fundamentals of the design and was not to scale. In Figure 6.3 (a) the horse approaches from the left. The table top inclines as required to present the depth of the jump. The spring loaded guide rod moves horizontally before encountering the inclined track. In 6.3 (b) the table is seen to have folded nearly flat. The preliminary table top model showed promising results, so a half-dimension scaled prototype was then built for further analysis of the design feasibility and overall understanding of table jumps in general.

6.2 Prototype Construction

Since a full size cross country table jump could be approximately 12 ft long, 4ft tall, and 6ft deep, a half-dimension scaled prototype was created for testing within the lab. The prototype was 6ft long, 2ft tall, and 3ft deep. The moving section of the scaled jump weighed approximately 88 lb. Therefore, the moving section of a full size model of the jump would weigh over 350 lb. A few aspects of construction would be different if done by a course builder. However, the prototype served the purpose of this project. Appendix B contains the list of supplies, tools, and costs to create the prototype. The construction of the prototype is shown below in Figures 6.4 through 6.6. Figures 6.4 (a) and (b) show the base, support walls, and planked top and back walls.

(a) (b)

Figure 6.4 Construction of Table Prototype

The table top is supported by the back wall on a sliding track system. The back wall has wheels held in a groove, so that it won't move until the collapse is triggered. When the table top is pushed backwards horizontally by contact of the horse, the metal guide rod compresses the springs on either side of the jump allowing the rod to move horizontally and then to slide down the inclined slotted track. As the table top moves backwards and the rod moves down the slot, the top of the back wall is pushed backwards as well, which causes the wheels at the base to be pushed out of the groove and roll along the track toward the front edge of the jump, folding the three surfaces (front, top, and back) on top of each other (See Figures 6.2 and 6.8).

The concept allows the strength of the springs and the length of the horizontal portion of the guide track to be changed in order to create the desired "design critical load" at which the table top collapses. A flap with a latch covers the spring and block mechanism to secure the spring in place during compression. Two removable planked walls attach to the sides of the jump with Velcro to cover the rod and slot mechanism on either side to maintain the typical look of a wood fence, but to allow access necessary for resetting the jump.

(a) (b)

Figure 6.5 Construction Features of Table Prototype

This prototype was designed for use within the lab, not for outside use in a competition. Therefore, components would have to be changed in a full size model to deal with the increased mass/weight and the environmental conditions of being outside. For example, a metal track system would probably need to be used in place of the wooden rod track and in place of the rear wall base wheels rolling on a wooden track. Also, the decorative wall covers would have to be attached to the jump in a different manner, since Velcro may not hold up well in the outdoor elements.

The final prototype fence was stained to help protect the wood against light exposure to the elements during demonstrations. Figure 6.6 shows the completed prototype in the untriggered position.

Figure 6.6 Completed Collapsible Table Fence Prototype

Figures 6.7 (a) and (b) show the prototype in the collapsed position from the front and back views respectively. The collapsed moving table section is supported 3.5 inches off the ground to help prevent any limbs from being trapped under the fence. (Note, this height off the ground can be changed as desired.)

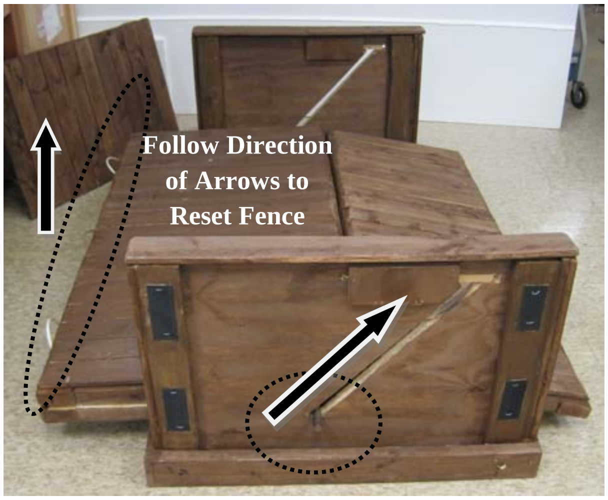
(a) (b)

Figure 6.7 Completed Collapsible Table Fence Prototype in Collapsed Position

The edges of all of the wood corners were cut and sanded to a rounded edge to acknowledge the risk of injury on contact. Even though this is only a concept level design, this project has seen the importance of including details like this in test articles and models for demonstrations. Not only does it convey understanding of the range of concerns and requirements, but it also allows focused discussion on the design at hand, rather than tangential subjects. Due to the weight and choices in construction methods, the table fence prototype is cumbersome to reset. Jump judges, who typically work in pairs, will not be able to safely lift the table to reset it without mechanical assistance. A wheel and wooden track system was used in the prototype simply for ease of construction and to reduce the cost of the prototype. In a full size model a metal track system would be required for reliable sustained performance. Other changes for a full size model are discussed later in Section 6.4 Design Challenges and Possible Redesign Suggestions.

When operating the prototype, the need for care was realized, when the fence is in the untriggered position and when resetting the jump, to prevent the possibility of the fence collapsing on someone. Due to the wheel system, it is possible for the wheel to roll out of the groove in the track and trigger the table top unexpectedly as a result of someone leaning on the fence from the front or even on top. The prototype was not designed for a specific design force and the back wall may not have been completely balanced during construction. Therefore, it may be possible to collapse the prototype fence by leaning on top of the table top, even though a properly designed full size model should not.

Setting up the model table involves 2 or 3 people. The process starts with unlatching the flaps on each side, and removing the springs and blocks. With one person on each side, the rope handle on the back wall that is closest is gripped and lifted to pull the rod up the track at the same time moving the table back into its initial position of the flat region of the slot. Then the springs and blocks are reinserted and both flaps are re-latched. The wheels connected to the back wall must be in the correct place on their track (in the groove). If they are not, the rope handles on the back of the wall should be lifted to place the wheels in the groove. It is important to have 1 or 2 people holding the guide rod while moving the back wall around to catch and stop the table top if it were to trigger while a person was standing behind it. Serious injury could occur if someone was standing directly behind the jump and it triggered unexpectedly. There are also possibilities of pinching or trapping your fingers and hands when resetting the jump. Figure 6.8 (a) shows the table in the collapsed position and indicates the rope handles and metal rod that should be used to reset the fence. Figure 6.8 (b) shows the fence after it has been reset into its untriggered position.



(a)

(b)

Figure 6.8 Process to Reset the Table Prototype

This process is being executed in Figure 6.9 where the rope handle and rod are being used to guide the table back into its desired position. Another person would be needed to do this same thing on the other side of the table.

Figure 6.9 Example of Table Prototype Being Reset

The prototype was designed as one half the dimensions of a full size table fence. While the dimensions for the prototype were half dimensions for the full size model, the volume of the prototype is 1/8 the volume of the full size model as seen in Figure 6.10. The prototype table fence is shown as the white rectangle in the front right corner.

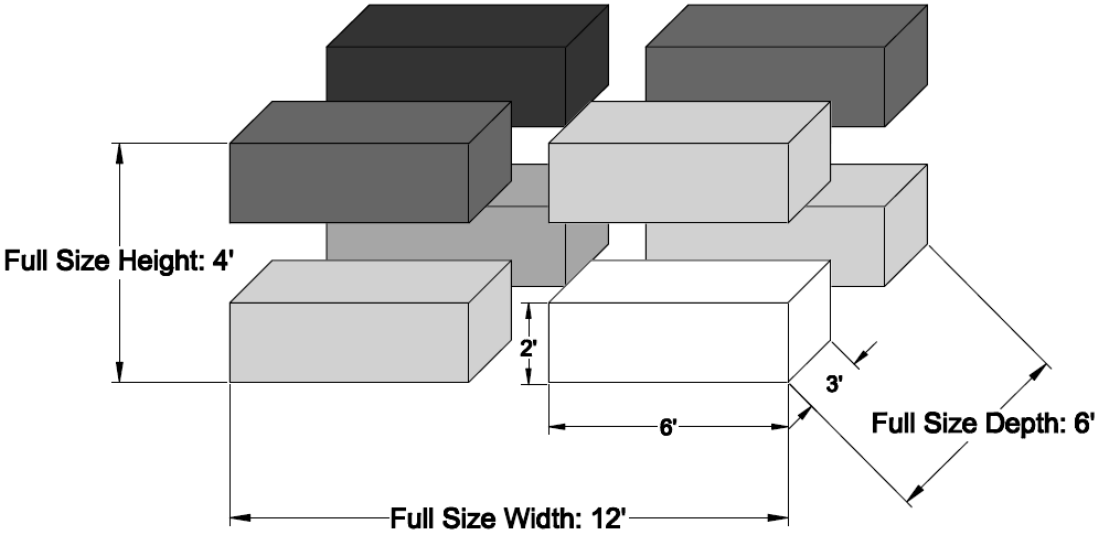


Figure 6.10 Comparison of Prototype Size to Full Size Table Fence

However, assuming the same density of wood was used to construct the full size model, the mass of the full size model would only be 4 times the mass of the prototype instead of 8 times. The mass of the fence is in the surfaces, so the area is a squared, not cubic increase. In other words, since the inside of the jump is hollow the mass factor can be seen by looking at the increase in surface area instead of looking at the increase in overall volume from the prototype to the full size model.

6.3 Preliminary Lab Testing

The scaled prototype table fence was constructed for overall design feasibility and understanding. The spring stiffnesses and the length of the horizontal track were chosen for ease of testing and do not scale directly to the dimensions and stiffnesses that would be required on a full size fence. But these design points can easily be changed without altering the overall concept.

This collapsible table fence is designed to allow the horse to land on top of the table top and jump off without the device triggering a collapse. The mechanism was qualitatively tested by using the instrumented sledge hammer to lightly impact vertically downward on the table top. Figure 6.11 shows the impact force time histories.

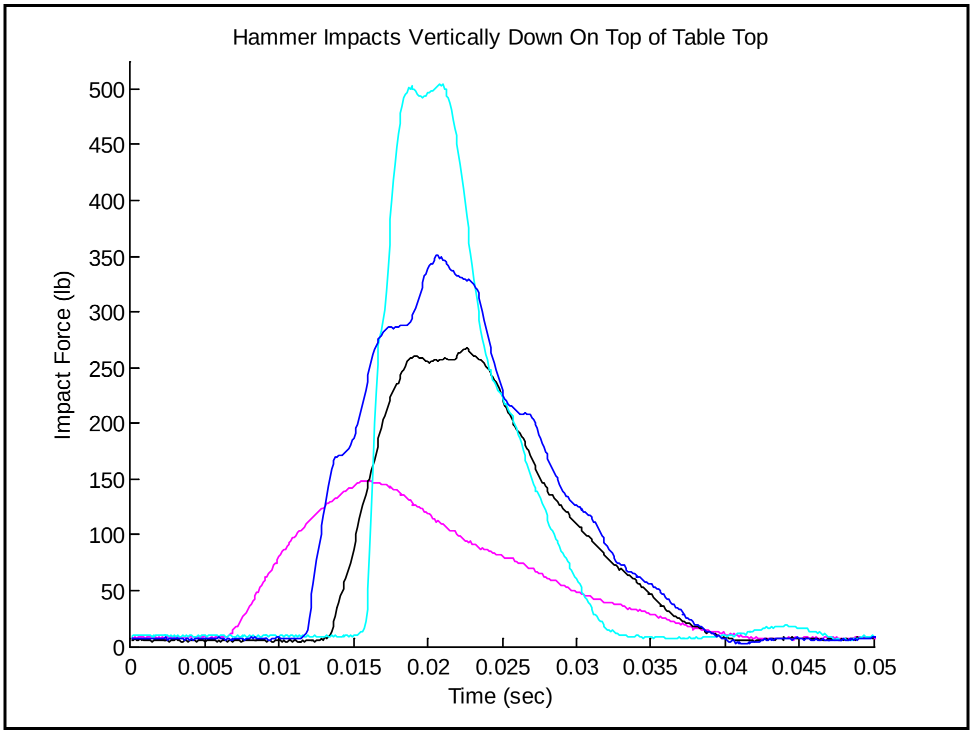


Figure 6.11 Hammer Impacts on Table Top

The mechanism successfully handled the table top impacts without collapsing. The impact plots from the impacts showed an interesting rough pattern compared to prior impact studies. This is assumed to be from the slight play in the support or from vibration in the wood from previous hammer impacts. The table top for the prototype was not reinforced to allow for high force impacts on the table top without damaging the wood planks, so only low force impacts were tested. For a full size fence model meant for use in competition, the table top would have to be reinforced to allow for horse to land on top of the jump without breaking the wood planks (like the currently used cross country table fences). This will add to the moving mass of the system.

The collapsing behavior of the fence was also analyzed using the instrumented sledge hammer and high speed video camera (1000 frames per second). The fence is designed to move away from horizontal contact forces as the spring mechanism compresses and absorbs energy. If it is a light, low energy impact then the fence will “give” slightly allowing the horse room to get their legs over the fence, but will not collapse. Figure 6.12 shows the rod of the mechanism allowing the table top to move to the left away from the impact on the right and then back into place instead of collapsing after a light impact. The motion can be best seen by observing the gap between the rod and guide slot indicated.

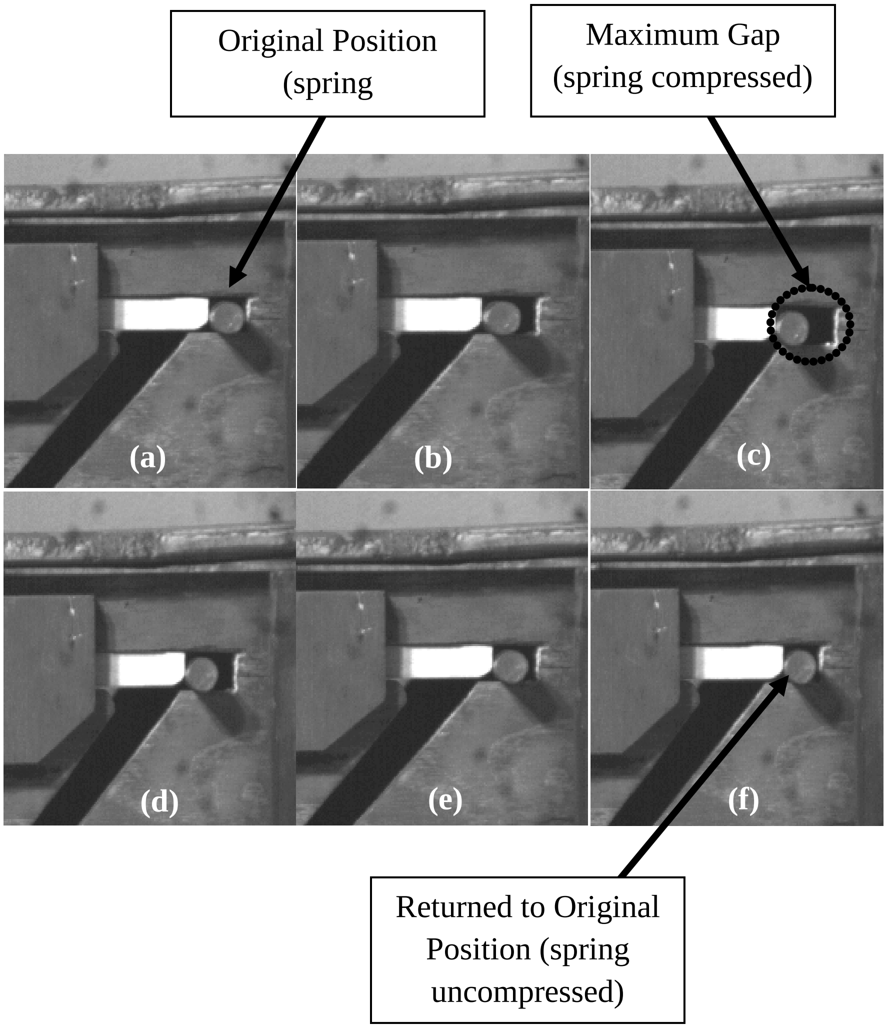


Figure 6.12 High Speed Video of Impacting Table But Not Collapsing

However, if an impact reaches the design energy level then the springs will compress completely allowing the rod supporting the table top to reach the inclined section of the guide track, which collapses the table fence. This behavior is seen in Figure 6.13 which includes frames from the high speed video (1000 fps) of the spring mechanism while the table collapsed. Notice in the figure how the gap increases as the rod forces the spring and block system backwards (Figure 6.13 (a)-(d)), then when the rod reaches the inclined track the block gets pushed back to its original position by the spring (Figure 6.13 (e)) as the rod slides down the track (as the table top collapses and folds back) (Figure 6.13 (f)-(i)).

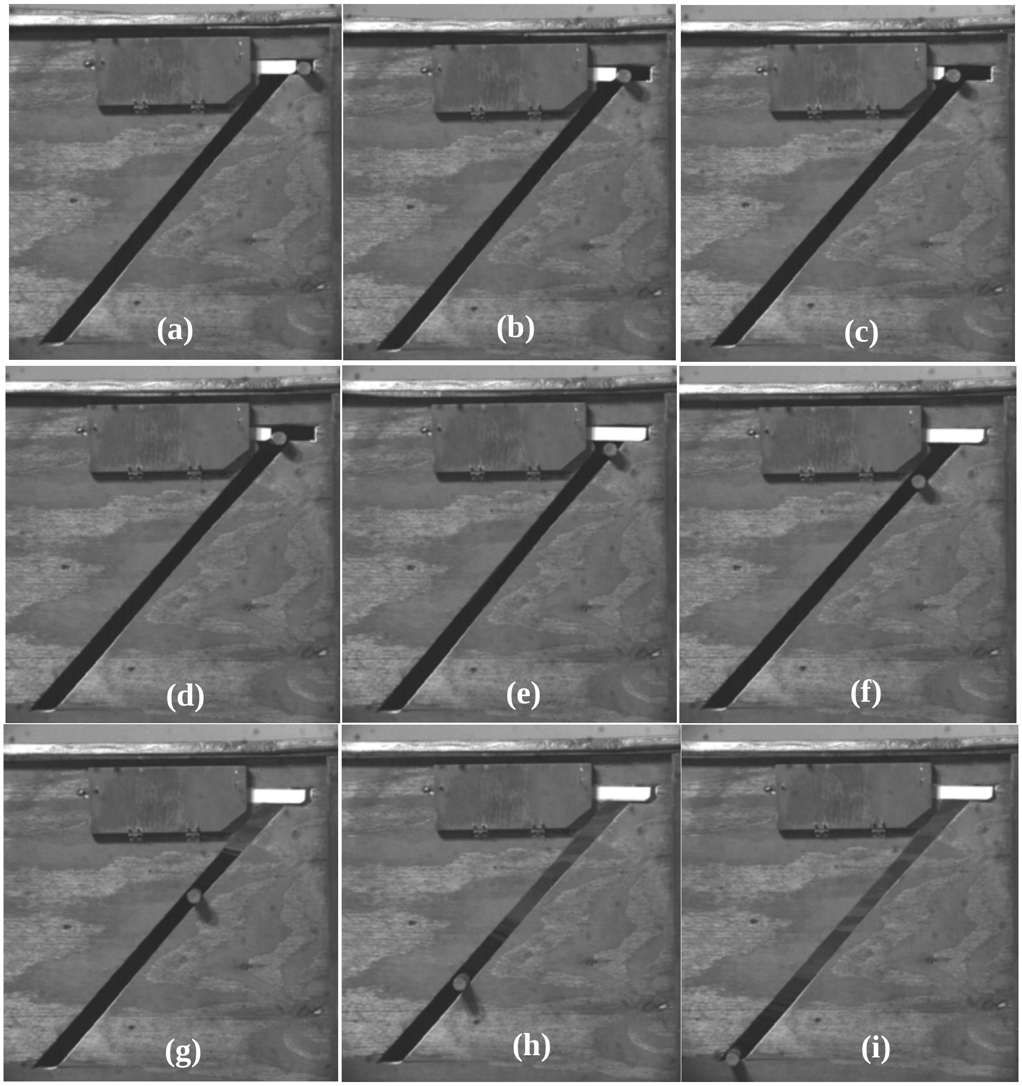
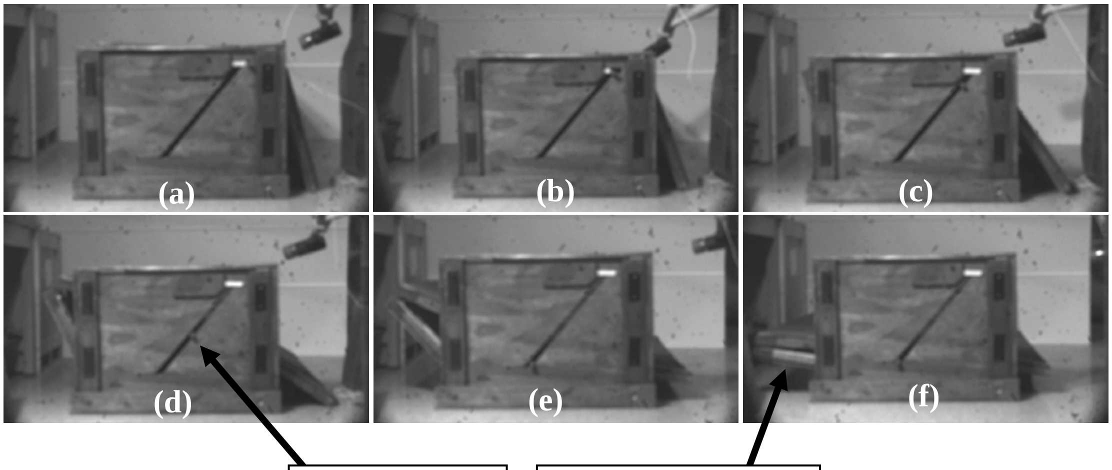


Figure 6.13 High Speed Video of Table Fence Collapsing

A small gap is maintained between the collapsed fence and the ground by the base system in the back, helping to reduce the risk of trapping a rider or horse under the collapsed fence. Figure 6.14 shows snapshots of the fence collapsing.



Notice rod moving down track

Notice back wall folding under as fence collapses

Figure 6.14 High Speed Video of Table Being Impacted with the Hammer and Collapsing

Based on the 1000 frames per second high speed video of the table collapsing it took approximately 0.59 seconds to impact and completely collapse the prototype table fence. This design has the table collapsing almost entirely out of the way since it is unclear exactly how far out of the way the fence must be to prevent rotation in all situations. Therefore, it is possible the fence has moved far enough away from the horse in a much shorter period of time, before it has finished collapsing. This model is only ¼ the mass of the full size model, however in Section 6.4 ideas for decreasing the overall mass are briefly discussed.

The preliminary testing helped to analyze one of the design issues also. If the table is not impacted directly in the center, it was thought possible for only one side of the table to trigger and then the table would not collapse. Figures 6.15 (a) and (b) show a situation where the table prototype was impacted closer to the left side and only the left side triggered so the table top has not collapsed. It is assumed (without a specification for the sport) that this limited movement would not be sufficient to prevent a rotational fall.

(a) (b)

Figure 6.15 Triggering Only One Side of Prototype

In order to use this design in competition, it would then be imperative to develop a mechanism to ensure that if one side triggers the other side triggers automatically. Otherwise, the risk exists that the fence may partially trigger instead of completely collapsing during a serious off-center impact.

Figure 6.16 compares examples of the force time plots of the above mentioned impacts. The impacts are shown for when the fence “gives” but doesn’t collapse, when it collapses completely, when only one side triggers, and finally when the fence collapses completely when one side has already been triggered.

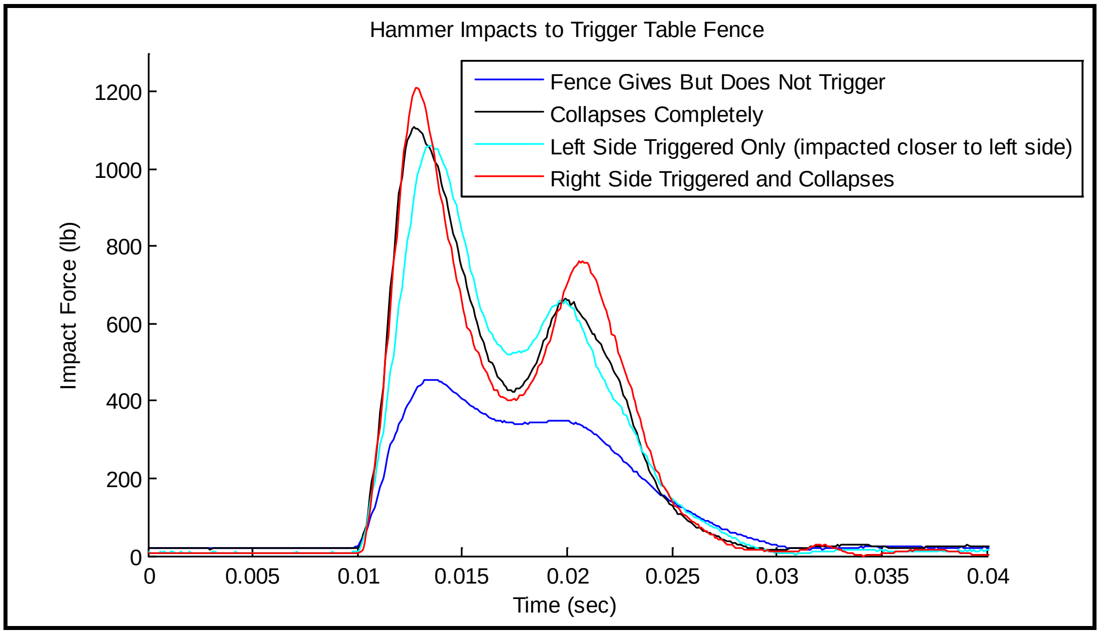


Figure 6.16 Hammer Impacts On Front of Table Prototype

The impacts show a consistent double peak behavior. The plot of the fence moving slightly but not collapsing has a more flattened result. Therefore, it is possible that the first peak in the double peak plots is from the initial impact with the fence and the second peak may be caused when the spring has fully compressed and the fence is forced to trigger. When the left side triggers it also exhibits this double peak behavior even though the fence doesn't collapse. However, this is makes sense since the left side where the impact is occurring still goes through the same behavior: initial impact, spring completely compressed, rod pushed into slanted track. This design is highly dependent on the amount of energy during the impact, since the spring mechanism depends on the springs absorbing enough energy to compress completely. Since the fence was placed on the slick, smooth lab floor when being tested and was not fastened down, the fence slid backwards during impact, possibly affecting the impact plots, although this is assumed to be slight. A fence in competition would be secured into the ground just like any portable fences that are currently in use within the sport.

6.4 Design Challenges and Possible Redesign Suggestions

After completing the prototype, the design was analyzed to determine design challenges from the perspective of increased understanding. The prototype was also demonstrated to the other members of the University of Kentucky Research Team and to a group of course designers and course builders for additional expert suggestions about possible changes to improve the concept. Those consulted included David O'Connor (President of the United States Equestrian Federation), Mike Etherington-Smith (Chief Executive of British Eventing), and Mick Costello (lead course builder at the Kentucky Horse Park) among others.

Figure 6.17 Demonstration and Discussions with Field Experts

As a result of an analysis of the design and discussions with field experts, several design challenges were identified.

- The total mass of a full size version of this design could be unmanageable for resetting. A winch/jack system would need to be developed to lift the weight up the track or mass-reduction concepts would need to be incorporated such as the use of foam or wood/foam composites.
- The total mass of a full size model may be too large to efficiently move out of the way when triggered.
- The gaps between the hinged joints are currently too large for use in competition (they increase the chance of pinching a horse or rider).
- The current track system was made for demonstration purposes and would have to be redesigned for use in a full size model. Several areas that would need to be considered include being weather resistant, being able to handle the weight of a full size model, and ensuring that it does not accidentally trigger if a horse landed vertically on the table top.
- The device currently consists of two independent triggering devices, one on each side. Therefore, it is possible for one side to trigger without the other side triggering which may prevent the table from collapsing when necessary.
- The current design is not easily portable since it is heavy and difficult to set up at the start of a competition or to move from one location to another.
- It is necessary to consider any situations where the table may unexpectedly collapse on top of someone (ex: during setup, during impact, etc.).

- The current design requires the decorative walls to be taken down to see if the fence has been triggered and to reset the device.
- The fence may result in more nuisance triggers than desired, since horizontal force of a rotational fall as determined by TRL [1] is very low. Therefore, it is difficult to set the force or energy levels in such a way to differentiate between a hoof and body strike.

One of the major challenges of this concept is the immense size, weight, and mass of a full size table fence. A full size model using the current concept and using the same materials may be too large and heavy to be easily portable, move out of the way quickly enough when triggered, or be easily and quickly resettable. A possible solution to this would be to create the moving portion of the jump out of stronger lighter material that could still be either covered in a thin layer of stained wood for aesthetics or be painted to look similar to wood. For example the frame of the fence could be made out of a light weight but strong aluminum alloy then covered in wood planking to maintain an authentic appearance. Also, a jack/winch system would need to be created where a crank would move the table top system back up the track and into the untriggered position.

The concept prototype was built for a general understanding and not following standard practice everywhere. Therefore, there are a few things that would have to be changed for a full size model. For ease of construction and to reduce costs a wheel and wooden track system was built into the prototype. A full size model would require a more substantial track like a metal track system. The track may make it easier to incorporate a jack/winch system for resetting purposes. It may also prevent the table top from twisting making it more difficult or even almost eliminating the fences ability to only partially trigger. Since the prototype is set up on wheels it is easy for the table to twist where one wheel gets ahead of the other making it easy to trigger only one side.

Additionally, the sides of the jump are covered with a wood paneled cover to hide the track system and maintain the current sport appearance. However, with the covers on it is difficult to identify if the fence has been partially triggered and needs to be reset. It is possible to look at the fence from the front and see if one side is lower than the other, indicating that one side has been triggered. However, for better efficiency a flag system may be able to be designed to pop up in the view of the jump judge if one side or other has been triggered. However, research would have to be done to determine if such a design could be created with relative simplicity and for little additional cost.

During discussion about the fence, David O’Connor mentioned a possible different approach of making only a small portion of the table collapsible. It may be possible to make only the middle third section of the table move, or even only make the front corner deflect inward, instead of allowing the entire table top to move completely out of the way. It was suggested that allowing the front corner to deflect may allow the horse enough room to pull their legs out and over the fence. However, research to date has not specified distances and times sufficient to prevent a rotational fall. More research, and a safety-device requirement, are needed.

The gaps between the table top and the front and between the table top and back wall could be decreased or removed through the use of different hinges, different construction methods, or through the use of a rubber guard. Figure 6.18 shows an example of using a rubber guard to fill the gap.

Figure 6.18 Rubber Guard to Fill Gap

While this would prevent a horse or rider getting pinched, the color and texture of the solution affect the overall aesthetics of the fence. Therefore a more desirable solution may be to eliminate the gaps all together through different construction methods or different hinges. The jump construction crew at the horse park indicated that traditional fences are made such that the top of the front wall comes up flush with the top of the table top and the back of the table top comes back far enough that it is flush with the outside edge of the back wall, as shown in Figure 6.19.

Figure 6.19 Traditional Table Fence Construction

A professional jump builder or a professional wood worker could develop a construction plan to remove the gaps altogether. The following suggestion was developed by the author and implemented as a small section of the table to demonstrate the concept. Figure 6.20 (a) shows the front of the newly designed hinged section. As can be seen, the front wall now comes all the way to the top of the table top leaving no front gap for the horse or rider to contact. This was achieved by connecting a regular door hinge to the back of the front wall and connecting the other side to the top of the table top. However, on the table top a section of the wood was cut out to allow the hinge to lie flush in the table top. A thin layer of wood was then used to cover the hinge for to maintain as natural appearance as possible. Figure 6.20 (b) shows how changing the way the hinge is attached in the back allows the table top to go back far enough to be flush with the back edge of the back wall.

(a) (b)

Figure 6.20 Model of New Hinge Construction

Figures 6.21 (a) and (b) show this new design in comparison to the current construction. The gap between the front wall and table top is evident in Figure 6.21 (a), but is clearly almost entirely eliminated with this new construction method. The elimination of the gap between the table top and the back wall can be seen in Figure 6.21 (b).


(a) (b)

Figure 6.21 New Construction Suggestions Compared to Current Construction

For the back wall construction the hinge would still be attached to the bottom of the table top and to the inside of the back wall, but the hinge would be attached closer to the front of the table top. The hinge would be mounted in enough that the entire back wall is underneath the table top. These changes to the front wall and back wall construction should still allow the fence to collapse the same as before.

6.5 Conclusion

It may be possible to incorporate a resettable spring system or a collapsing track driven section on other types of jumps. One of the current problems with implementing safety devices throughout a course is the cost of replacing frangible devices as they break. If designs are based on being resettable, instead of frangible, the life cost of the fence could be greatly decreased. Also, it may be possible to apply a sliding section of the fence on many different types of fences. The developed concept is set up as a closed table fence design, but for an open concept the front wall could be removed and thin post supports could be used to support the back of the fence instead of a full back wall. Or a redesign on the rod guide track system may be able to create a table top that still slides on the track but is unable to rotate in the track, eliminating the need for the back wall. However, additional research and development would be needed to design a system of that type that could hold the weight of a horse and rider landing and jumping off of it without collapsing.

Chapter 7: Conclusion

7.0 Summary of Work

The overall objective of this study was to evaluate frangible and deformable equestrian cross country fence designs. The study was motivated by serious and even fatal accidents during cross country competitions over the past 10 years. During the process testing methods were explored and specifications for particular safety designs were considered. The study also provided a better understanding of the sports culture and future direction.

The following sections summarize the primary aspects of each chapter included in this thesis.

7.1 Literature Review

A brief description of the history of the sport of Eventing and the general rules were discussed to provide the reader with an understanding of the sport.

- Since the fence designs being analyzed are for the portion of Cross Country, background information and rules specific to this phase of the sport were summarized.
- Statistics were provided showing the safety challenges the sport has been facing for the past 10 years to explain the motivation for this project.
- The current state of the sport was displayed through a discussion of the possible factors that have contributed to safety concerns. The steps that are being taken within the sport to face these challenges were also explored.

- Finally a summary of research that has been conducted on horse motion, on horse mass and moment of inertia, and on factors that can contribute to “good” or “bad” horse jumping form was created to specify what areas have yet to be explored.

7.2 Overview of Cross Country Eventing Safety Designs

One component of cross country eventing is that each jump is designed to have a different appearance to and ask a different question of the horse and rider team. Therefore, various safety designs are required to encompass all cross country jump designs. This chapter outlined the available safety designs and general safety jump parameters.

- A summary of the currently available frangible and deformable designs was provided (i.e. Frangible pins, EPS Logs: Prologs®, another collapsible table jump design created by Doug Payne, Mim New-Era Devices, and concept designs from the University of Kentucky).
- A summary was created of general cross country fence parameters, as well as, a summary of considerations that are important to sports in general.

7.3 Testing and Validation Methods

This chapter outlined available testing techniques and outlined the University of Kentucky design development guideline.

- A brief background of the use of crash test dummies in vehicle safety certification provided a standard or example to compare how safety fences may be effectively evaluated.
- A discussion was included of the type of testing and horse simulator models that have been created and used within the sport of cross country eventing.

- Since no force specification has been defined, Competitive Measure created an instrumented fence to collect data on horse impact force levels during competitions.
- A possible guideline for fence design testing includes developing an equation based or computer modeling representation of the design (ex: Use of Monte Carlo), constructing a prototype, conducting laboratory and field testing (ex: Use of Instrumented Sledge Hammer and High Speed Video), testing limited implementation, redesigning and moving towards full design implementation.

7.4 Hinged Gate Study

The hinged gate study was motivated by the objective of evaluating frangible and deformable safety fence designs.

- Two hinged gate models (other than the UK prototype) have been built and have been in limited use in competitions.
- Monte Carlo computer simulations were used to study the variable interaction in the hinged gate design (variables included horse impact force, impact height, pin height, and pin material among others).
- A full size hinged gate prototype was built in two locations (a private farm and the Kentucky Horse Park) for field testing and the development of a pin specification.
- A pin specification for the hinged gate included finding a suitable material, determining the number of frangible devices required, and determining the optimum location of the frangible pin.

7.5 Collapsible Table Jump

The general process of fence evaluation was applied to the collapsible table jump concept.

- The design was initially developed through considering the physics of a rotational fall and building a miniature working model to determine design feasibility.
- A scaled prototype (1/8 the full size volume) of the collapsible table jump was constructed to evaluate design challenges.

7.6 Appendices

The appendices provide four areas of supplementary information.

- Appendix A provided a list of supplies and a cost estimate for the construction of the hinged gate prototype.
- Appendix B gave an overview of the construction supplies and the cost to build the collapsible table jump design.
- Appendix C summarized the fences that were included in the 2009 Rolex and included pictures for a selection of the fences as reference for the reader of the diversity of jumps included in one cross country course.
- Appendix D summarized the process to set up the frangible pin system at one of the fences for the 2009 Rolex.

7.7 Contribution

In a broad view, this thesis has summarized the history, the current state, and the future direction of safety of the sport of eventing. Although the sport has been around for almost a century, many changes have recently been occurring in the rules and culture of the sport. Therefore, it is important to the continued success of researchers, fence builders, and course designers to stay abreast of the current state of the sport. This has been provided by summarizing specific research that has studied horse motion and factors that may contribute to increased risk, as well as summarizing the findings of safety committees, and field experts. Also, summarizing currently available frangible and deformable technology in addition to those concepts that are on the horizon, help to keep the sport's leaders, designers, and builders informed of what is coming next for the sport. Also a lack of communication about available safety technology can prevent forward progress, since course builders and fence designers may not be aware of all of the available safety resources that can be built upon to improve safety in the years to come.

A specification has not been set for the sport. Therefore, the evaluation of the hinged gate and the developmental study of the collapsible table jump helped to identify the challenges in creating a specification that can be widely applied without excluding viable safety options. Both challenges and considerations specific to those designs and about designs in general were identified, which may prove helpful when a specification is designed. On a more detailed level, a general specification was created for the frangible device in the hinged gate design.

In addition to needing a specification, a testing method needs to be developed. The method must be capable of being easily set up and moved across courses and be applicable to the diverse range of fences on a cross country course. The evaluation of an instrumented sledge hammer as a horse impact simulator provides path finder research on the feasibility of developing a test mechanism that fits those requirements: small, portable, affordable, and effective. While the instrumented sledge hammer may not be used, the research can become a stepping stone for the appropriate equipment and testing method.

Taking an overall view, the collapsible table jump study presents the need to move towards creating safety designs that are applicable to a broader range of fences other than just a post and rail fence. Also, the study highlighted the feasibility of creating resettable, instead of replaceable, deformable safety devices. Resettable technology or ideas may be able to be incorporated into other designs in the future to address the challenge of making maintenance costs of these fences affordable.

7.8 Future Work

As more and more frangible and deformable designs continue to emerge within the sport, the need for a specification and an evaluation method will increase. Therefore, further research is needed to understand the relationship between rotational falls and impact forces and energy so that a specification can be created. So far within the sport, fence designs have been evaluated mainly in the laboratory with different test rigs, but for widespread evaluation of designs a portable testing machine is necessary to analyze fence after fence installed in course, from course to course both nationally and internationally.

The work included in this study has explored new concept safety devices, but further research would need to be conducted to fine tune designs to make them ready for implementation. Also, if designs are found to not be suitable for implementation, certain aspects of the collapsible table fence for example, may be applicable for future designs (ex: resettable instead of replaceable parts).

APPENDIX A

Hinged Gate Construction Materials and Cost

- Dimensions: 12ft by 3ft Gate, less than 3 inches between slats

- Supply List: (Full Scale)
    - Gravel (for posts)
    - 1: 2” X 12” X 12 ft Board (base)
    - 3: 2” X 6” X 12 ft
    - 3: 2” X 6” x 3ft
    - 20 : 2” x 4” x 3ft
    - 2 Boxes: Deck Mate All-Purpose Screws 2 ½” (at least 138 screws)
    - 3: Extra-Heavy T-Hinge 10”
    - 27 : Hex Bolts (for hinges) 5/16” (two different lengths because amount of wood bolts go through is different from position to position—see diagram)
    - 27: Flat Washers (for hinges)
    - 27: Hex Lock Nuts (for hinges)
    - 2: 8” Corner Brace
    - 6: 12” Hot Galvanized Spike (put through base to anchor into ground)
    - 6: Fender Washers (between spikes and wood base)
    - 10: Screws for L-Bracket attachment into posts and base
    - 2: Metal U-brackets to attach pin to gate (prevent pin from flying away after breaking)

- Required Tools:
    - Hand held power drill
    - Drill bits (drill holes for bolts)
    - Circular saw
    - Tape measure
    - Architect’s square
    - Hammer
    - Shovel (dig base in, dig holes for posts)
    - Drill bit for hole in post for frangible pin
    - General Purpose Brush (for staining gate)

- Estimated Construction Time:
    - Gate Construction: approximately 1 working day (get wood, cut, construct)
    - Putting Posts in: approximately 1 to 1.5 hours
    - Staining Gate: approximately 2 to 3 hours

- Gate Construction Costs from Receipts (Lowes and Home Depot)

Quantity	Item	Price for each	Total Price (tax not included)
5	2X4-12 HT-WW Wood Board	$3.25	$16.25
4	2X6-12 HT WW Wood Boards	$5.58	$22.32
2	Box of Deckmate TAN#1 Screws 2 1/2"	$8.69	$17.38
1	2X12-12 #2PT Wood Board	$17.97	$17.97
1	1 Gallon Olympic Maximum Neutral Base Deck Stain (color: Tobacco)	$32.96	$32.96
3	Extra-Heavy T-Hinge 10"	$8.46	$25.38
2	Corner Brace 8"	$4.78	$9.56
12	Hex Bolts	$0.50	$6.00
15	Hex Bolts	$0.35	$5.25
27	Flat Washers	$0.13	$3.51
27	Hex Lock Nuts	$0.17	$4.59
6	12" Hot Galvanized Spikes	$0.65	$3.90
6	Fender Washers	$0.24	$1.44
1	2" General Purpose Brush	$4.97	$4.97
1	1" Galvanized 2-Hole Pipe U-bracket (3 brackets in 1 pack)	$1.27	$1.27
		total:	**$172.75**

Notes:

- not included in prices above—2 posts, gravel, screws for L-Brackets
- Pricing for frangible pins, drilling hole, and sleeves are shown elsewhere
- Pricing for the Hex bolts and lock nuts are approximate

APPENDIX B

Collapsible Table Construction Materials and Cost

- General Construction Material List: (Half Scale)
  - Lumber (base, walls, front, top, back, base track)
  - Steel rods to support top (2)
  - Hinges (6)
  - Wheels(2)
  - Hardware to connect base frame, and frame of sliding table
  - 2 springs
  - 2 blocks
  - 2 track flaps
  - Velcro (attach side walls and top of walls)
  - Rope handle on back

- Required Tools:
  - Hand held power drill
  - Drill bits (drill holes for bolts; drill starter hole for screws to prevent splitting)
  - Circular saw
  - Hack saw
  - Hand saw (additional cutting tools could increase the efficiency of construction)
  - Tape measure
  - Architect’s square
  - Clamps
  - Hammer
  - General Purpose Brush (for staining gate)

- Estimated Construction Time:
  - Difficult to accurately estimate since the prototype was built incrementally over a long space of time. Rough estimate: 1 to 2 full days

- Table Jump Prototype Construction Costs from Receipts (Lowes and Home Depot)

Quantity	Item	Price for each	Total Price (tax not included)
1	High Strength 1045 Medium-Carbon Steel Rod--Diameter 3/4", 3' Long (cut in 1/2, rod supports table jump in track)	$11.94	$11.94
1	Plywood for walls (1 sheet cut into 4 pieces)	$26.94	$26.94
1	4x4x8' (cut into 4 posts for 4 corners of base)	$6.97	$6.97
6	2x4x12' (lumber for base to attach planks to and base of jump)	$3.48	$20.88
14	1x4 (not sure of length--called super strip)--wood for planks	$1.77	$24.78
1	Box of Screws	$8.69	$8.69
8	L Brackets to frames together	$3.73	$29.84
3	Hinges (top to back)	$8.27	$24.81
4	Hex Bolt (5/16X6)	$1.24	$4.96
8	Fender Washer (5/16)	$0.23	$1.84
4	Hex Nut (5/16)	$0.19	$0.76
4	L Brackets for frame of front (3x3)	$2.28	$9.12
25	Hex Bolt	$0.48	$12.00
25	Hex Nuts	$0.11	$2.75
25	Washers	$0.13	$3.25
6	Misc. Plastic Bag Hardware (bought 3 and 3?)--timeframe means something for table jump	$0.98	$5.88
4	Braces to bolt 4x4 post to the jump frame	$1.69	$6.76
1	Box of Screws	$8.69	$8.69
3	Hinges (top to front)	$2.58	$7.74
15	Super Strip Lumber (for planks for front and walls)	$1.77	$26.55
3	2x4-8'	$2.17	$6.51
2	2" HD Rigid Caster wheels for back wall	$2.98	$5.96
8	3/4" Brackets to hold metal rods to table top	$0.09	$0.72
1	3/4" U bracket to hold metal rods to table top	$2.48	$2.48
1	Rope for handle on back of jump (3')	$0.63	$0.63
1	Red bag of screws (used for little brackets between post and base)	$0.98	$0.98
		total:	**$262.43**

Note: This list does not include every item used in the construction of the prototype. Scrap supplies were used from the lab.

APPENDIX C

Examples of Cross Country Fences From Rolex

Note: Pictures taken by Michelle Tucker and Katie Kahmann [29, 56]
Dimensions and fence names from Rolex 2009 Website [49]

The following is a list of the fence names and dimensions in the order they appeared in the course in the Cross Country portion of the 2009 Rolex. Only pictures for a selection of the fences are available.

1) Name: Flower Box
Height: 3’11”
Spread: 6’ base spread

2) Name: Rock Walls
Height: 3’11”
Spread: 5’6” top spread

3) Name: Mr. Mushroom
Height: 3’11”

4) Name: Ms. Mushroom
Height: 3’11”

5) Name: Dray
Height: 3’11”
Spread: 6’ top spread

6a) Name: HSBC Duck Marsh--Rails
Height: 3’8”

6b) Name: HSBC Duck Marsh--Duck
Height: 3’9”

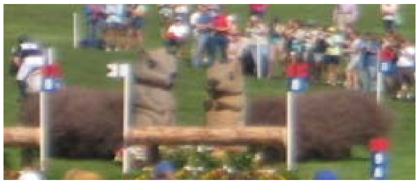
6c) Name: HSBC Duck Marsh--Brush
Height: 4’7”

7) Name: Walnut Tables
Height: 3’11”
Spread: 5’6” top spread

8) Name: Rails, Ditch & Squirrels--Rails
Height: 3’9”

9a) Name: Rails, Ditch & Squirrels-- Ditch
Spread: 4’3” wide ditch

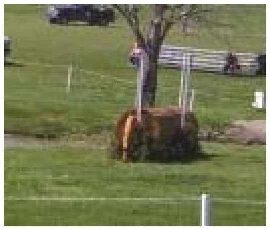
9b) Name: Rails, Ditch & Squirrels-- Brush
Height: 4’7” brush



10) Name: Trakehner
Height: 3’11”
Spread: 9’9” base spread

11a) Name: Infield Water-- Rolltop
Height: 3’5”
Spread: 3’3” base spread

11b) Name: Infield Water-- Rolltop
Height: 3’11”
Spread: 3’6” base spread



12) Name: Oxer
Height: 3’11”
Spread: 6’6” top spread

13a) Name: Sunken Road-- Bench
Height: 3’10”

13b) Name: Sunken Road—Step Down
Height: 3’9”

13c) Name: Sunken Road—Step Up
Height: 3’9”

13d) Name: Sunken Road-- Bench
Height: 3’10”

14) Name: Cordwood
Height: 3’11”
Spread: 5’3” top spread

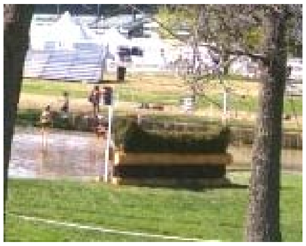
15a) Name: Head of the Lake—Cigar Lane Sycamores
Height: 3’10”

15b) Name: Head of the Lake—Brush into Water
Height: 3’4”
Spread: 6’6”

15c) Name: Head of the Lake—Brush Corner
Height: 4’7”

16) Name: Step out of Water
Height: 3’7”

17) Name: Cedar Brush
Height: 4’7”



18) Name: Log Cabins
Height: 3’11”
Spread: 5’6” base spread

19) Name: Log Cabins
Height: 3’11”
Spread: 5’6” base spread

20) Name: Sheep Shelter
Height: 3’11”

21a) Name: The Hollow—Sycamore Log
Height: 3’7”
Spread: 4’ diameter

21b) Name: The Hollow—Step Up
Height: 3’8”

21c) Name: The Hollow—Step Up
Height: 3’8”

21d) Name: The Hollow—Garden Cottage
Height: 3’10”

22a&b) Name: Double Diamonds-- Corner
Height: 3’10”

22c&d) Name: Double Diamonds-- Corner
Height: 3’10”-3’11”

23) Name: Keeper’s Brush
Height: 4’7”
Spread: 9’ base spread

24) Name: Tobacco Stripping Bench
Height: 3’11”
Spread: 6’6” top spread

25a) Name: HSBC FEI Classic^{TM} Series
Normandy Bank—Over
Ditch Up Bank
Height: 3’10”

25b) Name: HSBC FEI Classic^{TM} Series
Normandy Bank—Pine Rail
Height: 3’3”

25c&d) Name: HSBC FEI Classic^{TM} Series
Normandy Bank—Triple Brush
Height: 4’7”
Spread: 5’10” base spread

26) Name: Wattle and Daub Cottage
Height: 3’11”
Spread: 5’6” top spread

27) Name: Hong Kong Brushes
Height: 4’7”

28) Name: Hong Kong Brushes
Height: 4’7”

29) Name: Burning Bush
Height: 4’7”
Spread: 6’6” top spread

30) Name: Blooming Bonanza
Height: 3’11”
Spread: 5’6” top spread

The following shows a Prolog in use in the Cross Country portion of the 2010 Rolex [29].

APPENDIX D

Process of inserting British Eventing Frangible Pins at Rolex 2009
Date: Tuesday, April 21st, 2009

Competition Date: Rolex 2009 April 23rd-26th

Participants: Mick Costello and Jump Construction Crew (Aaron, Aaron, and others) described and showed process to Katie Kahmann

Location: Kentucky Horse Park, Rolex 2009 Jump # 25, Normandy Bank

Process:

Each post and rail jump that will be pinned is repined in the days leading up to the competition. Usually the jumps are not decorated until after the pinning had been completed, but in this case the course inspectors wanted to view the jumps and finalize the jump heights before the pinning was done. This final inspection of the jumps happens only a couple of days before the competition, so for sake of time the jumps had already been decorated. This made the task a little more difficult, since the log jack had to be placed directly in the middle of the flower beds and the wood shavings from drilling and cutting the support logs spread around and over the newly decorated flower beds.

The first step is to use the jack to hold up one end of the log (only one end is jacked up at a time). The log must be tied to the post first on both ends to ensure that the log does not roll off of the jack and cause injury. The top of where the pin should be and thus the middle of the pin where the hole should be drilled is measured and leveled in relation to the post to make sure the log will be level after the pins are in.

Once the appropriate measurements have been made the drill is used. As seen in the picture below a level is used along side of the drill to ensure that the drill is making a level hole through the post. A drill bit the same size as the pin sleeve is used to ensure a secure fit. It was mentioned that if the sleeve was smaller than the hole and was therefore a little loose in the hole, that it may take more load to break the pin since the pin could move around.

Since this drill bit is so large a person must spot the back of the post, to let the drill operator know when the drill is about to break through the back. There is a sharp point on the bit that comes through the back before the full diameter of the bit comes through. Since the drill is so large, if the operator is unprepared, breaking through the back could jerk the operator's hand into the front of the post.

The sleeves all come in the same size length, so usually the sleeves are inserted into the post and then are cut to be the width of the post that is being used for that specific jump. In this case, the jump crew decided to measure the sleeve to match the width of the post and cut the sleeve to match before inserting it into the post. However, cutting the sleeve leaves sharp edges, so the picture below shows these edges being grinded to smooth edges. Also the truck included in this picture shows the equipment and generator that are brought right up to the base of the jump to power the equipment used in this process.

Since the size of the sleeves are so close to the size of the drilled hole a wooden mallet made by this jump crew is being used to hammer the sleeve into place. The jump crew told me how it is somewhat of a problem preventing the aluminum sleeve from bending when it is being forced into the post. They mentioned they have considered making a rubber gasket to slip into the end of the aluminum sleeve and then hit this rubber cap to force the sleeve into the jump, thus preventing damage to the sleeve. However, in this case the wooden mallet seemed to work pretty well with minimal damage to the sleeve.

The following picture shows the pin fastened to the inserted sleeve. The jump crew commented that the pins come in two different lengths, so they bring both lengths up to the jump to decide which size will work best for each jump. The indicator line on the pin must be directly under the lowest point (center) of the log. This is achieved through a combination of two different length pins and the three different holes on each pin to allow for different lengths when attached to the sleeve.

The following picture shows the drill and wooden mallet used in the process described above.

Once both pins are in place, the logs must be tied to the posts in a way that will allow them to fall the specified distance in the case of an impact where the pins break.

New rope is used when the jumps are retied. The rope is looped around the post and up and over the log on each side and is then brought back to the back of the post. The ends of the rope are brought together and secured with a u-shaped nail.

The rope is then looped several times around this triangular shape that is crated at the side of the post. This makes the v smaller and thus makes the ropes tighter around the post and rail. It also adds a clean aesthetically appealing look to the jump.

There is not a set number of times that the rope should be looped, but a consistent number is used on all parts of one jump. In this particular case approximately 7 loops were used. However, for a larger post it may have been 10 or even more if necessary. The jump crew said they just agree on a number for each jump to ensure consistency at that jump and determine how many are necessary based on how tight the ropes get. The following two pictures show the post and rail after the ropes had been successfully tied. Both ends are shown, one in each picture.

Note: the post and rail jumps that are not pinned are tied with a different type of knot than the pinned post and rail jumps.

Now in order to allow for the post to fall the specified distance the support posts under the logs had to be measured, leveled, and cut accordingly. The following pictures show the support posts being marked and cut with a large chain saw.

The following two pictures show the final jump, the sleeve and pin have been inserted and positioned properly, the log has been secured to the post, and the underneath support logs have been cut to the appropriate height.

Note the horse jumps this jump coming at it from the side shown in the two pictures above. The following shows a horse and rider jumping the fence during the 2009 Rolex on April 25th.

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