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Evaluation of Ballistic Materials For Back Protection Under Low Velocity Impact

Marina Carboni
Worcester Polytechnic Institute

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Evaluation of Ballistic Materials for Back Protection Under Low Velocity Impacts

A Thesis

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of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in

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by

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Marina Carboni

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Approved:

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Professor Allen H. Hoffman, Ph.D., Major Advisor

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Professor Kristen Billiar, Ph.D., Committee Member

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Janet Ward, Natick Soldier Center, Committee Member

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Abstract

Low velocity impacts to the back are known to cause severe injury to crucial components such as the spine and kidneys. Researchers at Natick Soldier Center want to develop a solution that incorporates protection against low velocity impacts with the ballistic body armor (vest and plate) that is used today. The current ballistic body armor was developed to provide ballistic protection. Ballistic protection is designed to stop the penetration of bullets at velocities exceeding 300 m/s. Techniques to provide low velocity impact protection include reducing transmitted force by elongating collision time. In order to develop back protection for the soldier against low velocity impacts the performance of the ballistic body armor and impact protecting foams was evaluated. Low velocity impact tests were performed based on European standards for back protectors for horse riders (EN 13158) and motorcyclists (EN 1621-2). Performance requirements outlined by the standards and published literature established peak forces of 4 kN and 9 kN transmitted through materials under impact as minimum levels of safety before significant injury occurs. Experiments were conducted at an energy level of 4 J to compare the performance of different materials. Energy levels were then increased until maximum acceptable force transmissions were reached. At 4 J the ballistic materials showed peak transmitted forces between 11.0-16.2 kN. This indicated that the ballistic materials were not an adequate method to provide sufficient back protection. The addition of polyurethane foams to ballistic materials reduced peak force values by a factor of 15. Energy levels of 25 J and 40 J were reached with peak forces of 3.5 kN and 6.6 kN. This research provided a basis for the future development of protective equipment that provides both ballistic and low velocity impact protection.

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1 Introduction

Development of back protection for the US soldier under low velocity impacts is an area where Natick Soldier Center would like to make advancements. Low velocity impacts include situations where soldiers are impacted by foreign objects or propelled through the air into other objects at velocities below 20 m/s. Traditional body armor worn by soldiers was designed for ballistic protection. This body armor consists of a ballistic vest and plate that provide protection against bullets and fragmentation at velocities above 300 m/s. Until now, the ballistic armor has only been evaluated for its ability to provide ballistic protection. In order to provide low velocity impact protection several factors were addressed. The risks and levels where injury to the back occurs under low velocity impact were identified. Methods used today to evaluate back protectors in sports were implemented in order to assess material performance under low velocity impacts. These tests methods relate values of force transmission through materials to levels of safety. An assessment of the ballistic materials along with improved methods provided a baseline for future work in low velocity back protection for the soldier.

The ballistic vest consists of several layers of ballistic fabric such as Kevlar® stitched together. The strength of the vest can vary mainly due to material type and number of plies. The rigid armor is formed into a concave shaped plate and provides enhanced ballistic protection. Materials for the plate consist of a ceramic face with a fiber reinforced back. The plates can vary due to material type, ceramic thickness, backing thickness, and resin used to bond the materials together. Typically, the plate is placed on the chest and back of a soldier, where it protects the major organs located in these regions.

It was critical to understand the mechanisms of injury and the levels of force to the back that cause injury in low velocity impacts. Injuries of concern included damage to the spine, ribs, kidneys, muscle strains, and tissue damage (e.g. bruising). Studies indicated that most back injuries occur due to a variety of bending and twisting motions (Levine, 1998). These injuries are extremely difficult if not impossible to protect against without immobilizing a persons body from undergoing these motions. Therefore a focus was placed on analyzing injuries from forces transmitted perpendicular to the back. Different areas of the back vary in their risk of injury. Spinal injury due to direct blows occurs at a force level of 4 kN (CEN/TC 162/WG 5 Document N 657, 2002). However, the literature shows that a combination of motions can result in injury at smaller forces. Injury to the shoulder blades occurs from forces greater than 9 kN (EN 1621-2, 2001). Values of injury obtained from the literature were used as measures of safety.

Commercial back protectors for horse riders and motorcyclists are certified through the European testing standards EN 13158 and EN 1621-2 respectively. These standards use low velocity impact tests and relate the peak force transmitted through materials to levels of performance in safety. The maximum protection level for EN 13158 is 4 kN and for EN 1621-2 is 9 kN. Based on these standards a test evaluation method was developed to evaluate ballistic materials and impact protective foams in relation to protection for the back.

2 Background

The major goal of this project was to evaluate ballistic materials for back protection under low velocity impact. In order to achieve this goal several topics including risks and levels of injury, ballistic body armor, and back protection were researched. In this section the areas of the back susceptible to severe injury and the levels where injuries occur under low velocity impact are outlined. An overview of ballistic body armor, impact protection foams and back protectors is provided. Finally, common test methods for back protectors used in sports are described. This information was the basis for the methods of evaluation used for the ballistic materials.

2.1 Risks of Injury

There are several components of the back where protection should be provided. The spinal column and kidneys are the two major elements that need protection. They perform functions essential for a person to live a normal life. Other areas where protection should be provided are the ribs and scapulae. They are important structures where considerable discomfort could be caused by injuries.

2.1.1 Spine

The spinal column can be considered the most structurally important element in the body. This complex structure plays a crucial role in our activities of daily living. The main functions of the spine are to communicate between the brain and the body, to provide structural support and flexibility. Various anatomical and physiological elements work together in order to supply these functions. The three major components of the spine are the neural elements, the spinal column, and the supporting structures. Each of these components contain elements that interact together to provide the functions of the spine.

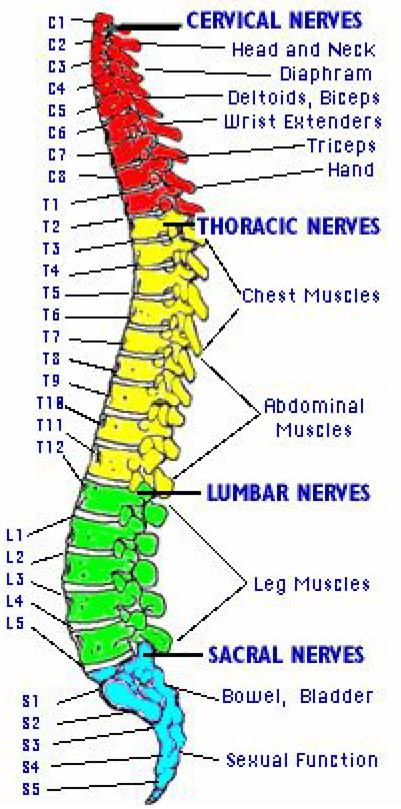

Figure 2-1 Lateral view of the spine indicating the five sections and the bodily components that these sections interact with (Spinal Cord Injury Information network, 1999).

Structurally the spine is divided into five sections: cervical, thoracic, lumbar, sacral, and coccyx (Figure 2-1). Each section is used to identify various functional and structural attributes. The neural elements comprise the Central Nervous System (CNS) which is the communication coordinator between the brain and the body. The neural elements are comprised of the spinal cord and nerve roots. The spinal column houses the spinal cord. The spinal column has many functions which include: protecting the spinal cord, providing structural support and mobility, providing flexibility and serving as an anchor point for attachment of muscles and ligaments. Its most important function is to protect the spinal cord from trauma, if the spinal column is damaged injury to the spinal cord is likely.

2.1.2 Kidneys

The kidneys are an extremely important organ in the body which are necessary for survival and maintenance of homeostasis. They have many responsibilities which include removing wastes from the body, regulating electrolyte balance and blood pressure, and the stimulation of red blood cell production (Legal Briefs, 2002). The kidneys are responsible for producing the urine that removes the wastes from our body. They are a “bean” shaped organ located in the back of the abdomen, one on each side of the spinal column (Figure 2-2). For the adult male and females the kidney are located around the T12 vertebrae and are about 5 inches long and 3 inches wide, weighing in a range of 4 to 6 ounces. The right kidney is lower than the left kidney, it is found at the 12th rib and the left kidney is found between the 11th and 12th ribs (Gray, 1977).

The location of the kidneys provides a natural protective environment (Figure 2-2). The spinal column protrudes further out than the kidneys and therefore provides an initial contact base for large objects. The kidneys are also protected by the lower rib cage and several large muscles located in the back (Legal Briefs, 2002). The most common types of injury to the kidneys from impacts are bruising or even laceration of the kidney lining. This can result in serious injury because the kidneys are a highly vascularized organ. Other complications include: acute renal failure (sudden loss of function), shock (lack of blood flow), and uretral damage (injuries to kidney tubes that carry urine).

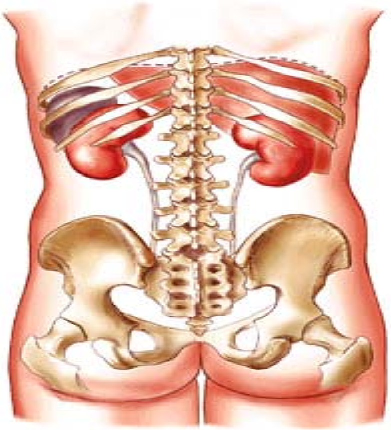

Figure 2-2 Posterior view of the kidneys within the human body (About the Kidney).

2.1.3 Scapulae and Rib Cage

The scapulae are most commonly known as the shoulder blades. They are triangular, thin, flat bones found in the back of the shoulder girdle (Gray, 1977). They are attached to the clavicle and are situated behind the rib cage (Legal Briefs, 2002). Several ridges on the scapulae serve as places for muscle attachment. The scapulae serve as the main location for the deltoid muscle attachment. The scapulae are very strong due to the large muscular coverage and location of the ribs. Unfortunately fracturing a scapula can cause rib damage and spinal injury due to the disruption of the bone (Gray, 1977).

Twelve pairs of ribs form the sturdy thoracic cage that shapes the chest. The twelve pairs are identified as true or false. The first seven ribs attach to the sternum and spine, identifying them as true. The next three attach to the spine but not the sternum. The last two ribs are called the floating ribs because they attach to the spine and nothing else. Ribs also differ in size, each rib increases in size from the first rib to the tenth rib.

Their purpose is to serve as a protective barrier to many internal organs including our heart and lungs. These organs are vital to maintain life and therefore the ribs are very important to protect. The ribs also serve as a helping tool for breathing. There are several intercostal muscles in between the ribs that lift the rib cage up in the process of inhaling and expanding the lungs (Gray, 1977).

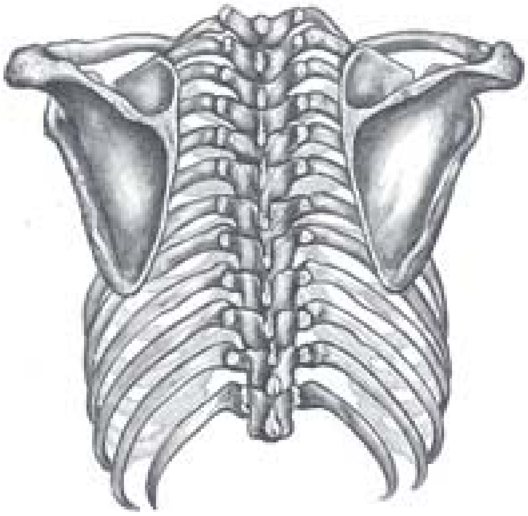

Figure 2-3 Posterior view of the rib cage and scapulae (Legal Briefs, 1977).

2.2 Levels of Injury

Mechanisms of injury are important to understand in relation to back injury under low velocity impact. The spine, kidneys, ribs and scapulae are defined as areas where protection to the back should be provided.

Spinal injuries are categorized into five main types of injuries by physicians. These injury mechanisms are known as flexion, extension, rotation, shear and lateral bending injuries. Often, a spinal injury can occur from a combination of two mechanisms where there is translation and rotation involved. The twisting and bending motions are the mechanisms that result in the most severe spinal injury. Twisting, bending and axial compression are responsible for most spinal injuries (White, 1990). Figure 2-4 shows a diagram of how the spine can rotate and translate. Numerous types of motions can result when a person is thrown in the air or hit by an object. It would be extremely difficult if not impossible to try to prevent all categories of possible spinal injuries (Levine, 1998). Therefore, the method of injury which will be investigated for protection is a force applied perpendicular to the back (negative z-direction according to Figure 2-4).

Since numerous effects can be involved in injury to the back it is difficult to categorically decide an acceptable level of force that can be applied to the back without causing severe injury. Dr. Woods of Cambridge University has established a set of allowable force transmitted values through materials to which he believes standards should follow (CEN/TC 162/WG 5 Document N 657, 2002). Table 2-1 shows force values that represent threshold values for severe injury. Based on this data Dr. Woods suggests that 4 kN is an acceptable threshold level of injury to the back specifically for the spine and the back in general. Therefore he believes based on research that all areas of the back including the kidneys, ribs and scapulae should be protected at the same level as the spine needs.

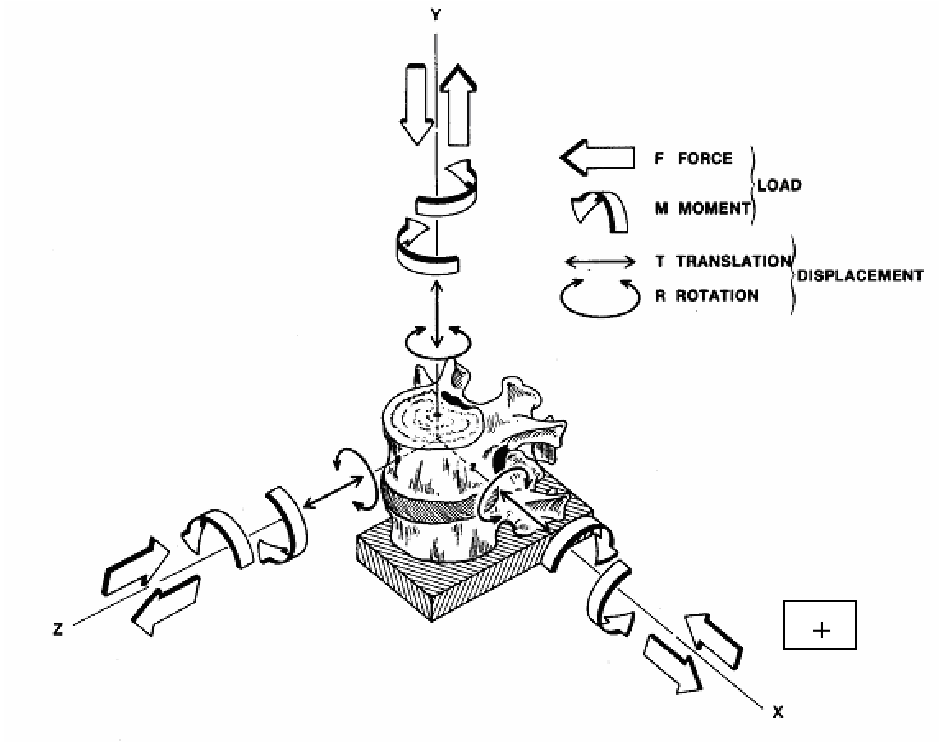

Figure 2-4 The three dimensional view of all possible spinal motions (White, 1990).

Body Part	**Minor Injury (kN)**		**Severe Injury (kN)**	
	Repeated Impact	Single Impact	Repeated Impact	Single Impact
Spine: Central posterior torso from neck to end coccyx	2	3	4	4
Outer posterior torso from shoulders to buttocks	4	4	4	4

Table 2-1 Recommendations for peak transmitted force requirement outlined by Dr. Woods (CEN/TC 162/WG 5 Document N 657, 2002).

2.3 Ballistic Body Armor

Ballistic resistant body armor is developed for a variety of scenarios and levels of protection. Factors that are considered when developing body armor include weight (i.e. areal density), type of bullet, bullet velocities, and comfort. The idea behind stopping a bullet is to reduce its energy. When the bullet hits the ballistic resistant system, it absorbs and disperses the energy of the bullet by deforming it into a mushroom shape (Selection and Application Guide to Personal Body Armor, 2001). Typically, military ballistic armor consists of soft and rigid components. The soft armor forms the flexible, protective vest. It contains several layers of ballistic fabric material(s). The rigid armor is used for enhanced protection in specific areas, normally this is over the chest region to protect vital organs. The rigid armor is in the form of a plate that is inserted into a pocket of the vest. The entire body armor system has a carrier, usually made of nylon that has the sole purpose of supporting the ballistic material and securing the armor to the body for correct positioning and comfort (Figure 2-5).

Figure 2-5 Typical structure of a ballistic vest and plate which is inserted in a front panel (Simula, 2003).

The ballistic fabric materials can be arranged to provide effective protection. Each body armor developer has its own method when developing protective systems. The fibers are usually plain woven together, although there are other methods of weaving that are used. Some armors use one single material stacked in multiple layers, others use several types of materials. Each layer of material can be comprised of varying directional fibers. Additional layers of material increase the ballistic resistance and blunt trauma protection, but the weight is also increased. Several stitching methods are employed to hold the layers together. For example, a bias stitch can be applied around the perimeter of the materials. There are several other forms of stitching which include rows of parallel or overlapped vertical, horizontal and diagonal lines (Selection and Application Guide to Ballistic Body Armor, 2001). Stitching of ballistic materials has been shown to slightly improve ballistic integrity and enhance protection against blunt trauma (Mouritz, 2001).

There are several types of ballistic fabrics that are used today. Kevlar® is the most commonly known ballistic aramid fiber. It is a product of DuPont company and has had several generations of development. Kevlar® 29 was the first ballistic protective material developed. Then came generations of Kevlar® 49, Kevlar Protera and Kevlar KM2®. Its structural makeup consists of organic fibers which have long molecular chains that are highly oriented with strong interchain bonding (Kevlar, 2001). This results in properties that are excellent for high stress applications. For example, Kevlar® 29 is stronger than steel at 1/5th the weight. Kevlar's dynamic strength properties include: high tensile strength to low weight, low elongation to break high modulus (structural rigidity), high toughness (work to break), high cut resistance, flame resistant and excellent dimensional rigidity (Kevlar, 2001). Twaron® is another aramid fiber marketed by Teijin which is comparable to Kevlar® at 5 times the strength of steel with similar strength properties. Twaron® has been available for over two decades. A newly developed fiber from Toyobo in Japan is Zylon®, also known as PBO. Zylon® is similar in density to Kevlar® and Twaron® and also provides exceptional ballistic protection. It consists of rigid-rod chain molecules of poly(p-phenylene-2,6-benzobisoxazole) hence the name PBO. Although Zylon® has a high ballistic performance to weight ratio, a decrease in resistance occurs under heat and humidity. Therefore its mechanical properties degrade much more quickly than other ballistic fibers. Other common ballistic fibers are Dyneema® that was developed in the Netherlands and SpectraShield® that was developed in the United States. Both are ultra high strength polyethylene fibers that are so light they can float on water (Selection and Application Guide to Ballistic Body Armor, 2001).

The rigid armor is in the form of a hard mold developed out of a metal or ceramic with a fiber reinforced backing. The rigid armor is used to defeat high velocity and armor piercing rounds that fabric cannot. The hard metal/ceramic face deforms the bullet and dissipates the high energy of the bullet. The fiber backing and ceramic are molded together using a resin. The type and amount of resin used has been shown to affect ballistic integrity (Maffeo, 2000). Typically ceramics are more commonly used over metals because they can stop projectiles with less unit per weight. The more common ceramics are boron carbide (B_4C), aluminum oxide (Al_2O_3), and silicon carbide (SiC) (Reaugh, 1999).

2.4 Impact Protection

Impact protection is provided by two methods. The first is to increase the time of impact to decrease the peak acceleration and force. This can be determined if one looks at the impulse of a collision. The impulse is defined as $\boldsymbol{I} = \int \boldsymbol{F}(t)\, dt$. Where $\boldsymbol{F}$ is equal to the force over time, and $\boldsymbol{I}$ is equal to the impulse or the area under the force vs. time curve. A collision with the same change in momentum will have the same impulse; therefore, the only way to reduce the peak force is to lengthen the time of the collision. One method of doing this is to use a foam, which takes energy to deform the structure of its walls and time to compress the air within the foam walls. The second impact protection approach is to distribute the load over a larger area, and away from crucial areas. Stiff materials are used in this instance because it takes a high energy and force to deflect the material, therefore the material distributes the load over a larger area. Examples of materials are foams or plastic which have a high stiffness.

As indicated, foams are a common material used today to provide “cushioning” under loads. They are used in a variety of applications to provide protection and support in areas such as packaging, seating, and sports equipment. The performance of a foam is dictated by several factors including the cellular structure (open or closed cell), environment (temperature and humidity), the fluid enclosed in the matrix (usually gas), and the nature of the loading and deformation characteristics (Cunningham, 1994). These characteristics need to be carefully considered when choosing a foam to perform a function. For instance in static loads, a firm foam is better to use and is defined by its Indentation Foam Deflection (IFD). The IFD is a measure of the foams firmness and is a relation to comfort used in seating (Cunningham, 1994). A foam can either be open cell or closed cell. A closed cell foam has the air trapped within the cells of the foam and they are not connected to other cells. Typical closed cell foams are made of polystyrene and found in packaging for shipping. However, closed cell foams are not effective in providing multiple impact performance. Open cell foams are more effective in hysteresis and multiple impact performance. These foams have a cellular structure which is interconnected. This structure provides impact protection through buckling of the cell walls and compression of air through the cellular matrix. Common open cell foams are made from polyurethane.

2.5 Back Protectors

Back protectors were researched to evaluate the levels and type of protection available. The most common types of back protectors are those used for sports such as horse riding and in racing for motorcyclists. The goal of most back protectors is to provide protection for the tissues, kidneys, shoulder blades, ribs, and the spine. They do this reducing the force transmitted through materials and providing resistance to abrasion. However, it is cautioned that they are not the ultimate protection. Some injuries, such as spinal injuries, are difficult to protect against. Most serious back and spinal injuries occur due to twisting and bending of the back. The back protectors can only help mitigate injuries related to direct blows to the back.

Several factors are considered in the design of a back protector. These factors include weight, abrasion resistance, comfort, and protection. All of these measures play significant roles in the design process. The average back protector uses several materials to meet these design criteria. A typical motorcyclist back protector is shown in Figure 2-6. The most common types of back protectors have special protection over the spinal area. This either consists of several layers of material or a stiff material which serves to distribute the load away from the spine. Common materials used in for this are carbon Kevlar® or stiff, high density, closed cell foams. Underneath the stiff materials are absorbent materials used to absorb energy. Most of these materials consist of low density foams (i.e. polyethylene, polypropylene) or rubber (i.e. sorbothane) (Miller, 2000). The large belt loop is there for support, comfort and to protect the kidneys and lower back. The materials in this region are usually the energy absorbing materials as well.

Figure 2-6 Clover Back Pro 6-P, a common back protector used by motorcyclists (Back Protectors and Body Armor, 2000).

The design of the back protectors can be used to help understand how the ballistic materials should be placed in order to minimize injury. The materials used in back protectors can be investigated as measures that may need to be incorporated into the design of the ballistic vest in order to enhance blunt trauma protection.

2.6 Safety Evaluation Methods

The most common types of back protectors are those used in sports. Two standards for testing back protectors were found. These two methods are used to evaluate back protectors for horse riders and for motorcyclists.

These standards were established by the European Committee for Standardization. They define the requirements and testing methods for protective clothing of horse riders and motorcyclists. The standard for horse riders is identified as EN 13158 and was established in March 2000. The standard for motorcyclists is identified as EN 1621-2 and was established in January 2001. The standards were developed to ensure the consumer purchased a product that would provide a specific level of safety.

Each set of protocols were designed to fit the specific scenarios that a horse rider or motorcyclists would face. Both standards implement similar testing protocols by evaluating localized impacts. Requirements were established to ensure the accuracy and value of the final results. The standards establish criteria for material coverage, material preparation, test equipment, and performance requirements. Both standards were developed to evaluate falls on the ground and impacts onto a variety of objects. These situations are similar to what a solider may see in duty. The levels of safety are based on values of allowable force transmission through protective equipment. The standards indicate that their goal is to reduce the severity of injury and they do not claim to provide absolute protection against all injuries.

2.6.1 Horse Rider Protection

The horse rider protection standard EN 13158 (Appendix B) establishes a level of protection against riders falling off horses and impacts against hard or soft ground and other objects. It is also to protect against being kicked, trodden on, or crushed by a horse. This standard separates back protection and shoulder protection. The testing equipment is used to determine impact energy transmission. Three different sets of impactors are used to simulate a variety of scenarios that a horse rider may face.

A solid metal anvil is mounted on top of a force transducer to simulate a measure of the force transmitted to the back. The protective material is placed over the anvil and impacted with one of three impactors: a flat impactor, a narrow bar impactor, or a wide bar impactor. The anvil is cylindrical and is 100 (± 1) mm in diameter with a radius of curvature on top of 150 (± 5) mm. The load cell is placed underneath the anvil and the entire structure must be attached to a mass of at least 1000 kg for a rigid support. A guard ring is placed around the anvil (120 mm internal diameter, 20 mm thickness) and bolted down to protect against movement on the anvil in response to impact.

The flat impactor simulates the hoof, it should be 80 (± 2) mm in diameter with a mass of 2500 (± 25) g. The narrow bar impactor was developed to represent a railing and shall be rectangular. The dimensions are 80 (± 2) mm in length and 20 (± 1) mm in width with a total mass of 2500 (± 25) g. The wide bar impactor was developed specifically for testing shoulder protectors. The impactor face is 80 (± 1) mm in length and 40 (± .5) mm in width, with 5 mm radius edges. The back protectors can be categorized into three levels of protection. The level of protection a back protector provides is defined by the level of impact energy where the peak transmitted force remains below 4 kN. A level 3 protection is the highest level of protection defined. The levels of impact energy with which the strikers should hit are outlined in Table 2-2. For shoulder protectors the transmitted force shall be below 25 kN and no single value should be above 30 kN.

Test Conditions	**Impact energy for the performance level (J)**		
	Level 1	***Level 2***	***Level 3***
Flat impactor, body protector	25	30	35
Narrow Bar Impactor, body protector	20	32.5	45
Wide Bar, shoulder protector	60	60	60

Table 2-2 Impact energy testing to performance levels 1, 2 and 3 for horse rider protection.

Measurements must be made according to the standard methods. A sampling rate of 10 kHz must be achievable with the working apparatus. Also, the complete system must have the capability of measuring forces in a range of .1 kN to 50 kN.

2.6.2 Motorcyclist Protection

The motorcyclist back protector standard EN 1621-2 was developed on the same testing ideology as that for the horse rider protector (Appendix A). However, while the testing method is almost identical, the levels of force transmission vary significantly. The goal of this standard is to provide protection to the back that includes coverage from the waist up to the neck.

The testing method is similar to the horse back riders in that there is a fixed, rigid anvil mounted above a force transducer. This assembly must be attached to a mass of 1000 kg to ensure a rigid structure. The protective material is placed above the anvil and impacted with a striker to obtain transmitted force measurements. For this standard there is only one striker which is used to mimic a curbstone or other object that a motorcyclist may encounter on a fall. The striker is 80 (± 2mm) in length with a width of 25 mm and a radius of 12.5 mm. The total mass of the impactor and guided mass should be 5000 (± 25 g) which is twice the amount of that for the horse rider protection method. The energy upon impact must be 50 J at a drop height of 1 m. Therefore the velocity at impact should be around 4.5 m/s. Two levels of impact performance requirements are identified into Level 1 and Level 2 protectors. Level 1 protectors shall have an average peak force of 18 kN and no single value should exceed 24 kN. Level 2 protectors shall have an average peak force below 9 kN and no single value shall exceed 12 kN. While the allowable force transmission values are much higher for the motorcyclist impact, the falling mass and energy on impact is much greater than that for EN 13158.

The force measurement instrumentation must use a quartz force transducer to make the force measurements. The range of the transducer is between .5 kN and 50 kN which is similar to that for horse riders. The output of the force transducer should be set to a charge amplifier and a digital sampling rate must be set at 10 kHz.

3 Experimental Methods

The design of this experiment was to evaluate ballistic materials and possible improved systems for low velocity impact protection. The materials were assessed in relation to measures of transmitted force during an impact. Testing methods for sports equipment designed to protect the back were consulted to identify how safety in relation to impact can be determined. Methods for evaluating horse riders' and motorcyclists' protectors (EN 13158, EN 1621-2) were the only measures found for testing back protectors. These methods incorporated protection against falling off a horse or motorcycle and being thrown into objects. These circumstances were similar to low velocity injury situations that soldiers may face.

Both standards have similar testing methods and elements for testing the ballistic materials were derived from these two standards. Acceptable peak transmitted forces of 4 kN and 9 kN through materials were derived from the standards and published literature. The equipment test set up for EN 1621-2 was followed for these tests. Preliminary studies were performed to evaluate the test equipment and ballistic materials to help finalize the test protocol. Based on the preliminary results impact protection foams were added into the test sequence to evaluate the effect of impact protecting materials.

Under the finalized test method all materials were evaluated at one energy level individually and in configurations to determine the most effective method to reduce transmitted force. The best material configurations were then tested at higher impact energies until the force specifications of 4 kN and 9 kN were met.

3.1 Test ideology

The test standards EN 13158 and EN 1621-2 established a set of test criteria that allow for designs which are both protective and comfortable. The standards outlined impact tests to be performed at specific energies which relate peak transmitted force through materials to levels of safety. Their main purpose was to provide a level of protection against direct impacts to the back and to reduce injuries such as bone fractures, bruising, and strains in horse riding accidents and falls from motorcycles. Neither method accounts for the axial loading, bending or twisting forces that cause the majority of severe back and spinal injuries.

The impact tests performed were modeled after the test structure of both standards. Each standard used similar equipment configurations to make measurements but differed in impact performance requirements. For EN 13158, a level of 4 kN at impact energies from 20 – 45 J was used as the allowable force transmission for protection against back injury. This force value was also the value recommended by Dr. Woods for full back and spinal protection at any impact energy. The highest measure of protection that EN 1621-2 permits was 9 kN for the entire back, at an impact energy of 50 J. The most critical aspect of the back to protect is the spine. Therefore a maximum transmitted force of 4 kN was considered safe to prevent spinal and kidney injury and a maximum value of 9 kN would provide protection for the remaining sections of the back. These values were the set of criteria through which the experimental tests for ballistic materials were designed.

3.2 Test Setup

The set up for testing was similar for each standard. These experiments followed the equipment protocol outlined by EN 1621-2. There were four main components to the test set up: the dropping apparatus, striker, anvil and force measurement instrumentation. The standard specified the method of force measurement. The material was impacted by the striker and the force transmitted through the material was measured by a force transducer underneath the anvil. A schematic of this test system is shown in Figure 3-1.

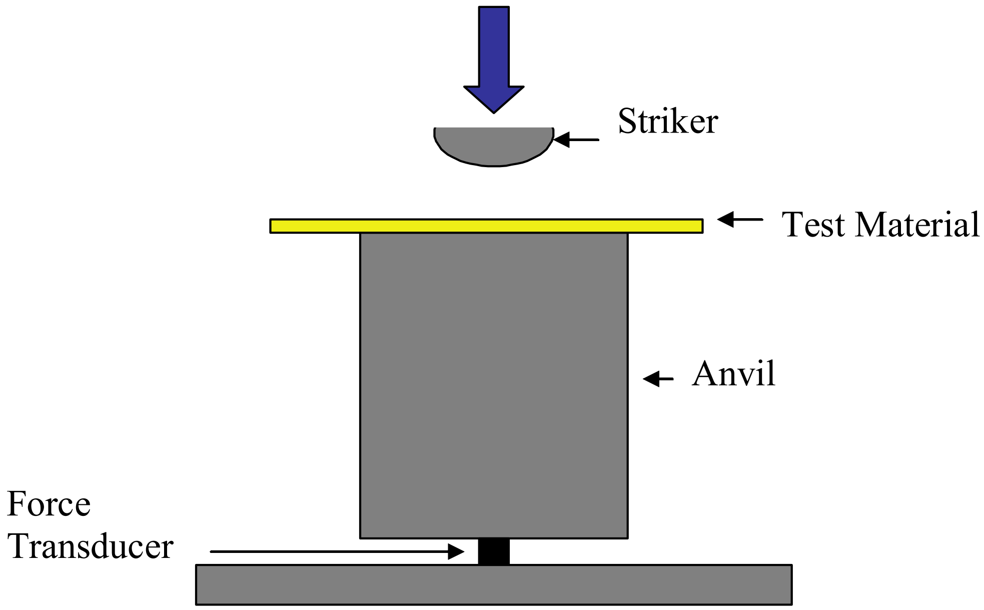

Figure 3-1 Schematic of test set up for measuring the impact force transmitted through a material.

3.3 Equipment

A guided vertical dropping apparatus was used to drop an impactor on the material being tested. The center of mass of the falling object was over the center of the anvil. Figure 3-2 shows the vertical rail impactor (U.S. Instruments, NJ) that was used in this test. It has a guided vertical track that can hold the striker. The guided track is on ball bearings to reduce the effect of friction of the falling mass. The release bar was used to set the drop height. The vise grip was locked onto the railing above the release mechanism to ensure that it remained in the same location for each test.

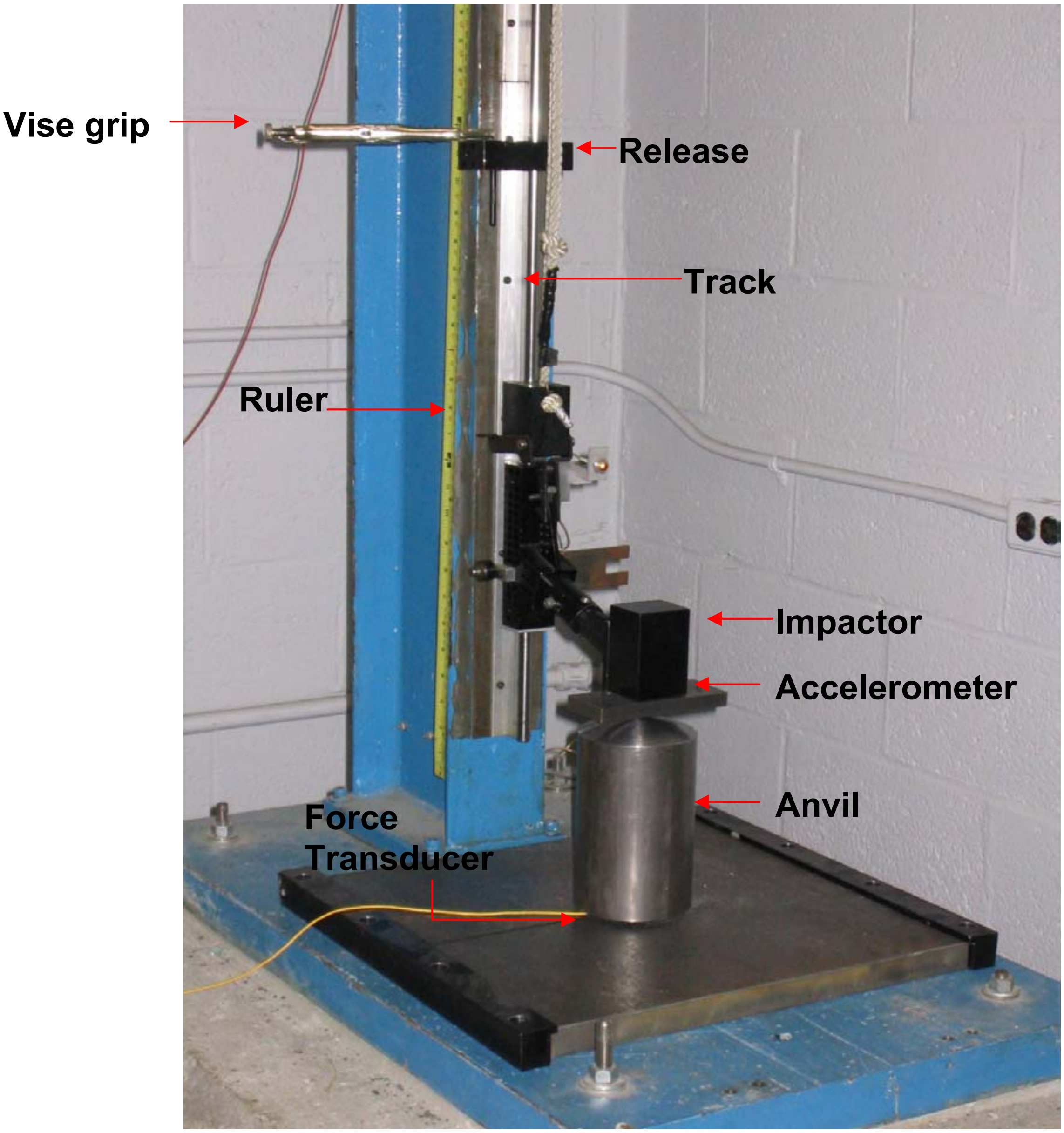

Figure 3-2 Vertical rail impactor used for drop testing.

The striker was cylindrical in shape with a radius of 12.5 mm to represent a curbstoned object. It was attached to the dropping apparatus through a special arm (Figure 3-3). The impacting system had a total weight of 5.4 kg, which was 400 grams heavier in weight than EN 1621-2 specified. The striker was made of steel, the arm was made of aluminum and a block of lead was added to the top of the striker to obtain the specified weight and to place the center of mass at the center of the striker. The center of mass of the impactor was aligned with the center of the anvil to have a direct impact. Pro/Engineer was used to model the center of gravity of the strikers and dropping apparatus in addition to hand calculations. A ruler was used to set a height which resulted in a specific energy on impact. The anvil (made of steel) was developed to represent the human back (Appendix A). It was cylindrical in shape with a hemispherical top. The anvil was 10 cm in diameter, 18 cm in height, with a radius of curvature of 5 cm. The hemispherical surface was designed to mimic the curvature of the back in a fall.

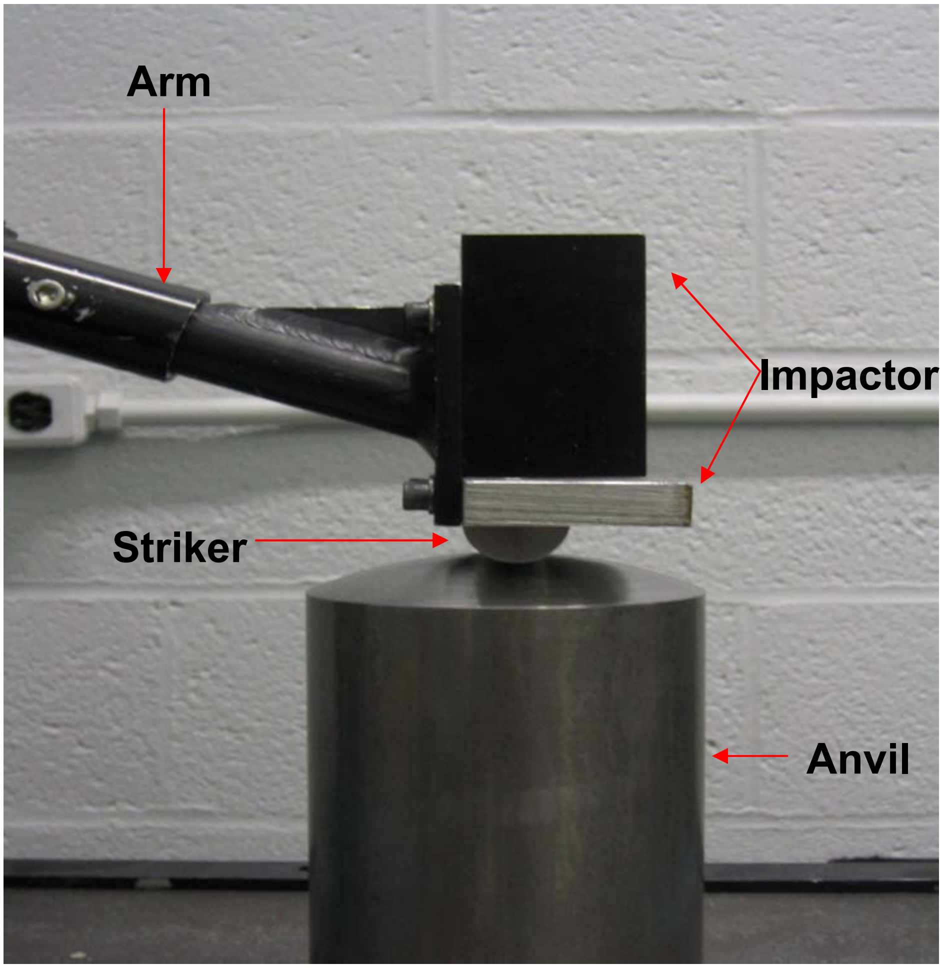

Figure 3-3 Assembled view of cylindrical striker attached to the arm on the guided vertical track.

3.3.1 Instrumentation

The standards' specifications state that the measurements of force must be obtained through a quartz force transducer that can measure between .5 kN and 50 kN. However, these specifications of force were based on testing all levels of protection for back protectors up to 30 kN in transmitted force. A force transducer that measures up to 50 kN was not available, nor was it needed when 4 kN and 9 kN were used as the maximum acceptable force measurements. The force transducer used was a Kistler 912 load cell (Figure 3-4) that has the capacity to measure from 0 to 22.2 kN. This was well within the ranges that were needed. The transducer is threaded on each side and was mounted to the anvil and base of the dropping apparatus through the threads. To reduce torque on the force transducer it was set 1/8th inch deep in the anvil and the base (Appendix C).

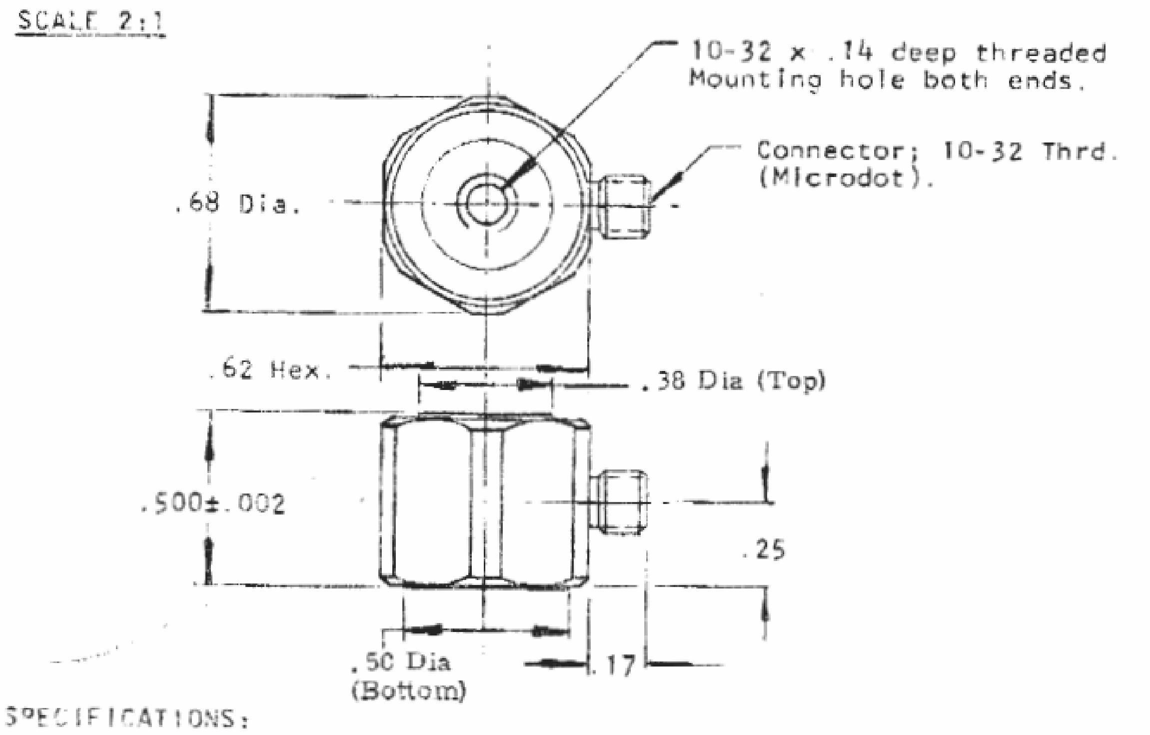

Figure 3-4 Top and side view of the quartz force transducer (Kistler 912).

To obtain measurements the force transducer was connected to a Kistler 507 charge amplifier. A data acquisition program previously developed at Natick Soldier Center using LabWindows/CVI Version 6.0 was used to gather both force vs. time and acceleration vs. time data. An Endevco 77084 accelerometer with a range of 500 g's was mounted on the impactor. Measurements were obtained using an Endevco 2721B charge amplifier. A photocell mounted on the impactor triggered the start of acquisition. The maximum attainable sample rate was 5 kHz. The standard requires a sample rate of 10 kHz, but this exceeded the capabilities of the equipment.

3.4 Preliminary studies

Preliminary studies were performed to evaluate the test system and to gather information to help finalize the test protocol. Initially, tests were run to verify that the equipment (i.e. force transducer, accelerometer, impactor) were working in accordance to the test standard. This included evaluating factors such as the sampling rate, and response time of the force transducer and accelerometer. Further tests were performed to observe the performance of ballistic materials under impact. This information helped shape the final test protocol based on the performance of the ballistic materials. For statistical purposes these data were used to determine the number of tests necessary to validate the results.

3.4.1 Instrumentation Validation

Preliminary tests using the ballistic fabrics showed that impacts occurred on a time scale of .0014 seconds. Therefore the sampling rate at 5000 Hz was considered to be sufficient since it was sampling nine times faster than the impact duration. The test standard EN 1621-2 stated that the force transducer needed to fall under the specifications of ISO 6487. The ability to evaluate the force transducer sufficiently was not available therefore another means was used. ISO 6487 was based on the SAE J2/11 impact measurement standard. The Endevco accelerometer used at Natick Soldier Center had been validated to meet the SAE J2/11 standard. Therefore in order to validate the force transducer in this measurement system its frequency response was measured against that of the accelerometer (Figure 3-6). The response of the accelerometer and force transducer over time is shown in Figure 3-5. The time response of the accelerometer and force transducer correlated well. Based on these results the system was considered satisfactory for impact measurements.

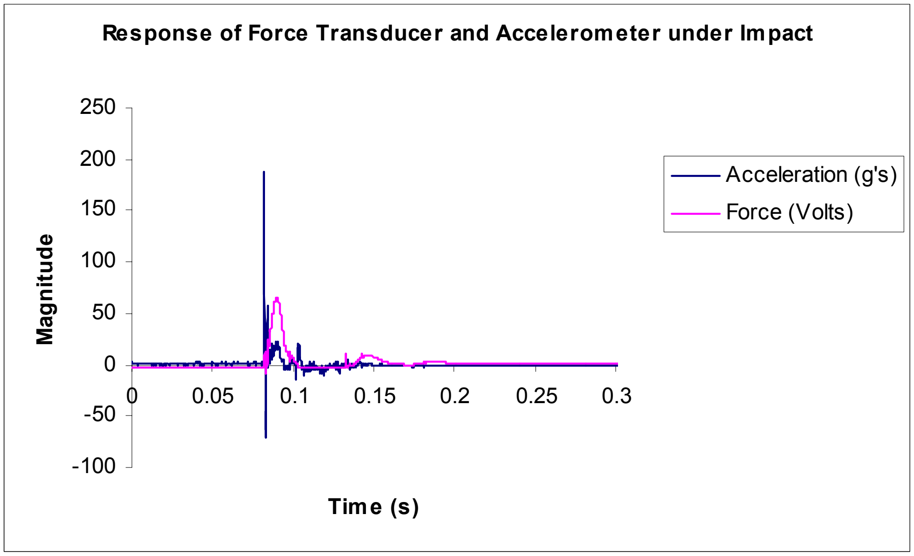

Figure 3-5 Response of accelerometer and force transducer under impact.

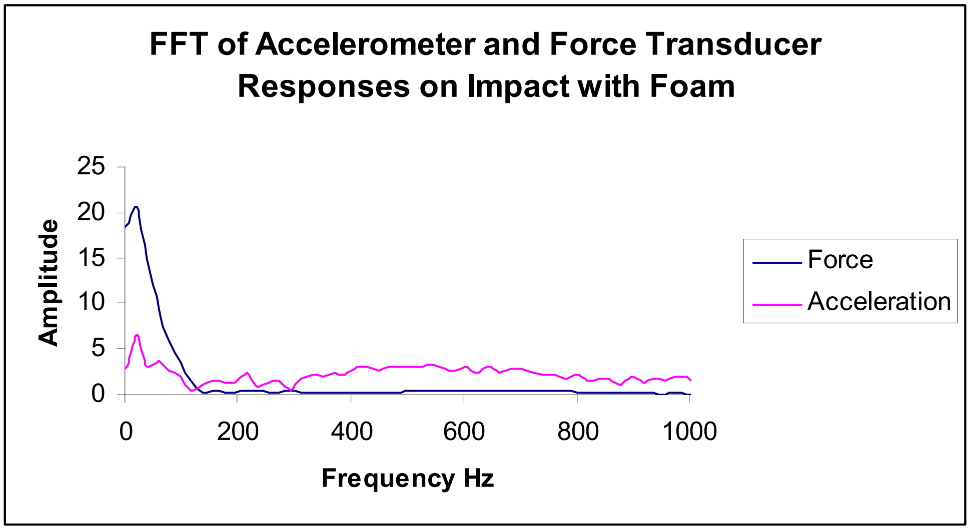

Figure 3-6 FFT of response of the force transducer and accelerometer to an impact test with foam.

3.4.2 Characterization of material performance

The initial goal of the project was to determine how the materials performed under low velocity impact, in relation to one another and to the test specifications EN 13158 and EN 1621-2. Preliminary tests were performed to determine one drop height where all of the materials could be tested. This measurement allowed the materials to be characterized based on material type. In order to obtain specific energy levels, conservation of energy was used. At a specific height the object would have a potential energy: $PE = mgh$. The variable m is the mass of the falling object, h is height of the object before it falls, and g is acceleration of the object due to gravity.

For an impact energy of 50 J and an impactor weight of 5.4 kg a drop height of .95 m was used to test the ballistic material. Eleven plies of Kevlar® 29 1500 denier were tested at .95 m for an impact energy of 50 J as EN 1621-2 states as a measure of impact. The data exceeded the measurement capabilities of the force transducer. Therefore more plies were added to the testing sequence to see if there was a change in response due to the number of plies. Twenty-two plies of Kevlar® 29 1500 denier were tested at 50 J. A total of four tests were taken and the results are shown in Figure 3-7. The data were truncated at 22 kN. It was apparent that the ballistic materials, regardless of ply number were well out of range of the force transducer capabilities at this impact energy. Therefore the drop height was lowered to .18 m to see how the material performed under this lower impact energy of 9 J. Figure 3-8 shows the results of the impact tests at 9 J.

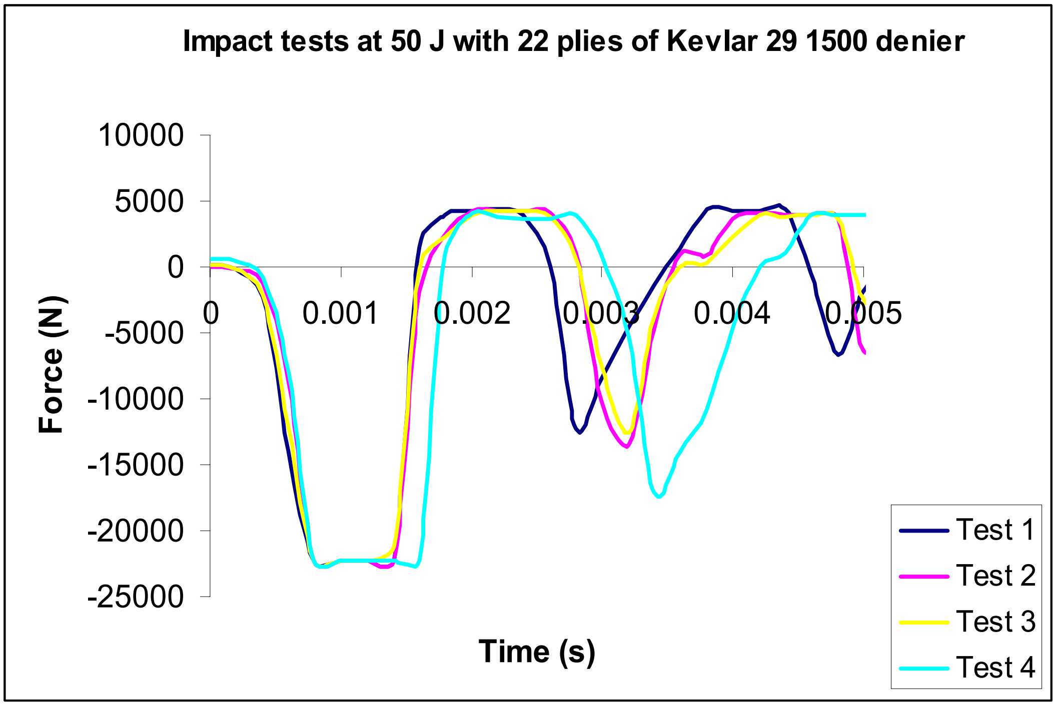

Figure 3-7 Transmitted force over time at a 50 J impact with 22 plies of Kevlar 29 1500 denier. The data were truncated at 22 kN.

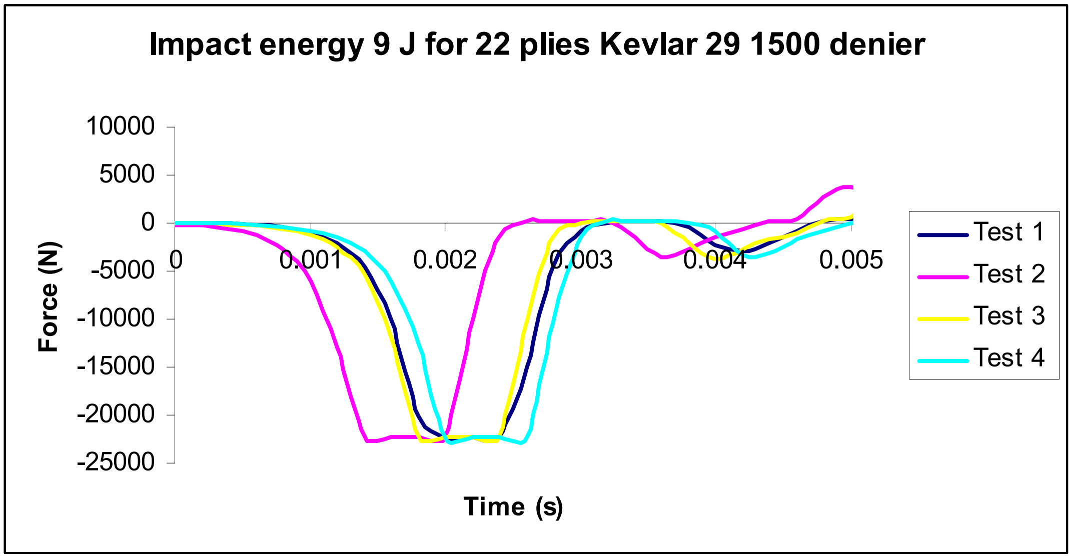

Figure 3-8 Transmitted force from an impact of 9 J on 22 plies of Kevlar® 29 1500 denier. The data were truncated at 22 kN.

Again, the limit of the transducer was exceeded. Other materials including Kevlar KM2® 400 and 600 denier were tested with similar results. The impactor was then set at a drop height of 7.6 cm, which gives an impact energy of 4 J. The peak transmitted force here did not exceed the limits of the transducer for Kevlar® 29 1500 denier, Kevlar KM2® 400 denier and Kevlar KM2® 600 denier. The data obtained at this drop height are shown Figure 3-9.

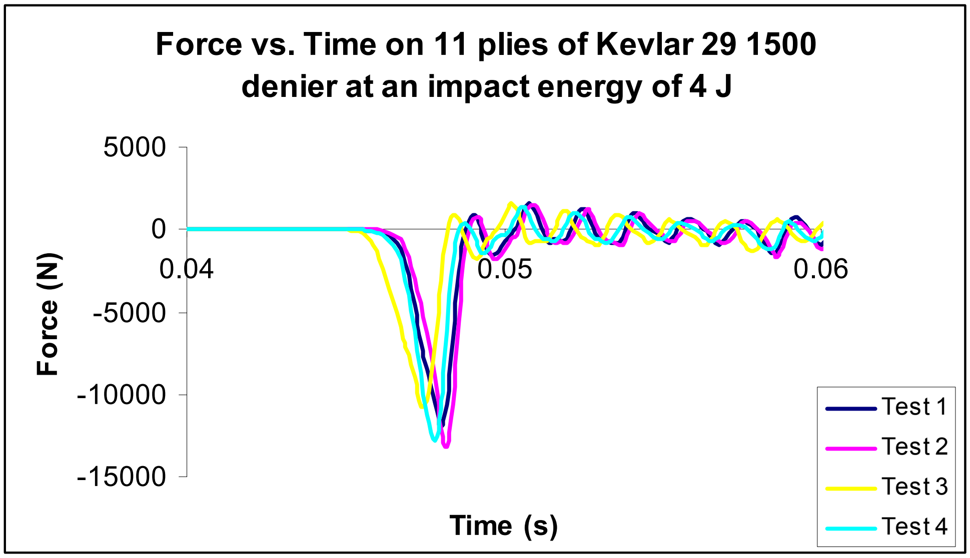

Figure 3-9 Transmitted force over time with 11 plies of Kevlar® 29 1500 denier at 4 J of impact energy. The data was not truncated.

Based on these results an energy level of 4 J was determined to be the impact energy where the materials would be tested to characterize and compare their performance. This was a small drop height that potentially increased variability in the results. It was decided to use a smaller impactor mass in order to obtain larger drop heights for the same impact energy. The impactor mass of 2.5 kg from EN 13158 was used. The impactor developed had a mass of 2.4 kg. This allowed the tests to be performed at larger drop heights, which decreased error in variance from drop height settings. It was also evident that the ballistic materials alone could not meet either standard specifications. Therefore foams were introduced into the test material protocol to improve impact protection.

3.4.3 Determination of test size

Statistically, it was important to ensure that enough tests were performed for reliable results. Preliminary data of impact tests were used to perform a power analysis to determine the number of tests needed (Montgomery, 2001). The tests, performed on the ballistic fabric Kevlar KM2® 850 denier, indicate that a sample size larger than 8 test samples will provide greater than 99% power.

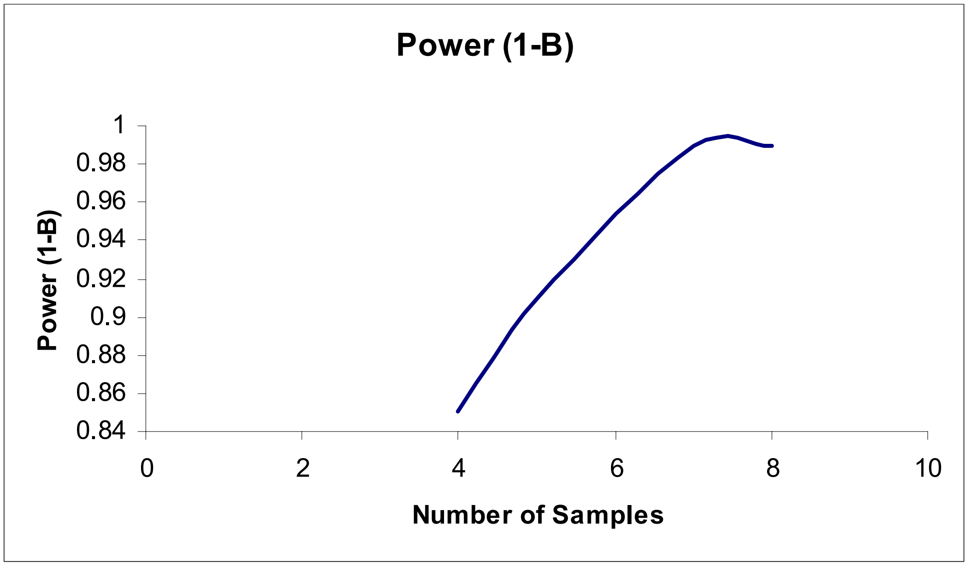

Figure 3-10 The power analysis performed indicated that a test size greater than 8 gave a power greater than 99%.

3.5 Specimen Selection and Preparation

The following section outlines the selected materials and specimen preparation for testing. The ballistic materials were obtained at Natick Soldier Center and the impact protection materials were acquired from a variety of distributors. EN 1621-2 did not have any requirements on material selection or preparation except that the materials must be held at a constant room temperature for 48 hours. The materials remained in the testing room at room temperature 20 C (68 F).

3.5.1 Ballistic Materials

The ballistic materials were selected based on commonly used materials in industry and those materials available at Natick Soldier Center. For soft fabrics, several deniers of Kevlar® 29, Kevlar KM2®, and Zylon® were evaluated. Preparation of these test specimens was based on meeting a specific areal density of 4.9 kg/m^2 (1 lb/ft^2). This areal density was the typical standard to that the Army developed samples for ballistic tests. The materials were cut into 17.5 x 17.5 cm^2 pieces and weighed to determine the number of plies needed to make a total areal density of 4.9 kg/m^2 (Table 3-1). For each material ten plies were sewn together with a single stitch around the perimeter, using a walking stitch needle. The sewn plies were added together and taped to meet the number of plies needed for 4.9 kg/m^2. This is the typical preparation performed when preparing samples for ballistic tests.

Material	*Size (cm^2)*	*Ply Weight (g)*	*Areal Density 4.9 kg/m^2 (1 lb/ft^2)*	*# of plies for 4.9 kg/m^2 (1 lb/ft^2)*
Kevlar KM2® 400 Denier	18 x 18	3.6	.021	48
Kevlar KM2® 600 Denier	18 x 18	5.9	.034	30
Kevlar KM2® 850 Denier	18 x 18	8.1	.045	22
Kevlar® 29 700 Denier	17.5 x 17.5	8.6	.056	18
Kevlar® 29 1000 Denier	17.5 x 17.5	10.4	.077	13
Kevlar® 29 1500 Denier	18 x 18	17.2	.097	11
Zylon® 500 Denier	17 x 18	5.0	.031	32

Table 3-1 The number of plies needed to meet an areal density of 4.9 kg/m^2 (1 lb/ft^2).

To make the rigid plate, ceramics were chosen with a fiber reinforced backing. The ceramics were boron carbide (B_4C) and aluminum oxide (Al_2O_3). The fiber reinforced backing were plies of Spectra Shield® (ssp). The available ceramics were 10 x 10 cm^2 tiles of B_4C at .5 cm thick and Al_2O_3 at 1 cm thick. The actual ballistic plates were not used due to cost. Ceramic tiles are often used as substitutes to plates for testing. Similar to the ballistic fabrics, ballistic plates have been tested based on areal density. The areal density the Army has used for plate armor is 24.9 kg/m^2 (5.1 lb/ft^2). The 10 x 10 cm^2 ceramic tiles and a Spectra Shield® ply were weighed to determine the number of Spectra Shield® plies in combination with the ceramics weights to meet an areal density of 24.9 kg/m^2. Constructing the rigid plate was a two step process. First 10 x 10 cm^2 plies of Spectra Shield® were cut and pressed together to form a solid structure. This was done by using a 350 ton Wabash hydraulic press at 17.6 MPa. When this was completed a thin layer of polysulfide adhesive was placed over the Spectra Shield® composite. The ceramic tile was placed on the adhesive and the sections were taped together to secure the hold while the adhesive cured. The final step was to place the structure in a vacuum bag at 2.6 MPa and allow for a curing time of 24 hours.

3.5.2 Impact protective foams

Based on the results of the preliminary studies foams were introduced into the test sequence as a method to improve impact protection. This was an attempt to understand how well the ballistic materials could perform with enhanced impact protection. Foams are the most popular materials used by industry to provide impact protective materials. Open cell polyurethane (PU) foams at several densities were selected for their ability to perform under multiple impacts. They are identified in Table 2 and will be referred to through their ID names. Closed cell foams are also excellent to use for impact protection, but their performance degrades with every impact. Several samples of foams used for impact protection from commercial products were obtained and tested. Due to time constraints the number of samples of the foams were minimized to those that had been obtained by testing time. The sample sizes of the materials were cut so each piece was a standard size of 9 x 7.6 cm^2. This size was determined by the sample size obtained from the Confor foam distributor.

Commerical Name	*ID*	*Density (kg/m^3)*	*Thickness (cm)*
Low Density Polyurethane	LDPU	8	2.5
Performance Analysis Foam	BF	64	2.4
Confor Foam	CF 42	91	2.4
Confor Foam	CF 45	96	2.4
Confor Foam	CF 47	93	2.5
HipSaver	HS	128	1.9
Tempur Pedic	TP	86	3.8

Table 3-2 Commercial foam materials that are used in industry for impact protection.

3.6 Experiment Approach

The final test protocol was assembled based on the merging of both standard requirements (EN 13158, EN 1621-2) and the information provided by the preliminary studies. The experiments were conducted to understand the material's performance under impact. Twelve impacts were performed on each sample 30-45 seconds apart. The ballistic fabrics were tested in twelve different locations. The ballistic materials and foams were tested for multiple performance by impacting the same location twelve times. Due to the limited number of foams only one sample was used per experiment. The materials were characterized in relation to each other and to the standard's peak force requirements. Initially, the materials were tested at an energy level of 4 J to compare all of the materials. Once the materials were characterized the best configurations were evaluated to identify the highest impact energy where the peak force did not exceed the standard requirements of 4 kN and 9 kN. Acceleration data were gathered to verify the velocity on impact.

3.6.1 Characterization of Materials

The performance of the ballistic and foam materials under impact was characterized by testing them at an impact energy of 4 J. The impactor was set at a drop height of 17.75 cm which was equivalent to an impact energy of 4 J and a calculated impact velocity of 1.8 m/s. On occasion, problems occurred with saving and recording a set of data. In these instances, additional tests were not taken to keep the number of drops on a material consistent. The materials were tested individually and in composite configurations.

First, the ballistic fabrics were tested stand alone and then with ballistic plates. This was done because soldiers do not always wear the plate protection, therefore the materials needed to be assessed with and without the plate. Three different ballistic plate configurations were used to characterize the role of the ceramic and of the Spectra Shield® backing. Figure 3-11 shows the test configurations. The ballistic plate was attached to the ballistic fabric using tape to simulate the firm attachment the plate has with the vest in a body armor system. To identify the effect of ceramic the number of spectra plies were held constant. The ceramic B_4C .5 cm thick and Al_2O_3 1 cm thick with 119 plies of Spectra Shield® (ssp) backing were tested to look at the effect of the ceramic material. To look at the effect of Spectra Shield® plies B_4C .5 cm thick with 119 ssp and with 83 ssp backing were tested. Due to time constraints and a small number of samples not all ballistic fabrics were tested with ballistic plates. Table 3-3 outlines the different test configurations for the ballistic materials.

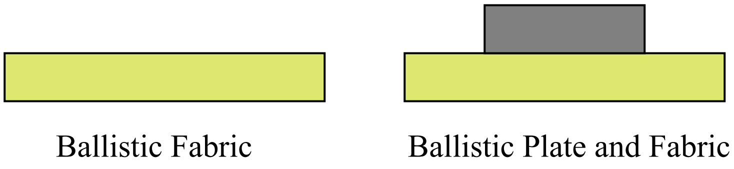

Figure 3-11 Material placement for ballistic fabric and plate testing.

Configuration	*Materials*
1	Ballistic Fabrics
2	B_4C .5cm 119 ssp/Ballistic Fabric
3	B_4C .5cm 83 ssp/ Ballistic Fabric
4	Al_2O_3 1cm 119 ssp/ Ballistic Fabric

Table 3-3 A total of four configurations of the ballistic materials were tested.

Foams were also evaluated individually and with the ballistic materials. All of the foam specimens were the same in width and length (9 x 7.6 cm^2) but differed in thickness depending on what the supplier had provided. Tests were also performed to look at the effect of sample size and thickness on the performance of foams under impact. The effect of sample size was tested with the HS foam using a 18 x 18 cm^2 sample piece. The effect of foam thickness was tested by using half of the thickness of the tempur pedic foam. The best performing foams were selected for testing with the ballistic materials. They were BF, CF and HS foams. The foam CF 42 was chosen for further testing over the better performing foam partners due to the fact that it was low in density and soft in texture. The CF 47 foam was ruled out entirely due to flaking of the material upon each impact. The polyurethane and the half thick tempur pedic foams were not evaluated due to their poor performance in regards to other foams. Figure 3-12 and Table 3-4 outline the test configurations made with the foams.

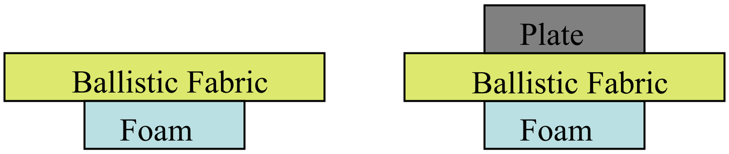

Figure 3-12 Configuration of materials for testing.

Configuration	*Materials*
1	All foams same sample size
2	HS foam 18 x 18 cm^2
3	TP foam at half thickness
4	Ballistic Fabric/Foam
5	B_4C .5 cm 119 ssp/Ballistic Fabric/Foam

Table 3-4 Test configurations involving impact protective foams.

3.6.2 Performance to Specifications

The improvement in impact protection with foams allowed for further testing to determine attainable impact energies while meeting maximum allowable transmitted forces of 4 kN and 9 kN. Again, ballistic fabrics were tested with and without the ballistic plate and with the top performing foams. Selected foams and ballistic fabrics were tested at this level due to time constraints. The materials were chosen based on their performance under previous impact tests. The ballistic fabrics Kevlar KM2® 400 denier, KM2® 850 denier and Zylon® 500 denier were tested. The B_4C .5 cm thick tile with 119 plies of spectra backing was used since it meets the areal density of 24.9 kg/m^2

(5.1 lb/ft^2). The foams used for this were BF and HS foams. These were among the top performing foams in previous testing and the amount of foam available was the largest therefore there was not a short supply of foam. The impact energies were increased until the initial transmitted force came within 1 kN of 4 kN or 9 kN. At this point the drop height was set and 11 more tests were repeated.

4 Results of Experiments

The methodology of the experiments performed was outlined in chapter 3. The set of experiments were developed to determine the level of impact protection regarding ballistic materials and foams that is achievable. The data outlined in this section illustrates the performance and results of subjecting the ballistic fabrics, several rigid plate configurations, and impact protection foams to low velocity impacts. The materials were tested independently and in composite configurations (Appendix D). These experiments were directed at developing an overall understanding of the performance of each material as well as to determine methods for improving impact protection. The best configurations were coordinated to establish how well the selected materials could meet the standards. In some cases, tests were minimized due to time and material constraints.

4.1 Characterization of Materials

The bulk of the experiments involved testing the materials at an energy level of 4 J to compare peak transmitted force under low velocity impacts. This defined a baseline of data to compare material performance. Testing was performed at a height of 17.75 cm which is equivalent to applying an energy upon impact of 4 J with a calculated impact velocity of 1.8 m/s. Table 4-1 shows the average peak force transmitted through the ballistic fabrics over twelve tests. Figure 4-1 is a box plot that shows the variation in data. The box outlines the end of Quartile 1 to 3 and the solid black horizontal line shows the median. Analysis of variance using Tukey's HSD and checking for data homogeneity showed that top performing Kevlar KM2® 400 denier, Kevlar® K29 700 denier and Zylon® 500 denier were significantly different ($p < .001$) (Appendix E) than the rest of the ballistic fabrics, but not from each other.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	13348	753
Kevlar KM2® 600 Denier	14886	747
Kevlar KM2® 850 Denier	15678	742
Kevlar® 29 700 Denier	12876	932
Kevlar® 29 1000 Denier	16183	617
Kevlar® 29 1500 Denier	15611	497
Zylon® 500 Denier	13006	498

Table 4-1 The ballistic materials were evaluated at an impact energy of 4J. The average peak force of the samples indicate the general performance each material had.

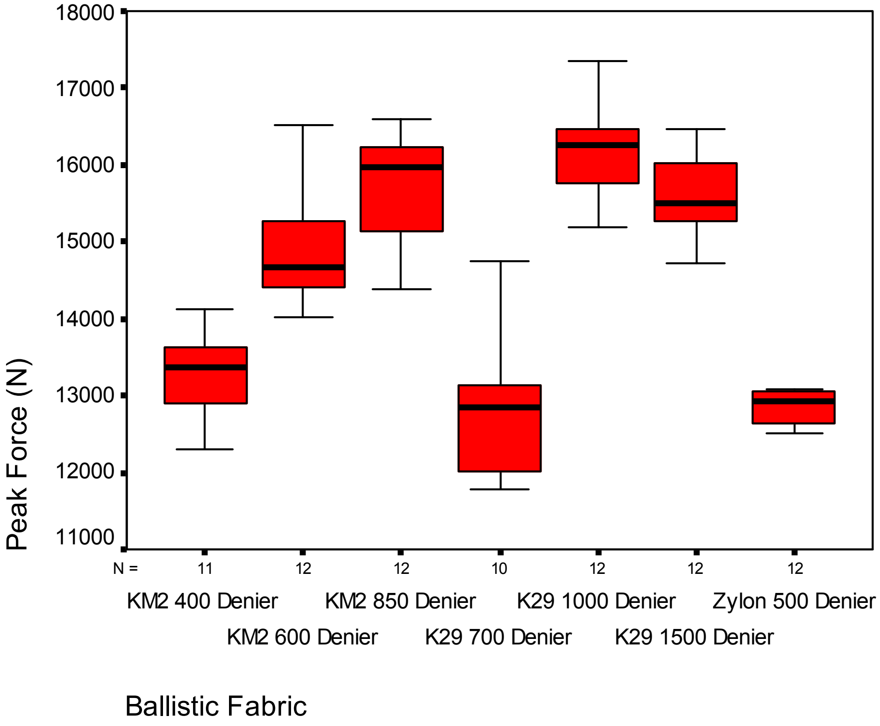

Figure 4-1 Box plot of impact tests on ballistic fabrics to show the mean and range of data.

The next set of impact tests involved the ballistic fabric materials and three different forms of ballistic plate protection. Boron Carbide (B_4C) with 119 ssp (areal density = 24.9 kg/m^2) was tested with the ballistic fabrics to look at the difference in transmitted force with the rigid plate. The ballistic plate B_4C 119 ssp showed either no change or significant reduction in average peak force versus that of ballistic fabric (Figure 4-2).

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	13487	836
Kevlar KM2® 600 Denier	12993	1045
Kevlar KM2® 850 Denier	12698	887
Kevlar® 29 700 Denier	10976	965
Kevlar® 29 1000 Denier	13156	1360
Kevlar® 29 1500 Denier	14479	1112
Zylon® 500 Denier	12126	1241

Table 4-2 Results of impact tests performed on a rigid plate and each ballistic fabric. The rigid plate consisted of the ceramic boron carbide backed with 119 plies of Spectra Shield®.

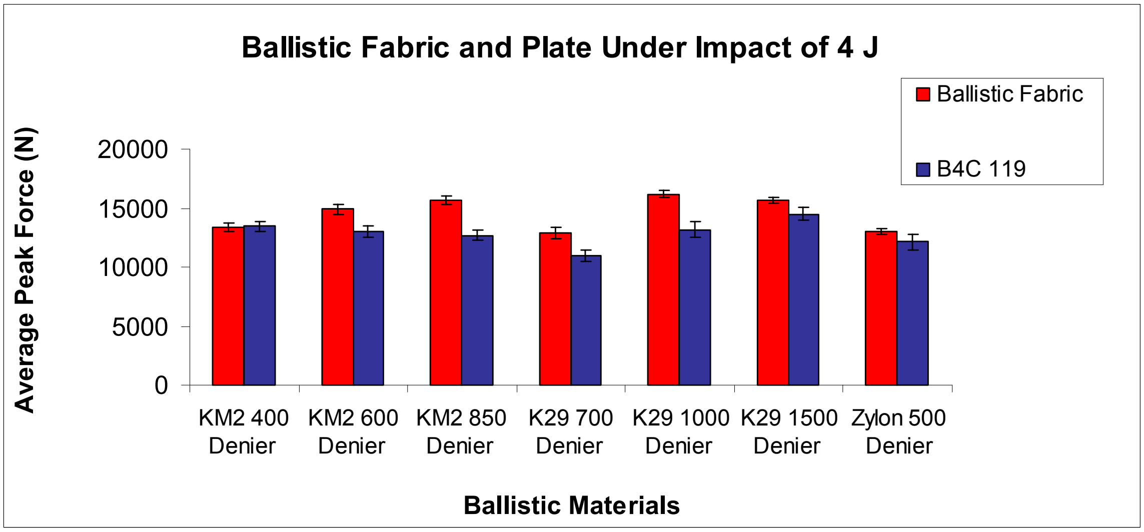

Figure 4-2 Average peak force values of ballistic fabrics and ballistic fabrics with B_4C 119 ssp.

Two different tests were performed to characterize the role of the ceramic and Spectra backing. The first test involved comparing B_4C at .5 cm in thickness (Table 4-2) and Al_2O_3 at 1 cm thick (Table 4-3) with 119 plies of Spectra Shield®. The second test was a .5 cm thick B_4C ceramic with 83 plies of Spectra Shield® as a backing (Table 4-4).

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	10355	1250
Kevlar KM2® 850 Denier	12850	768
Kevlar® 29 700 Denier	11694	757
Zylon® 500 Denier	11654	1697

Table 4-3 Results of impact tests performed aluminum oxide ceramic and 119 plies of Spectra Shield® backing.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	11935	1220
Kevlar® 29 700 Denier	12993	1134
Zylon® 500 Denier	12192	1894

Table 4-4 Results of impact tests performed on B_4C backed with 83 plies of spectra shield.

Figure 4-3 compares the different ceramics with the same Spectra backing, Kevlar KM2® 400 denier was the only configuration that showed a difference. Figure 4-4 shows the data of the ballistic fabrics with B_4C and different plies of Spectra backing. Only Kevlar® 29 700 denier showed a difference.

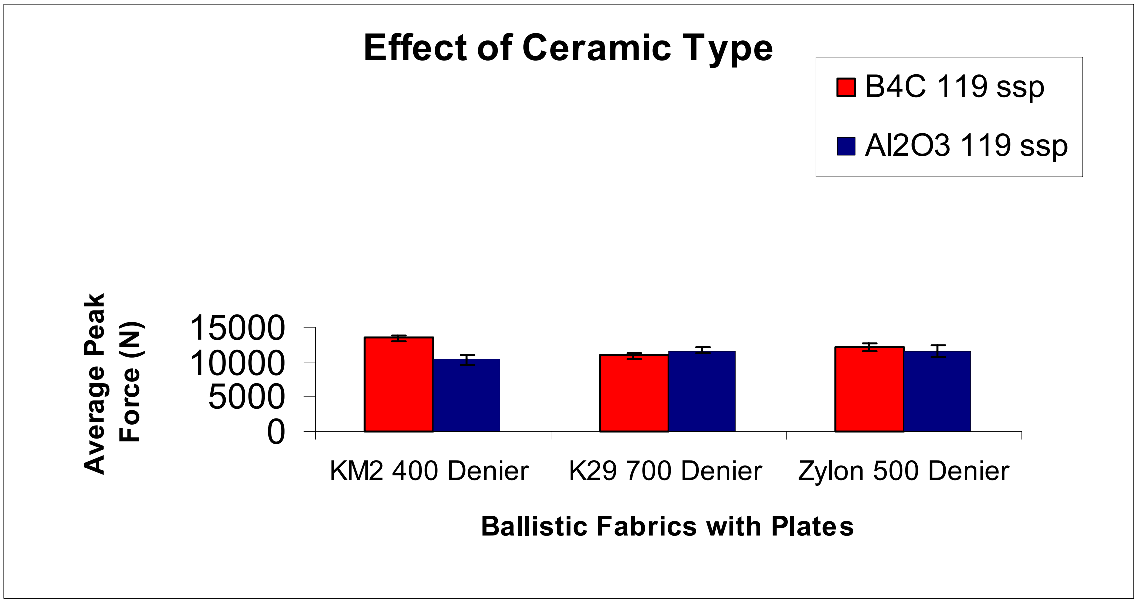

Figure 4-3 Average transmitted peak forces for aluminum oxide and boron carbide plates with the same number of spectra shield plies.

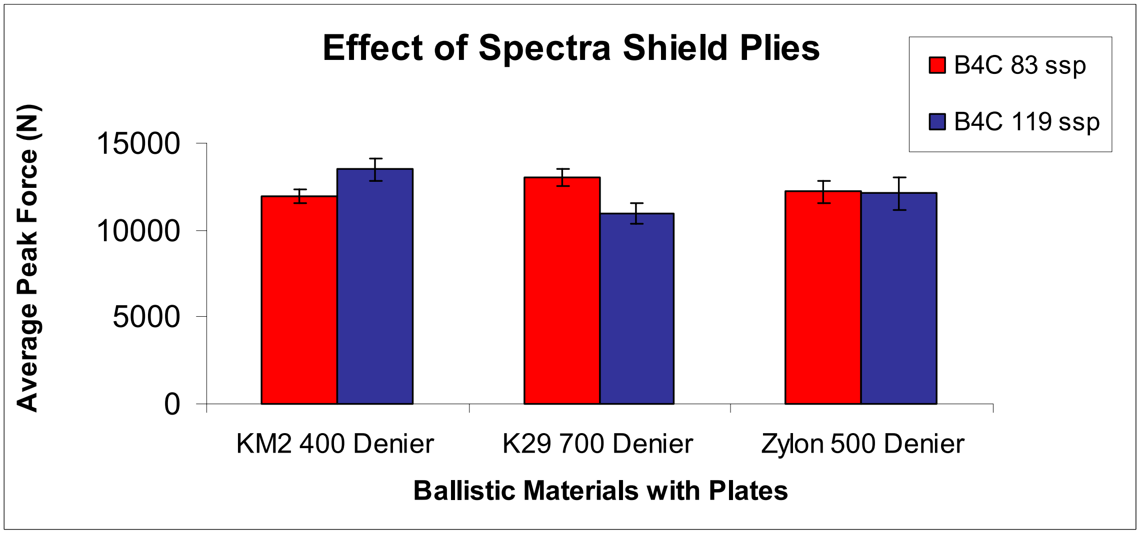

Figure 4-4 Effect of the number of spectra plies under impact.

From the preliminary studies, it was verified that the ballistic materials alone would not be able to meet the standards in regards to impact protection. Foams were introduced as a measure of observing the levels to which impact protection may be improved. The foams outlined in the experimental methods were: BF,CF 42, CF 45, CF 47, TP full, TP half, HS, LDPU. Initial tests were performed to characterize the effect of reduced transmitted force among the foam materials at an impact energy of 4 J (Table 4-5). A significant reduction in transmitted peak force occurred with the foams (Figure 4-5).

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Thickness cm*
BF	730	16	2.5
CF 42	921	53	2.5
CF 45	796	31	2.5
CF 47	756	49	2.5
HS	1810	258	1.9
TP Full	3674	316	3.8
LDPU	>20000	n/a	2.5

Table 4-5 Results of maximum transmitted force through foam materials at an impact energy of 4 J.

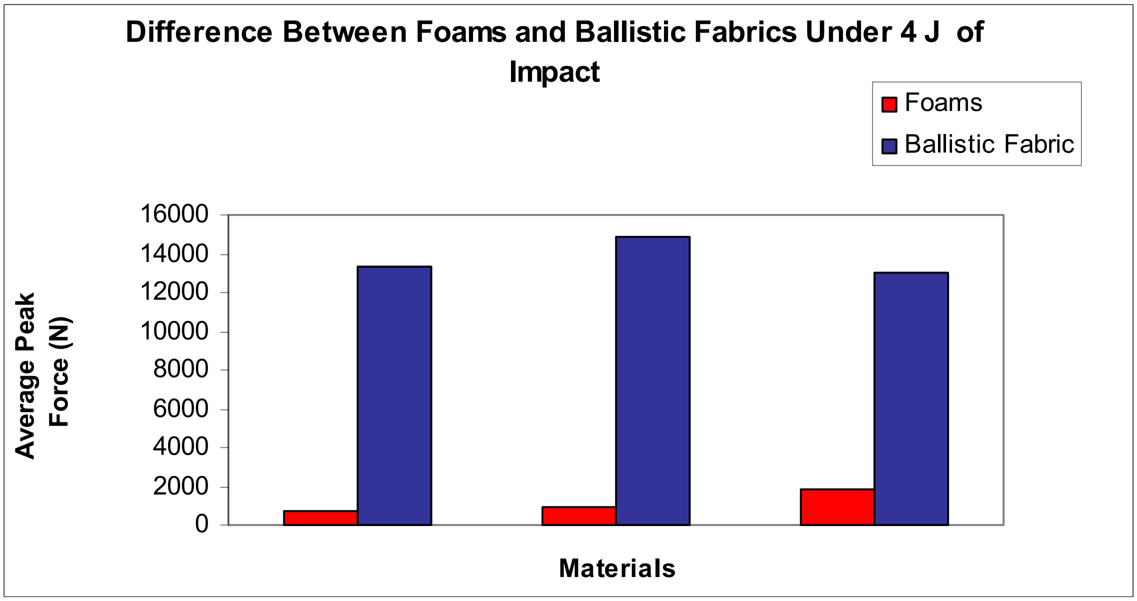

Figure 4-5 Comparison of top performing foams and ballistic fabrics to performance under impacts.

Further tests were completed to look at the effect of thickness of foam and specimen area. It was important to determine if the specimen size affected the impact performance. The first test performed was to look at the effect of thickness of a foam. Since the tempur pedic was the thickest at 3.8 cm it was tested at half its thickness (1.9

cm). A large difference was seen by changing the thickness of the foam material. The second test was performed to look at how the size of the test material may attribute to performance protection (Table 4-7). The HipSaver (HS) foam was chosen for this test due to the large quantity available. These data also showed that sample size contributes to the effectiveness in the performance of the material.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Thickness cm*
TP Full Thickness	3674	316	3.8
TP Half Thickness	>22240	n/a	1.9

Table 4-6 Results of impact tests for comparison on the effect of thickness of foam.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
HS (9 x 7.6 cm^2)	1810	258
HS (18 x 18 cm^2)	1231	90

Table 4-7 Results of impact tests for comparison on the effect of sample size.

The ballistic fabric materials were then tested with three top performing foams: BF, CF 42, and HS foam at an impact energy level of 4 J (Table 4-9). Tables 8 to 10 illustrate the performances of the ballistic fabric materials with the selected foams.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	725	22
Kevlar KM2® 850 Denier	747	9
Zylon® 500 Denier	721	13

Table 4-8 Results of impact tests with the ballistic materials and BF foam.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	745	37
Kevlar KM2® 600 Denier	762	33
Kevlar KM2® 850 Denier	765	49
Kevlar®29 700 Denier	962	28
Kevlar®29 1000 Denier	911	47
Kevlar ®29 1500 Denier	1061	62

Table 4-9 Results of impact tests with the ballistic materials and CF 42 foam.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	1242	50
Kevlar KM2® 600 Denier	1211	56
Kevlar KM2® 850 Denier	1276	82
Kevlar® 29 700 Denier	1393	80
Kevlar® 29 1000 Denier	1549	79
Kevlar® 29 1500 Denier	1489	102
Zylon® 500 Denier	1471	245

Table 4-10 Results of impact tests with the ballistic materials and HS foam.

The second part of this testing series involved evaluating all of the materials together. B_4C 119 ssp was tested with selected foams. Once again the tests were performed with the foams CF 42, HS and TP full thickness. The resulting data indicated values well below the 4 kN peak transmitted force value. Figure 4-6 shows the large improvement in peak transmitted force observed with the use of impact foams.

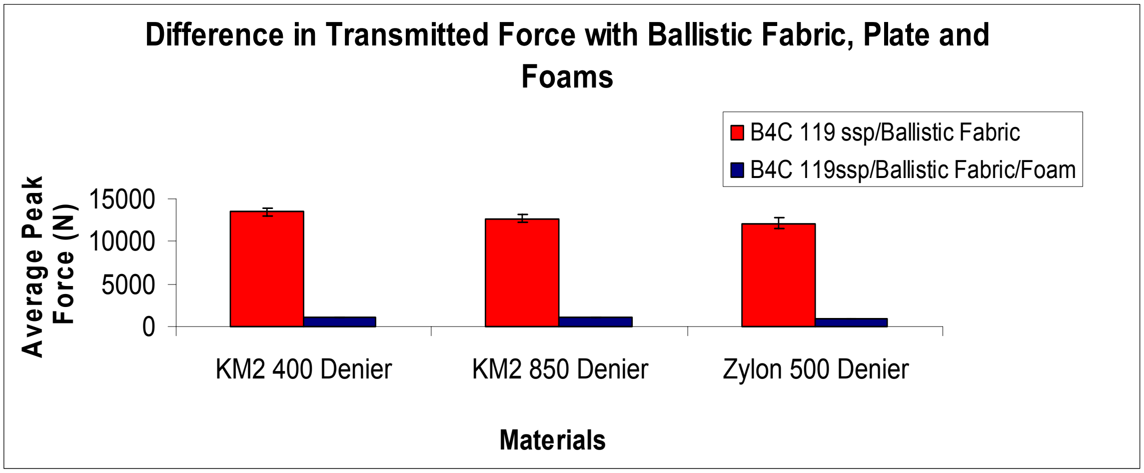

Figure 4-6 Reduction in peak transmitted force with the use of foams.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	1030	57
Kevlar KM2® 850 Denier	1041	62
Zylon® 500 Denier	987	89

Table 4-11 Results of impact tests performed with the B_4C ceramic plate and 119 plies of spectra, ballistic fabrics and BF at 4 J of impact energy.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Notes*
Kevlar KM2® 400 Denier	749	49	
Kevlar KM2® 600 Denier	807	110	
Kevlar KM2® 850 Denier	785	59	
Kevlar 29® 700 Denier	780	47	
Kevlar 29® 1000 Denier	843	50	
Kevlar 29® 1500 Denier	911	61	
Zylon® 500 Denier	1911	37	CF 42 previously damaged

Table 4-12 Results of impact tests performed with the B_4C ceramic plate and 119 plies of spectra, ballistic fabrics and CF 42 foam at 4 J of impact energy.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*
Kevlar KM2® 400 Denier	1237	62
Kevlar KM2® 600 Denier	1217	73
Kevlar KM2® 850 Denier	1280	70
Kevlar® 29 700 Denier	1339	36
Kevlar® 29 1000 Denier	1419	50
Kevlar® 29 1500 Denier	1409	43
Zylon® 500 Denier	1471	245

Table 4-13 Results of impact tests performed with the B_4C ceramic plate and 119 plies of Spectra Shield®, ballistic fabrics and HS foam at 4 J of impact energy.

4.2 Performance Specifications

The improvement in impact protection with foams allowed for further testing to look at attainable impact energies while meeting maximum allowable transmitted forces of 4 kN and 9 kN. As before, tests were performed involving: 1) ballistic fabrics/foams and 2) B_4C 119 ssp/ ballistic fabrics/foams. The BF foam showed excellent performance, by meeting a protection level 1 for EN 13158 standard.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Energy Level (J)*	*Notes*
Kevlar KM2® 850 Denier	3363	258	7	Foam Damaged

Table 4-14 Impact tests performed with Kevlar KM2® 850 denier and CF 42 foam to find the highest energy where the peak force remained under 4 kN.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Energy Level (J)*
Kevlar KM2® 400 Denier	3570	330	19
Zylon® 500 Denier	3420	442	16

Table 4-15 Impact tests performed with selected ballistic fabrics and the BF foam to find the highest energy attainable where the peak force remained under 4 kN.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Energy Level (J)*
Kevlar KM2® 400 Denier	2869	240	9
Kevlar KM2® 850 Denier	3518	276	9
Zylon® 500 Denier	3082	222	9

Table 4-16 Impact tests performed with selected ballistic fabrics and the HS foam to find the highest energy attainable where the peak force remained under 4 kN.

The following tests involved testing the ballistic plate, fabric and selected foams for the highest energy attainable without exceeding a peak force of 4 kN. Unfortunately, due to the method of plate attachment to the fabrics, it was not noticed until these tests that the B_4C ceramics were cracking under impact testing. These were localized failures of the composite, not complete failures. The spectra shield was not affected and the bond between the spectra and ceramics was not affected. Figure 4-7 and Figure 4-8 illustrate the damage done to the ceramics based on several different impacts. The cracking of the ceramic could be reasoning as to why the tests with the plate experienced large variances in results. Tests were continued with the ceramic until the twelve samples were completed.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Energy Level (J)*
Kevlar KM2® 400 Denier	3483	182	25
Kevlar KM2® 850 Denier	3363	182	22
Zylon® 500 Denier	4030	222	23

Table 4-17 Impact tests performed with selected ballistic plate, fabrics and the BF foam to find the highest energy attainable where the peak force remained under 4 kN.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Energy Level (J)*
Kevlar KM2® 400 Denier	7673	547	14
Zylon® 500 Denier	8674	921	14

Table 4-18 Impact tests performed with selected ballistic plate, fabrics and the HS foam to find the highest energy attainable where the peak force remained under 4 kN.

Material	*Avg. Peak Force (N)*	*Std. Deviation (N)*	*Energy Level (J)*
Kevlar KM2® 850 Denier	9332	716	36
Kevlar KM2® 400 Denier	6565	520	40

Table 4-19 Impact tests performed with selected ballistic plate, fabrics and the HS foam to find the highest energy attainable where the peak force remained under 9 kN.

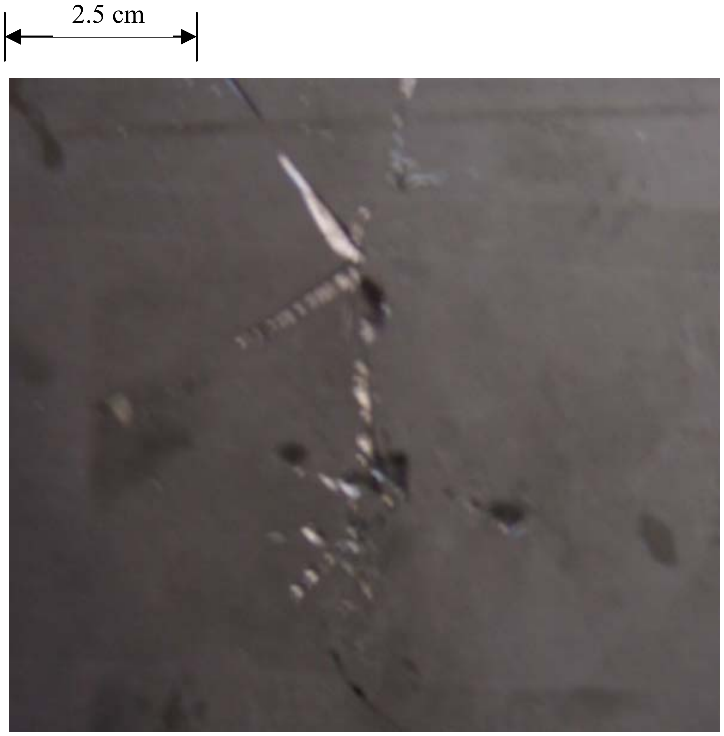

Figure 4-7 Ballistic plate with B_4C ceramic after 12 drops at 4 J

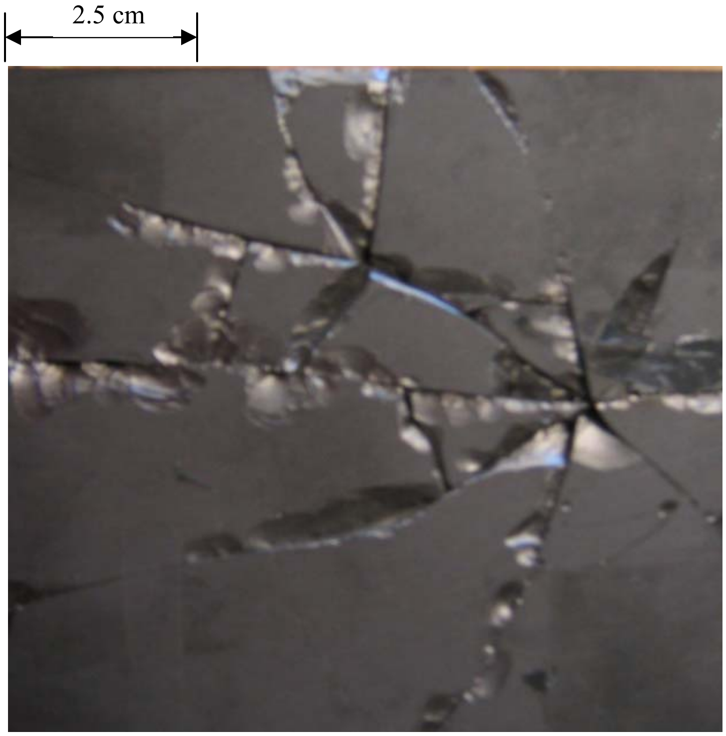

Figure 4-8 Ballistic plate with B_4C ceramic after several impacts at 14 J

During testing at these high energies it was observed that permanent deformation to the foams were occurring. Permanent deformation in the foam materials was not visible at impact tests of 4 J. Tests were continued to examine the increase in peak transmitted force over test number. This occurred when testing Kevlar KM2® 850 denier with CF 45 foam and Zylon® 500 denier with BF foam at an impact energy of 14 J.

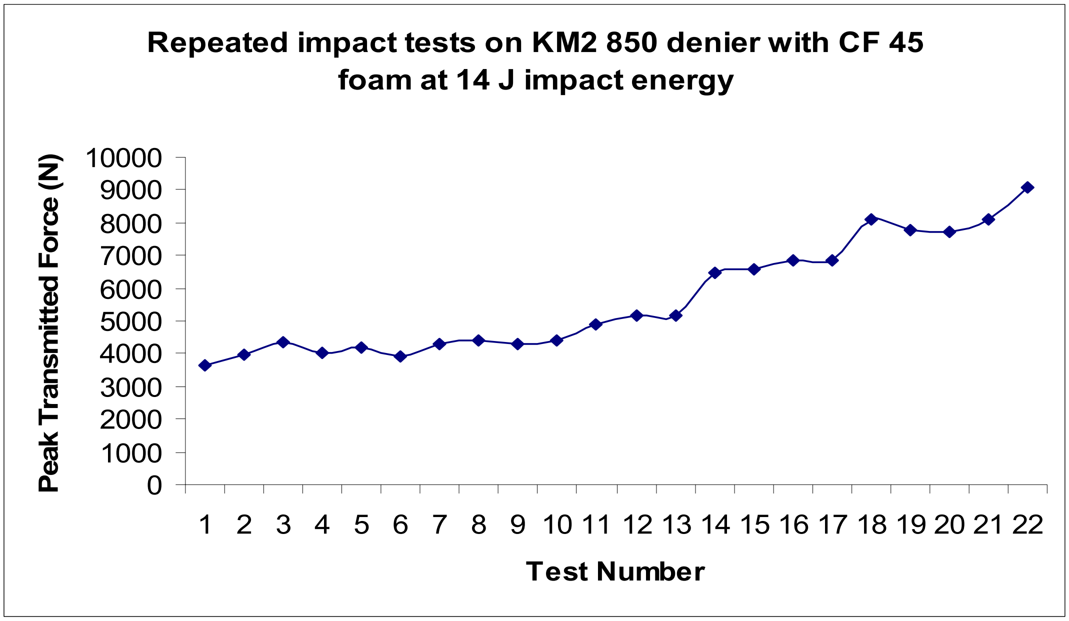

Figure 4-9 Several tests exhibiting the damage and degradation of the foam performance under a higher impact energy of 14 J.

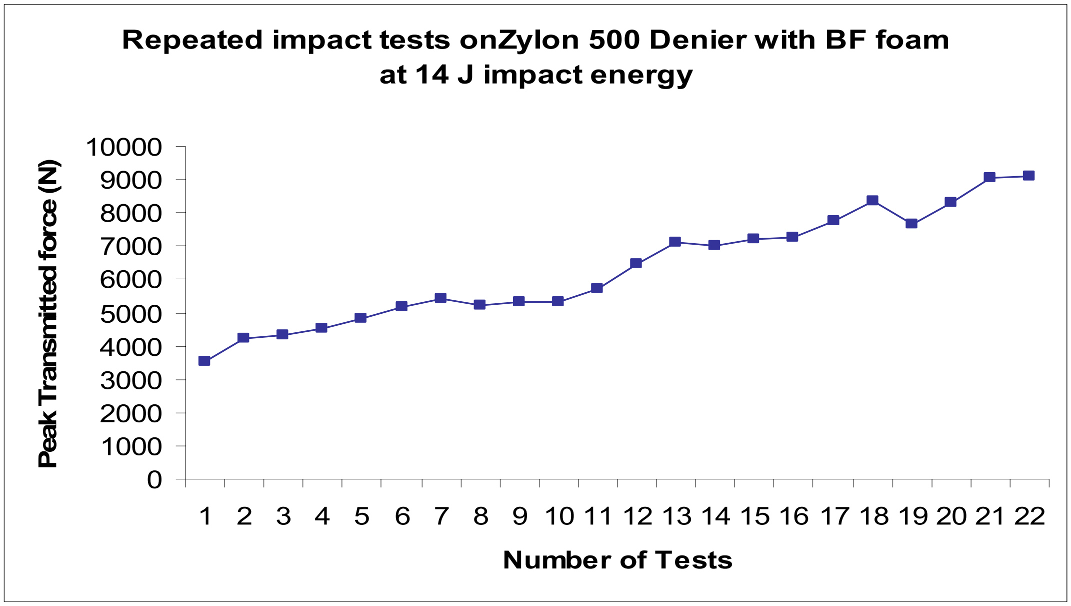

Figure 4-10 Repeated impact tests on Zylon® 500 denier with BF foam at 14 J impact energy.

4.3 Acceleration Data

Acceleration and force data were taken on the impacts involving foams, one set of ballistic fabric and one set of B_4C 119ssp/ballistic fabric data. In time, the data correlate, showing peak accelerations directly before peak force data (Figure 4-11). The data were then checked against each other using the impulse-linear momentum theorem. This simply states that the linear impulse ($\int F(t)\,dt$) = momentum ($m\int a\,dt$) where $\int a\,dt = v_2(t_2) - v_1(t_1)$ or Δv. $F(t)$ is the force of impact, m is the mass of the impacting object, a is acceleration and v is the velocity. Using the mathematical program Origin 7.0 the acceleration and force versus time data were integrated over the impact time and the values of Δv were derived from both sets of data. Assuming an inelastic collision the Δv's derived from the acceleration and force versus time data should be equal (Figure 4-12). Method 1 are the Δv values from $\int a\,dt$ and method 2 are the Δv values from linear impulse. All of the Δv values calculated from linear impulse were extremely consistent (R^2 = .96) indicating that the force data was extremely consistent. The Δv values calculated from the acceleration data did not fit as well ($R^2 = .45$). However, excluding tests 2 and 3 the Δv values derived from acceleration and linear impulse correlated well with respect to each test. This showed that the data from the force transducer is reliable.

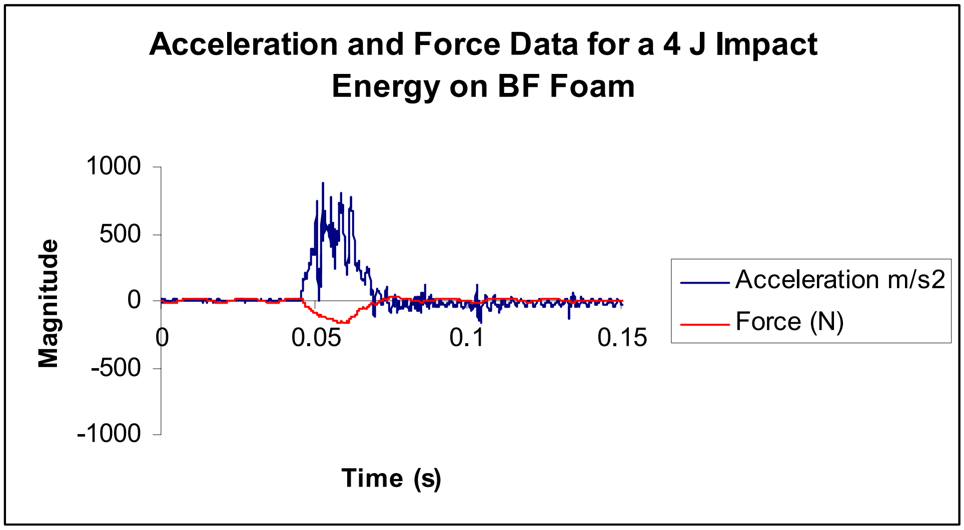

Figure 4-11 Graph of acceleration and force data for a 4 J impact on BF foam.

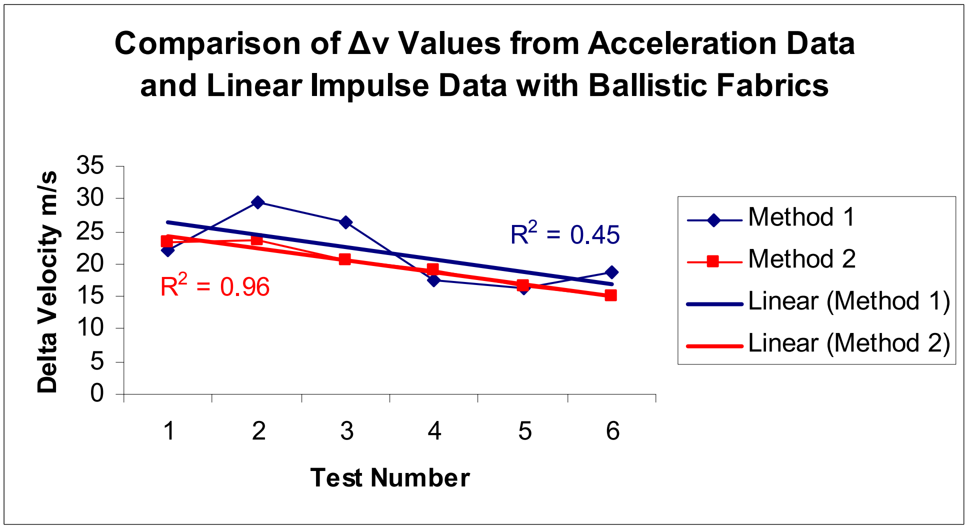

Figure 4-12 Comparison of Δv values derived from acceleration and linear impulse data.

5 Discussion

The major goals of this project were to determine a test method to evaluate the role of ballistic materials for back protection under low velocity impact. Two validated European Standards were implemented as a measure of evaluation. Tests were performed with ballistic fabrics, ballistic plates, and foams to explore avenues of lowering peak forces. This section outlines the significance of the test results and ideas for future work to improve low velocity impact protection.

5.1 Significance of results

The initial tests involved characterizing the materials at an impact energy of 4 J in five different configurations. Those configurations were: 1) ballistic fabric 2) ballistic plate/ballistic fabric 3) foams 4) ballistic fabric/foams and 5) ballistic plate/ballistic fabric/foams. In the second set of tests the top performing ballistic materials and foams were used in configurations 4 and 5 to determine the highest attainable impact energy under multiple impacts without exceeding values of 4 kN and 9 kN. These maximum energy levels were used to evaluate whether or not the materials could meet any of the standard specifications under multiple impacts.

5.1.1 Characterization of Materials

In testing the ballistic fabrics at 4 J of impact energy significant differences were observed. The overall range of peak transmitted forces for the seven ballistic fabric specimens was 12.9 – 16.2 kN (Table 4-1). Kevlar KM2® 400 denier, Kevlar® 29 700 denier and Zylon® 500 denier exhibited the lowest peak transmitted forces with ballistic fabrics with a range of 12.9 – 13.4 kN. A significant difference ($p < .001$) was observed among these ballistic fabrics versus the other Kevlar® 29 and Kevlar KM2® deniers. This was not surprising because these materials were the thickest test specimens produced (greater than .72 cm) for an areal density of 4.9 kg/m^2 (1 lb/ft^2). The thinnest pack was Kevlar® 29 1000 denier at .59 cm thick, this exhibited the highest peak transmitted force at 16.2 kN. However, a direct correlation between increasing thickness and performance could not be made because a complete trend of reduced force values versus specimen thickness was not observed among each set of data. For example, Kevlar KM2® 600 denier was the second thinnest packet of material (.66 cm thick) and had the fourth lowest transmitted force at 14.8 kN.

The addition of ballistic plate materials reduced the transmitted force observed for five out of the seven ballistic fabrics. Kevlar® 29 700 denier was reduced from an average peak force of 12.9 kN to 11 kN. Overall, the range in transmitted forces with the added B_4C 119 ssp/ballistic fabrics was 11-14.5 kN (Table 4-2), about 1.7 kN lower than with ballistic fabrics alone. However, this reduction in force was not sufficient enough to reduce peak transmitted forces below the peak force values of 4 kN or 9 kN specified by the standards. Tests performed to look at the effect of different ceramic materials and the number of Spectra Shield® plies on peak transmitted force showed no conclusive difference. A consistent trend was not observed in tests comparing Al_2O_3 and B_4C specimens (Figure 4-3). Some tests showed that Al_2O_3 reduced force better than B_4C while others showed the opposite result or no difference. This test could also be biased because the Al_2O_3 ceramic tiles were 1 cm thick and the B_4C ceramic tiles were .5 cm thick. Therefore, these tests were not an exact comparison of material performance. If Al_2O_3 ceramic tiles and B_4C ceramic tiles were the same thickness it is possible that the results may have been different. Also, no definitive conclusion could be reached relating the number of Spectra Shield® plies to transmitted force. In some instances B_4C specimens with 119 plies of Spectra Shield® reduced force better than B_4C with 83 plies of Spectra Shield®. Again the testing showed conflicting results (Figure 4-4). Larger variances in data for the ballistic plate with the ballistic fabric were observed. The average standard deviation for tests with ballistic fabrics was 700 N and for ballistic plate/ballistic fabrics it was 1 kN. An explanation for these larger variances could be the cracking of the ceramic during repeated testing. The cracks could change the level of energy dissipation, therefore affecting transmitted force readings. It was also very important to ensure that the plate was positioned properly on the anvil. If the specimen was not balanced properly on the anvil then the striker could have hit it prematurely, reducing the impact force. An example of this is shown in Figure 5-1.

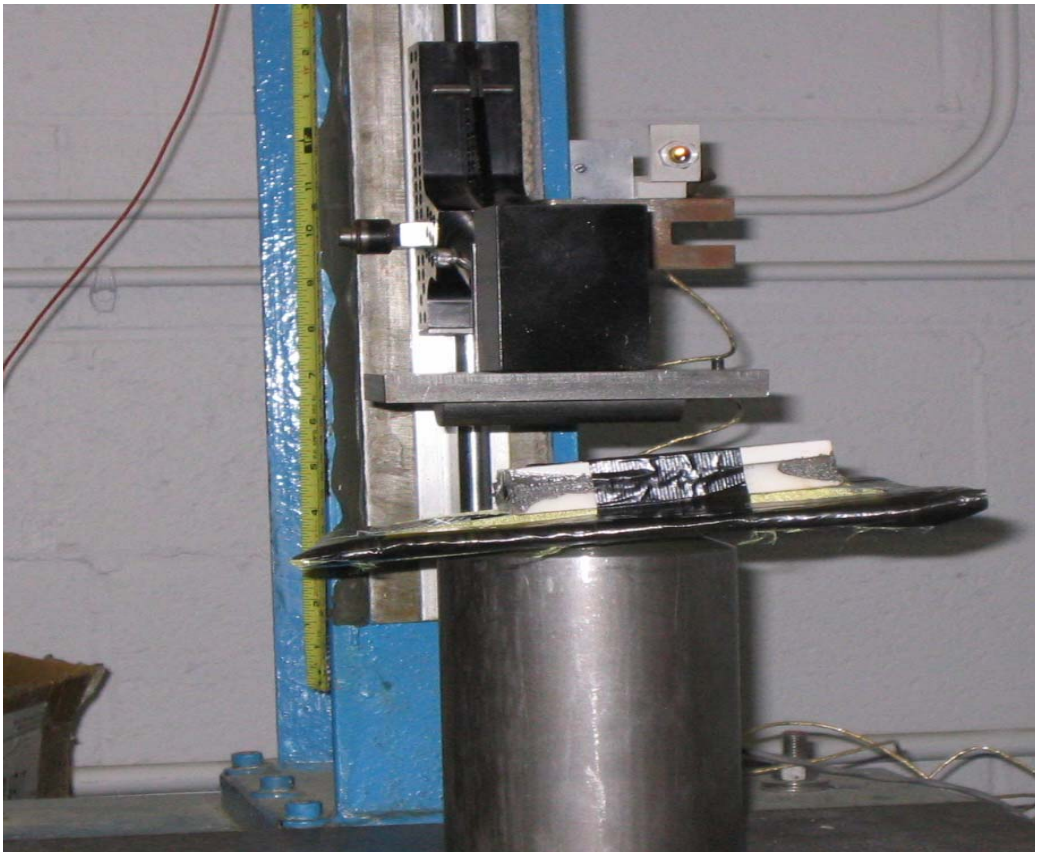

Figure 5-1 View of an unbalanced ballistic material specimen.

A power analysis was performed to determine the number of tests required to create a valid sample size for analysis on the configuration of ballistic plate materials/ballistic fabrics. Using the ballistic plate material data the power analysis showed that a test size of 12 has a power of 77%. Common statistical practice is a power of 80%, which is close to the results. Therefore in future testing more than twelve samples will be needed for each test.

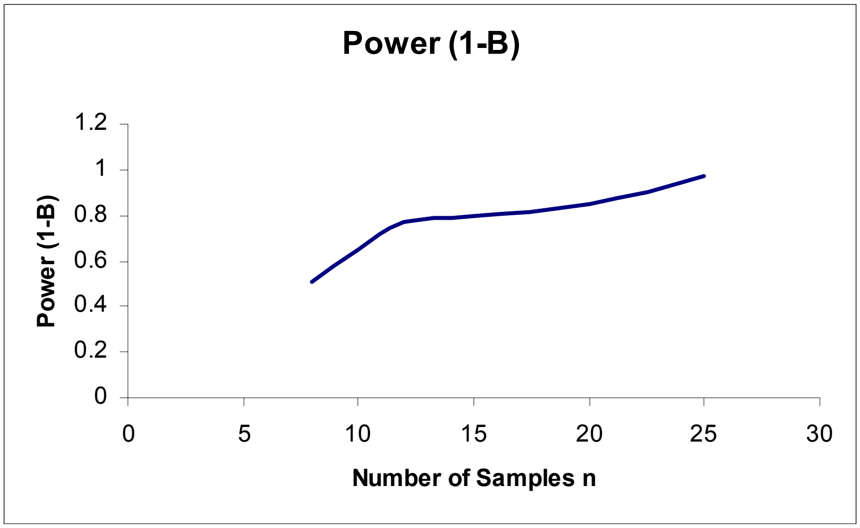

Figure 5-2 Power analysis of ballistic plate and fabric data.

The foams tested at 4 J had peak transmitted forces between .73 – 20 kN (Table 4-5). The low force values were expected because these foams were designed to provide impact protection. The peak force from LDPU was greater than 20 kN. This indicates that it is important to use a foam with a substantial stiffness that will resist deformation. The BF foams exhibited the lowest peak transmitted force at 730 N which was a reduction in peak force by a factor of 15 over the best ballistic material configuration. The performance of the BF, CF and HS foams by themselves exceeded the performance of any ballistic material configuration at peak forces below 1.8 kN. They were all within accepted force values. The addition of ballistic materials to foams further decreased the peak transmitted force. For example, the average peak force of impacts at 4 J on CF 42 was 921 N, on Kevlar KM2® 400 denier/CF 42 it was 745 N, and on B4C 119ssp/Kevlar KM2® 400 denier/CF 42 it was 749 N.

5.1.2 Performance Specifications

The second series of tests performed involved testing the BF and HS foams to maximum impact energies without exceeding 4 kN and 9 kN. The maximum energies attained were evaluated to determine if they met either performance requirements for EN 13158 or EN 1621-2. The tests performed on ballistic plate materials/ballistic fabrics/foams proved to be a successful combination of materials to meet standard levels. EN 13158 outlined three levels of protection. A Level 1 protection allowed a peak transmitted force of 4 kN at 20 J of energy. The B_4C 119 ssp plate material and BF foam with Kevlar KM2® 400 denier and Zylon® 500 denier met this level of protection (Table 4-17). The Level 2 and 3 protection measures were at energy levels of 35 J and 45 J respectively. It was not determined whether or not the second level of protection could have been met. In review of the data and performance over twelve impacts it seemed possible that the Level 2 protection could be met from one impact test. The standards only require one drop per specified location on the back and this testing was performed based on multiple impacts to the same location 45 seconds apart. Typically, the initial drop test showed a peak force about 800 N below 4 kN, a significant amount. At the higher energy levels, the foams exhibited a loss of recovery in performance under multiple impacts due to lack of significant recovery time. With increasing impacts the peak force increased in value. Figure 5-3 shows the degradation in the performance of Kevlar KM2® 400 denier/BF foam. At the initial impact the peak transmitted force was 3 kN and by the 12th impact the peak transmitted force was 4 kN. The literature shows that viscoelastic foams can have complete strain recovery if allowed 24 hours in recovery time (Figure 5-4). This was not feasible for the testing time allotted and attributed to the increase in peak transmitted force. The average values over twelve impacts were higher than the initial transmitted peak force. Therefore, obtaining higher energy levels under one impact is possible. However, it was important to study the effect of multiple impacts because a soldier's equipment will experience many low velocity impacts and it is not feasible to have a piece of armor which is a one time protective system.

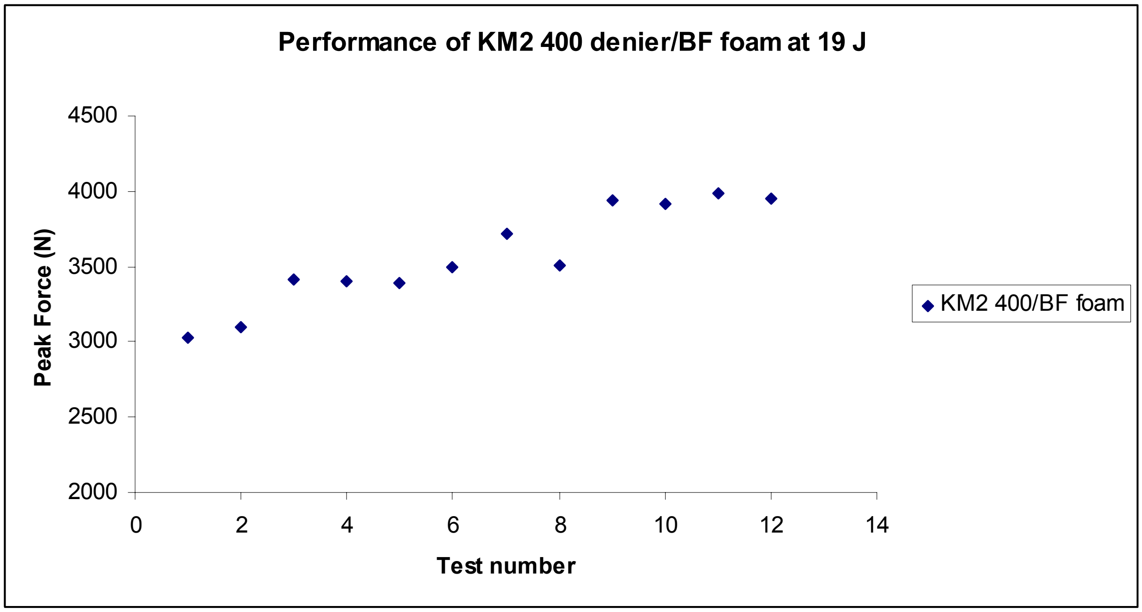

Figure 5-3 Performance of Kevlar KM2® 400 denier/BF foam at 19 J over multiple impacts. The peak force increases over multiple impacts.

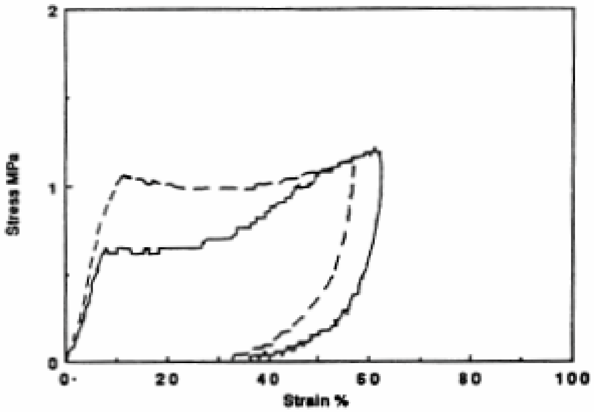

Figure 5-4 The stress-strain curves of High Density Polyethylene (HDPE) under two impacts. The foam was impacted a second time after complete recovery (Cunningham, 1994).

Finally, none of the tests performed showed whether the ballistic materials and BF foam could have met the 9 kN level at 50 J. Kevlar KM2® 400 denier had a peak force of 6.5 kN over twelve consecutive drops at 40 J (Table 4-19). As shown in Figure 5-5 the peak force of the initial impact was 5.5 kN and the 12th impact was 7.5 kN. From this data it is possible that the materials would have been below a peak force of 9 kN at 50 J for one drop. Overall, the foams provided a significant improvement in protection to the back under impact with the ballistic materials.

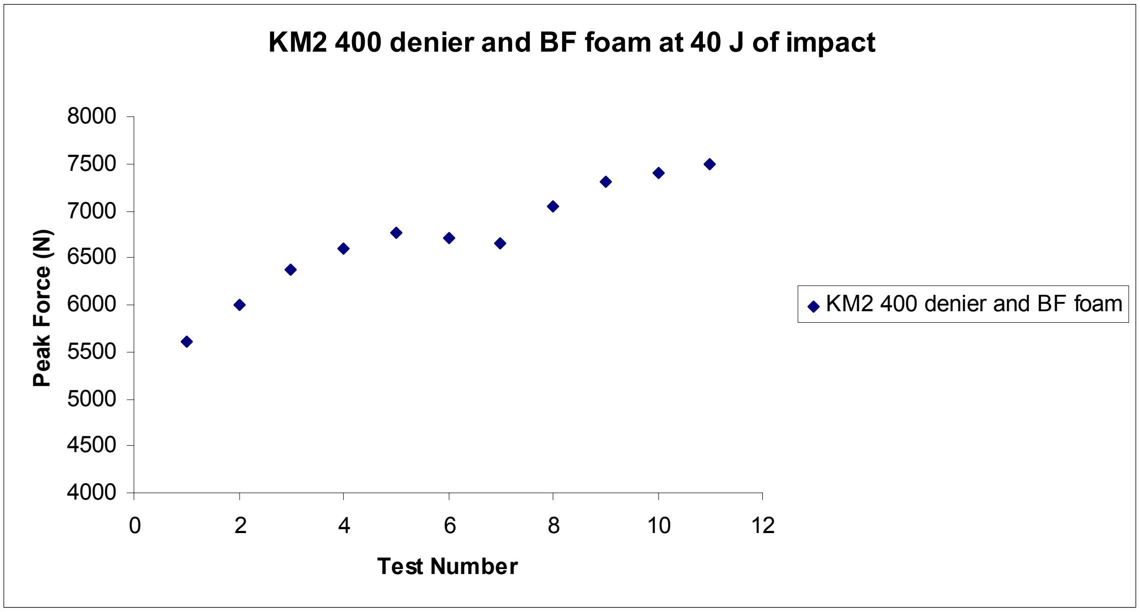

Figure 5-5 Performance of KM2 400 denier/BF foam at 40 J over multiple impacts. The peak force increased by 2 kN over twelve impacts.

5.1.3 Test Method

The test method itself was an important step into exploring the potential of improved material systems for low velocity impact. However, limitations to this method do exist. The method for evaluation was transmitted force through point contact onto a steel anvil. While these standards were developed in relation to injury, they do not directly investigate the performance of the shaped ballistic materials in coordination with the body. It is important to understand how the actual shape of the ballistic body armor interacts with the back under impact. A test system has been under development to account for the load spreading of the system. This may be a more effective manner to evaluate a protective material system as a whole (Figure 5-6). A series of segmented aluminum blocks are used to represent the vertebrae in the spinal column. The aluminum blocks are attached to each other by hinges to mimic the flexibility of the spine. The rubber crumb is used to mimic the deflection of the body. Pressure transducers were used to evaluate the load dispersed over the vertebrae under impact (Cunningham, 1994). This technique is an advancement in exploring more effective measures of incorporating the dynamic reaction of the spine and back under impact.

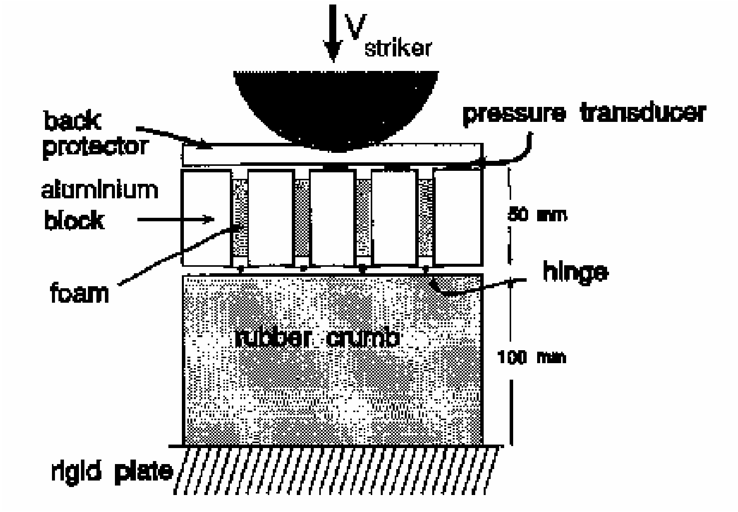

Figure 5-6 The flexible spine test rig measures the force distributed over the aluminum blocks (Cunningham, 1994).

5.2 Future Work

Two main points were derived from the tests. The ballistic materials alone were not an adequate system to reduce force in low velocity impacts and foams should be investigated as a material to reduce force. A number of foams exist that differ in material type, cell structure, density and stiffness. Parameters should now be defined to narrow the selection of foams for future testing. For instance, weight limitations, performance levels and reaction to environmental settings are all important factors that must be investigated.

Presently, the soldiers carry a large amount of weight with their equipment, and any addition to weight must be seriously considered. A weight limit is necessary to help narrow the foam base material and densities that are feasible to use. A balance between the foam base material, stiffness, and density is needed to obtain the necessary protection levels with the smallest amount of additional weight. As shown from the testing a foam higher in density does not signify an improvement in performance under impact. The microstructure of the foam (cell size and wall thickness) can change the density and/or stiffness which will affect its performance under impact. Environmental effects on the impact performance of foams are important to consider as well. Tests were performed on the foams at room temperature but a soldier is often exposed to extreme temperature conditions. These conditions have been shown to affect the performance of foams. For instance, low temperatures decrease the effectiveness of foam in reducing transmitted force (Figure 5-7). Therefore it is important to investigate the performance of a foam in several environment conditions. Foams also exhibit different performance levels with thickness. An increase in the thickness of a foam will improve impact protection. However, it is not feasible to have a foam that is 10 cm thick. There is a limit to providing impact protection by increasing thickness. This is shown in Figure 5-8 where the difference in performance between the same foam at 25 mm and 50 mm is large, but the difference between 50 mm and 100 mm is not significant.

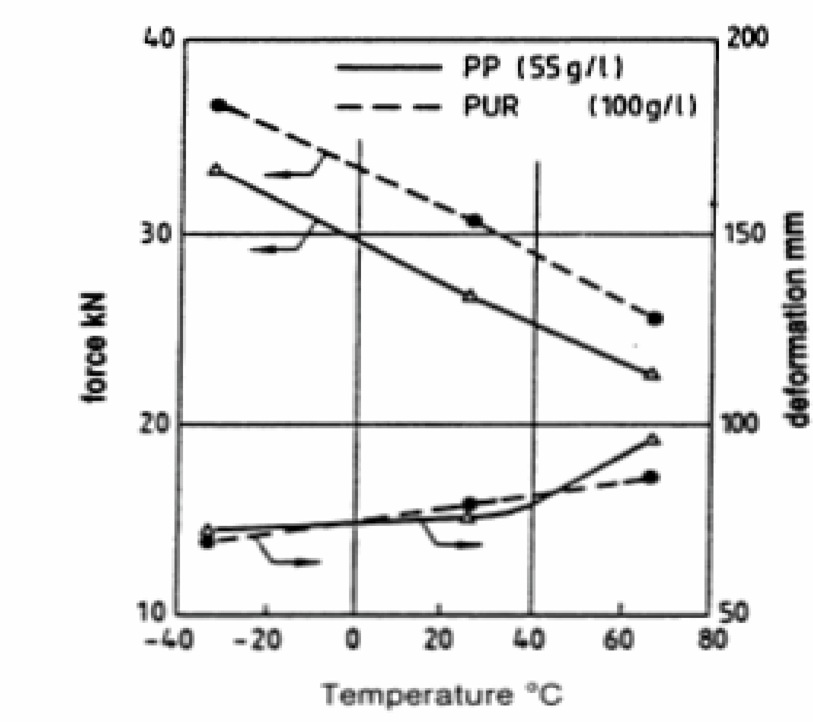

Figure 5-7 The change in temperature affected the peak transmitted force for both Polypropylene (PP) foam and Polyurethane (PUR) foam. At colder temperatures the performance degrades (Cunningham, 1994).

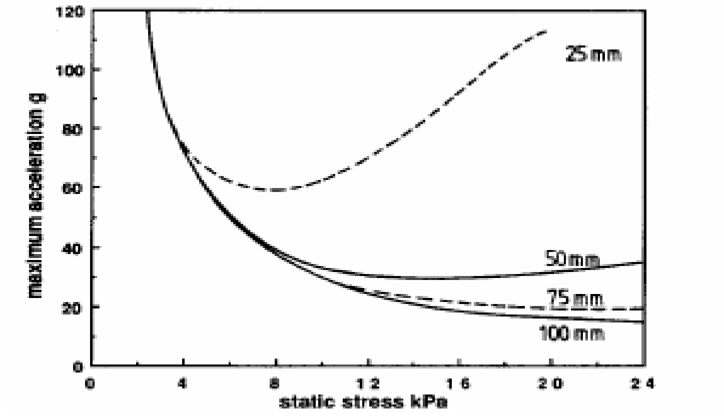

Figure 5-8 The cushion curve for Low Density Polyethylene (LDPE) (density = 70 kg/m^3) at varying thicknesses (Cunningham, 1994).

A level of multiple impact performance for the protective material system should also be identified. As shown in Figure 5-3 and Figure 5-5 the foams will degrade over multiple impacts if not allowed sufficient recovery time. A soldier's equipment will experience many low velocity impacts over time. The level of multiple impacts should be identified to determine the level which materials should be tested to. In general, the design parameters for improved impact protection need to be outlined in order to determine the best fitting foam that does not hinder the soldiers' capabilities and improves impact protection to a level of safety

Other areas where foams may provide improvements should be investigated. The ballistic plates are designed to have a maximum Back Face Signature (BFS) of 40 mm. The BFS is a measure of the deformation of the back face of the plate (fiber reinforced side) where a bullet has hit. A layer of foam could help reduce the force transmitted by the bullet through the BFS. A common occurrence among soldiers after being hit in the ballistic plate is bruising around the area from the large impact force which the bullet caused when hitting the plate and not penetrating the body. Again, the foams could help reduce the bruising by providing impact protection underneath the plate.

Further investigation into evaluating an entire ballistic vest and plate system with the back may provide more detail on the interaction of the materials with the body. Test methods should be investigated that account for the reaction of the body under impact situations. The proposed test method discussed utilizing segmented aluminum blocks is an example of this. It is an advanced attempt to identify how the back protection materials work with the back.

6 Conclusions

The major goals of this project were to 1) identify the risks and levels of injury associated with low velocity impacts to the back 2) determine a test method to evaluate ballistic materials in relation to levels of safety and 3) evaluate ballistic materials in relation to the levels of safety. Methods used today to evaluate back protectors for horse riders (EN 13158) and motorcyclists (EN 1621-2) were implemented in order to assess material performance under low velocity impacts. These test methods related values of force transmission through materials to levels of safety. Peak forces of 4 kN and 9 kN were identified as the minimum levels of safety through the literature and performance requirements of the standards.

Experiments were conducted at an energy level of 4 J to compare the performance of ballistic materials and additional impact protective foams. A total of five configurations were tested in the following order 1) ballistic fabrics 2) ballistic plates/ballistic fabrics 3) foams 4) ballistic fabrics/foams 5) ballistic plate/ballistic fabrics/foams. At 4 J the ballistic materials showed peak transmitted forces above 11 kN. This was not an acceptable transmitted force at any energy level. The use of foams showed a large improvement in performance. The best performing ballistic and foam materials in configurations four and five were tested at higher energy levels until peak transmitted forces of 4 kN or 9 kN were reached. Energy levels of 25 J at a peak force of 3.5 kN and 40 J with a peak force at 6.5 kN were obtained. This reduction in force met the minimum performance requirements outlined by a Level 1 protection for EN 13158.

The significant improvement in low velocity impact protection the foams provided, indicate that it is possible to meet the highest levels of safety outlined by the standards. The establishment of a test set up and the assessment of several ballistic materials and foams provided a basis for future research into low velocity impact protection.

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8 APPENDIX A EN 1621-2

Overview of EN 1621-2

The European Standard EN 1621-2 states that it "specifies the minimum coverage to be provided by motorcyclists' back protectors worn by riders in normal traffic situations. The standard contains the requirements for the performance of the protectors under impact and details of the test methods. Requirements for sizing, ergonomic requirements, and requirements for innocuousness, labeling and the provision of information are all included". The following information is an overview of several of the specifications from this standard. The standard outlines several other specifications which must be met including ergonomic structure to ensure the comfort of the garment.

A. *Zone of protection based upon Figure 8-1.*

	Waist to Shoulder	A	B	C	D
Control Dimension of User	100%		Waist to shoulder		
Minimum Zone of Protection	510 mm	72.5 %	29.4%	44%	29.4%

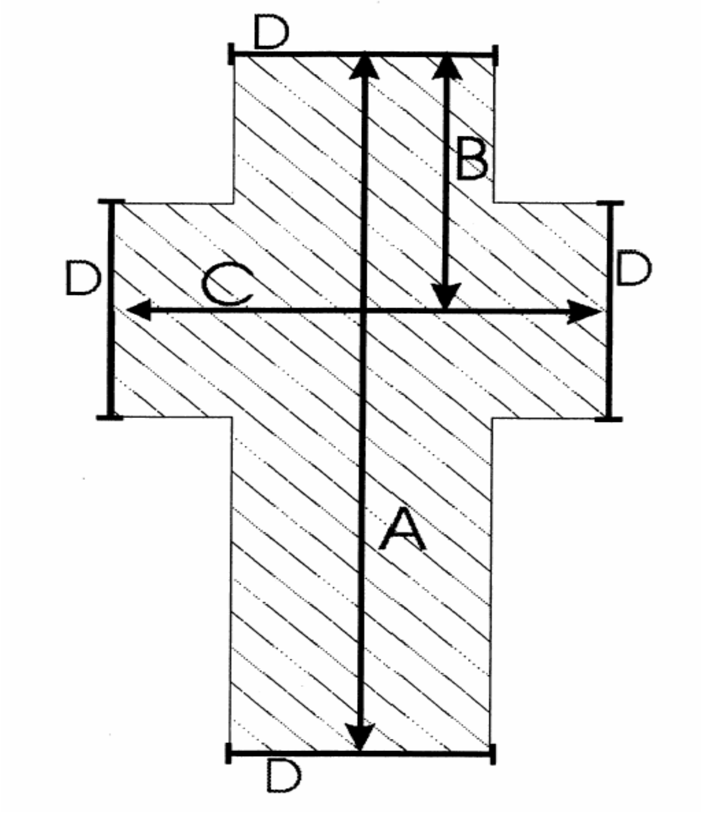


Figure 8-1 Minimum size requirements for the zone of protection on the back based upon a torso length of 510 mm (EN 1621-2).

B. *Levels of Protection*

The standard outlines two levels of protection based on different peak transmitted forces at one impact energy (50 J).

Level 1 Protectors: The average peak force should be below 18 kN, and no single value should exceed 24 kN.

Level 2 Protectors: The average peak force should be below 9 kN and no single value should exceed 12 kN.

C. *Test Equipment*

Dropping Apparatus: The falling weight must be released along a guided vertical path where the center of mass of the falling weight is over the center of the anvil.

Bar Impactor: The bar impact is cylindrical, 80 mm ± 2mm in length, and 50 mm ± 1 mm in diameter. The mass of the impactor should be 5000 g ± 25 g.

Anvil: The anvil must be made of polished steel and bolted to a mass of 1000 g.

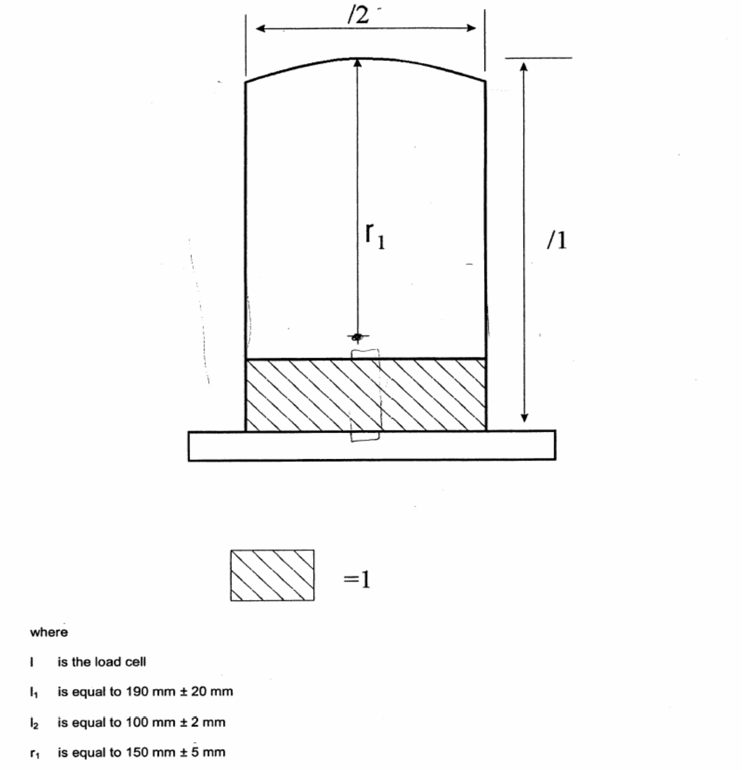


Figure 8-2 Dimensions for the anvil used to represent the back.

Force Measurement Instrumentation: A quartz force transducer should be used to gather the peak transmitted force through the material. It should have a calibrated range of 50 kN and a threshold of less than .5 kN. The output should be processed by a charge amplifier. The recording capabilities should either be peak force detection or continuous force time recorded. The digital sampling rate should be set to 10 kHz.

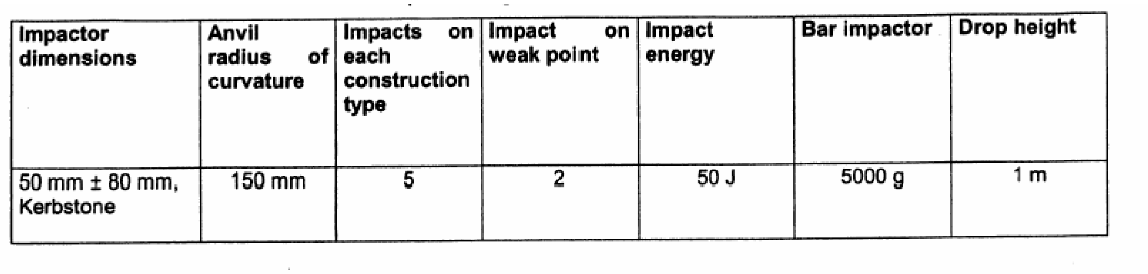
The entire measuring system should have a frequency response according to channel frequency class (CFC) 1000 of ISO 6487.

C. *Test Method*

Preconditioning and test atmosphere: Back protectors should be preconditioned according to the requirements indicated in EN 1621-1.

Measurements and marking: The dimensions needed for the minimum zone of protection are based upon the individuals torso length. Stated size markings will determine the templates used for samples showing the minimum zone of protection. The templates will be used to mark the minimum zone of protection on the back protector itself. Any points that appear weak should also be marked specifically.

Number of tests: The impact tests should be performed based on outline in Table 8-1. The impacts should be dispersed over the protectors. The centers of the impacts can be no more than 90 mm apart. A total of five impacts on one back protector should be performed. One should be 40 mm from the perimeter line, one should be 60 mm from the perimeter line and one should be at the center of the zone of protection. Two single impacts must be made on locations considered to be weak points.



Impactor dimensions	Anvil radius of curvature	Impacts on each construction type	Impact on weak point	Impact energy	Bar impactor	Drop height
50 mm ± 80 mm, Kerbstone	150 mm	5	2	50 J	5000 g	1 m

Table 8-1 Outline for the specifications of testing motorcycle back protectors (EN 1621-2).

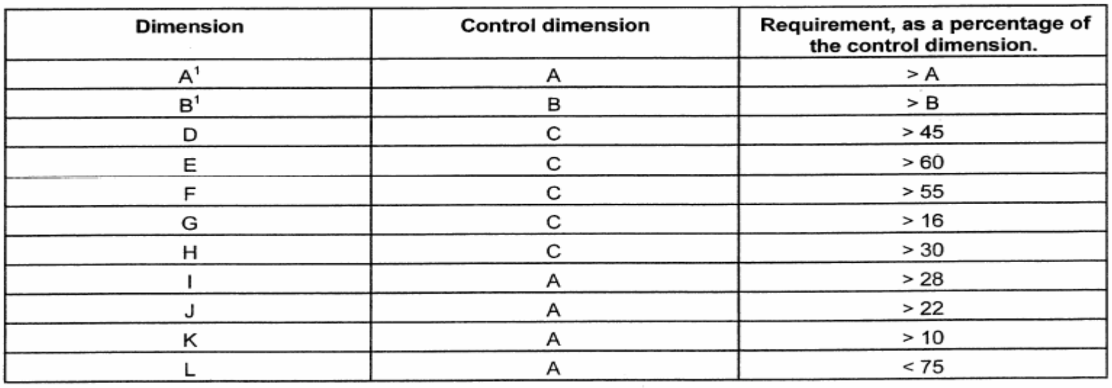
Test Report: A specific outline for the test report is needed and the back protector must be marked in locations with the symbols outlined by the standard.

9 APPENDIX B EN 13158

Overview of EN 13158

The European Standard EN 13158 states that it “specifies the coverage to be provided by protective jackets, body, and should protectors to be worn by children, youths, and adults of either sex while riding horses. The standard contains the requirements for the performance of the protectors under impact and details of the test methods. Requirements for sizing, marking and the provision of information are given”. The following information is an overview of several of the impact test specifications from this standard. The standard outlines several other specifications which must be met including durability and comfort of the garment.

A. ***Zone of Protection based on*** Figure 9-1.



Dimension	Control dimension	Requirement, as a percentage of the control dimension.
A^1	A	> A
B^1	B	> B
D	C	> 45
E	C	> 60
F	C	> 55
G	C	> 16
H	C	> 30
I	A	> 28
J	A	> 22
K	A	> 10
L	A	< 75

Figure 9-1 Dimensions outlined for a body protector worn by a horse rider.

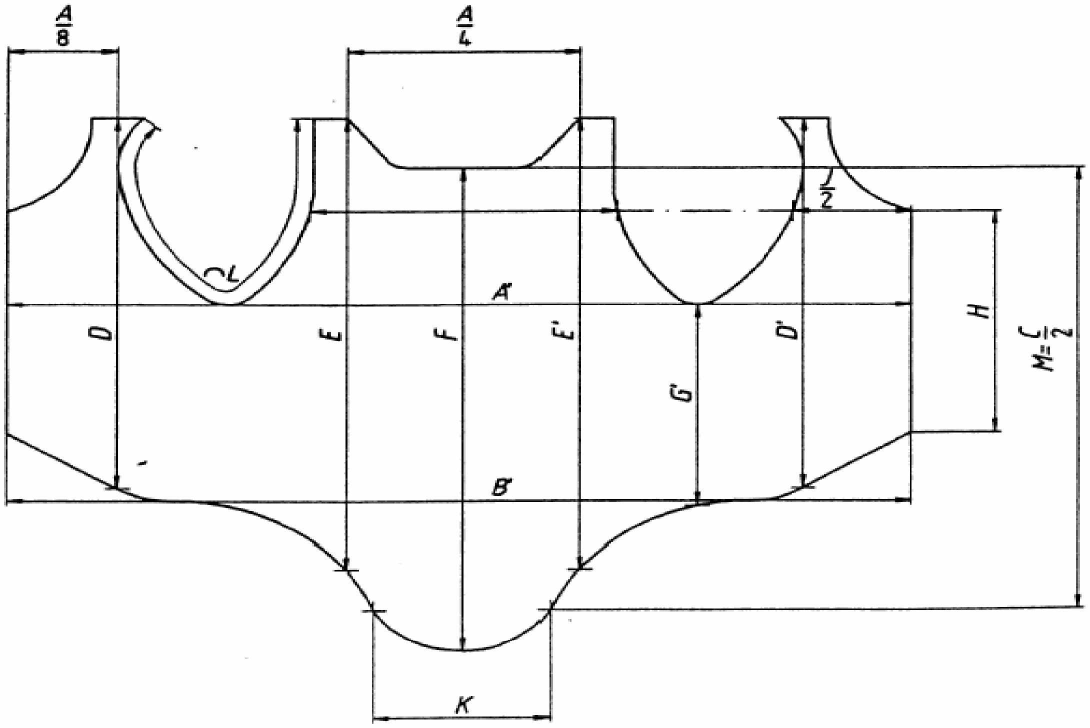


Figure 9-2 Identification of the dimensions needed to provide shoulder and back protection in horse rider equipment.

The values of the dimensions are based on several measurements which include an individuals chest and back length.

B. Levels of Protection

The levels of protection are identified in three levels. There are three different impact energies and only one acceptable level of peak transmitted force at 4 kN. There are three different impactors. The flat impactor (2.5 kg) is to mimic a horse hoof, the narrow bar impactor (2.5 kg) is to mimic general objects, the wide bar impactor (5 kg) is to mimic general objects at a larger mass.

Test Conditions	**Impact energy for the performance level (J)**		
	Level 1	***Level 2***	***Level 3***
Flat impactor, body protector	25	30	35
Narrow Bar Impactor, body protector	20	32.5	45
Wide Bar, shoulder protector	60	60	60

C. Test Equipment

The narrow bar impactor is cylindrical, 80 ± 2 mm in length and 20 ± 1 mm in diameter. The anvil shall have a 150 ± 5 mm radius domed top. And a guard ring should be placed around it and adjusted to 10 ± .2 mm above the anvil shown in Figure 9-3.

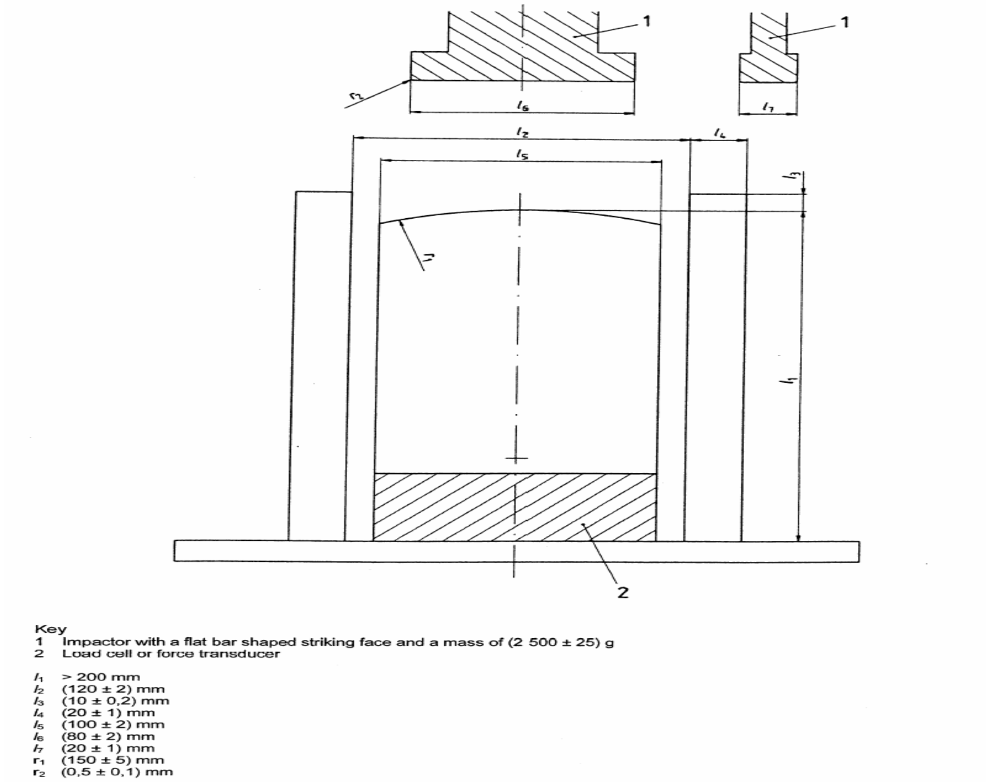


Figure 9-3 Dimensions of the anvil and guard ring used for the narrow bar impactor testing (EN 13158).

Force Measurement Instrumentation: A quartz force transducer should be used to gather the peak transmitted force through the material. It should have a calibrated range of 50 kN and a threshold of less than .5 kN. The output should be processed by a charge amplifier. The recording capabilities should either be peak force detection or continuous force time recorded. The digital sampling rate should be set to 10 kHz.

D. Test Method

Preconditioning and test atmosphere: Back protectors should be preconditioned at 20 ± 2 C and 65 ± 5 % humidity for a minimum of 48 hours before testing. Testing must be performed in that environment or within 10 minutes of removing the material from that area.

Measurements and markings: For testing the body protections should be cut into pieces 200 mm wide. The cut edges should be bound with adhesive tape. Any sites that appear visibly weaker than others should be marked "worst cases". If areas are found to be weaker during testing then each of those areas should be tested with at least six impacts.

Test Results: The results must be submitted in a formal report. Markings on the garments must adhere to the outlines identified by the standard.

10 APPENDIX C ProEngineer Drawings

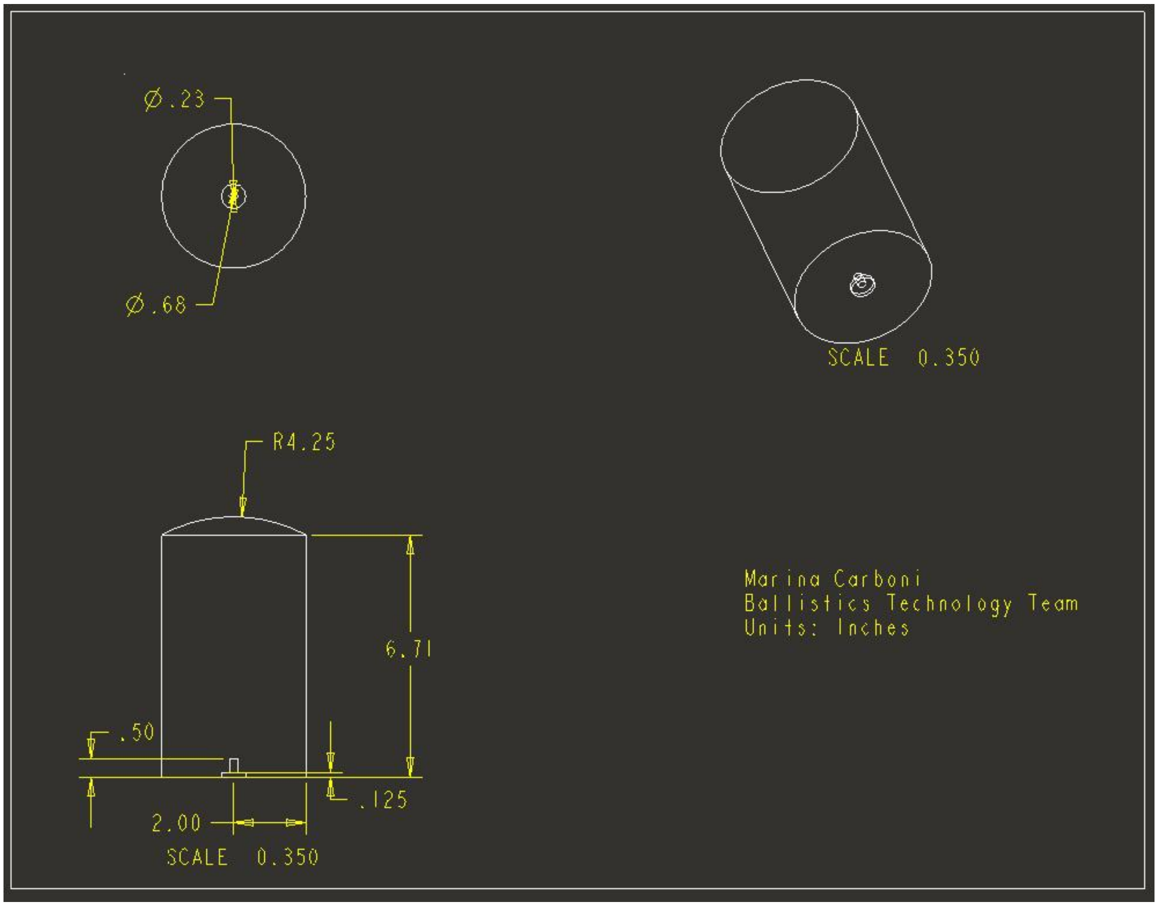


Figure 10-1 Drawing views of anvil.

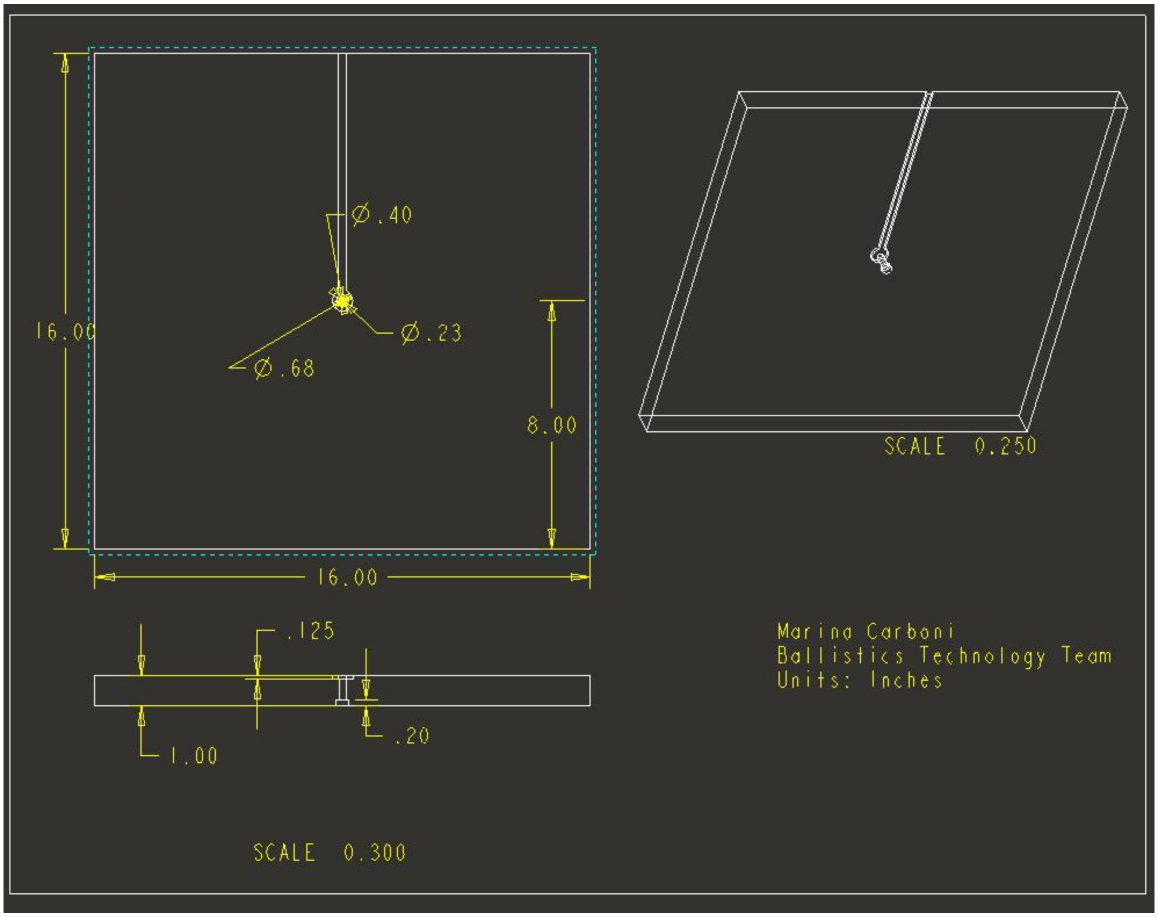
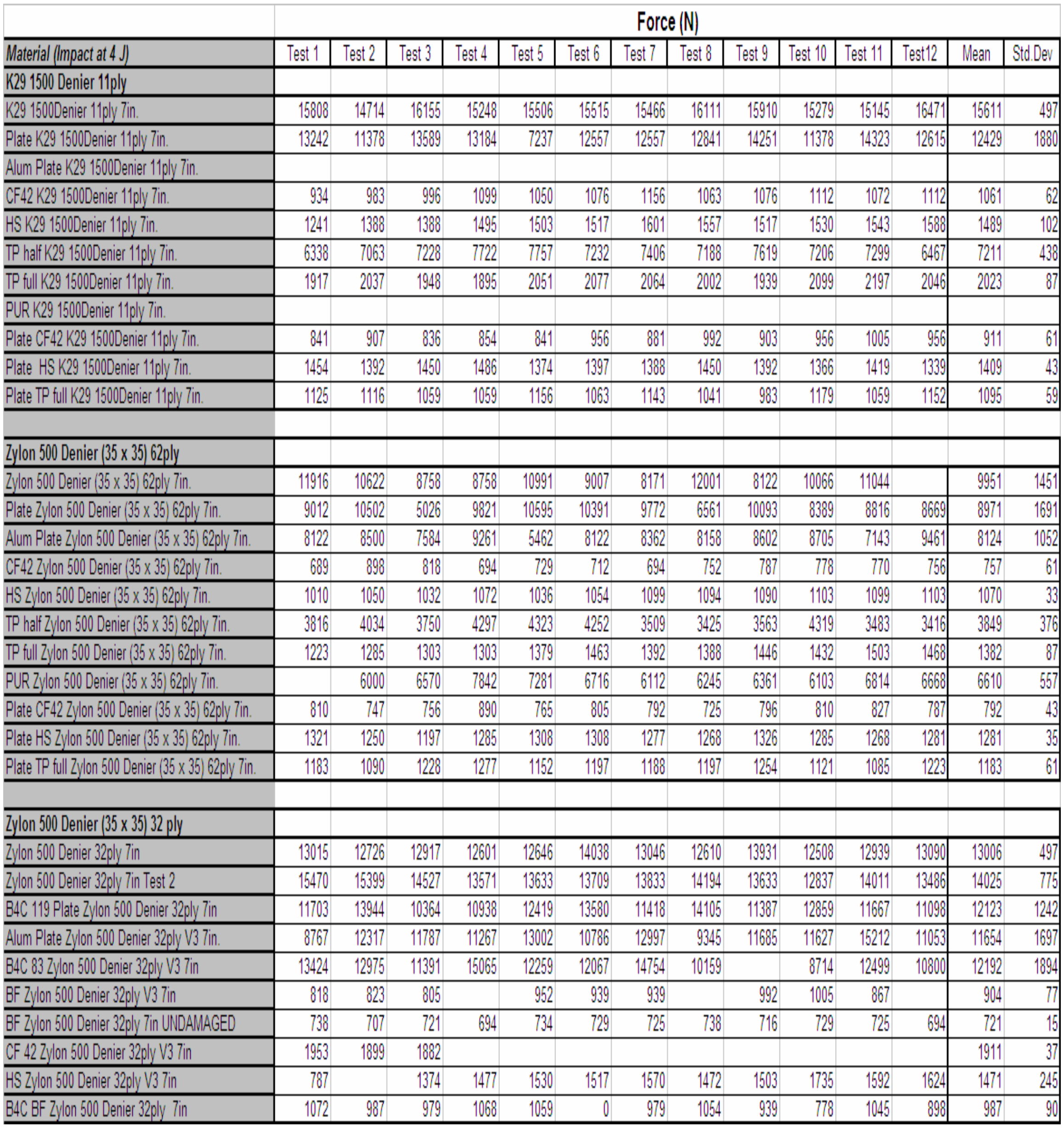


Figure 10-2 Drawing views of the holder. The .68" hole is for the force transducer to rest in the base, it will be assembled together using a screw. The slot allows for the wire to run from the transducer to the charge amplifier.

11 APPENDIX D Test Data

	Force (N)													
Material (Impact at 4 J)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
KM2 400Denier 48 plies														
KM2 400Denier 48 ply 7in.	13722	13188	13509	12846	13517	14131	12930	12294	12405	13380	14901		13348	753
B4C 119 Plate KM2 400Denier 48 ply 7in.	13544	12979	14145	13838	13722	12815	13998	13162	13211	14856	14025	11547	13487	836
B4C 83 Plate KM2 400Denier 48 ply 7in.	12890	13144	13357	10724	11640	11974	9501	12499	12521	10715	11062	13188	11935	1219
Alum Plate KM2 400Denier 48 ply 7in.	10782	9617	11391	11249	9439	8771	9581	11560	11507	11738		8260	10354	1250
BF KM2 400Denier 48 ply 7in.	707	729	707	734	707	716	774	689	694	716			717	24
BF KM2 400Denier 48 ply 7in. V2	747	721	729	703	734	725	752	743	752	703			731	18
CF 42 KM2 400Denier 48 ply 7in.	721	716	716	721	743	703	743	707	778	783	805	801	745	37
HS KM2 400Denier 48 ply 7in.	1143	1161	1232	1303	1241	1290	1205	1299	1263	1259	1254	1250	1242	50
TP half KM2 400Denier 48 ply 7in.	5195	4790	5658	4426	5298	6031	5533	5978	5146	6116	4355	5836	5364	606
TP full KM2 400Denier 48 ply 7in.	1303	1352	1428	1437	1437	1486	1606	1481	1481	1557	1495	1579	1470	88
PUR KM2 400Denier 48 ply 7in.														
B4C BF KM2 400Denier 48 ply 7in.	1027	1076	943	1036	1010	970	956	1063	1112	987	1081	1094	1030	57
Plate CF42 KM2 400Denier 48 ply 7in.	738	676	721	707	721	734	818	845	761	765	716	787	749	49
Plate HS KM2 400Denier 48 ply 7in.	1130	1214	1232	1237	1303	1223	1223	1268	1339	1294	1245	1134	1237	62
Plate TP full KM2 400Denier 48 ply 7in.	930	1108	943	1050	952	1152	1121	1032	1152	1059	1219	1032	1062	92
KM2 600 Denier 30 plies														
KM2 600Denier 30 ply 7in.	14607	14718	14896	14500	14380	14278	14011	14736	14429	16524	15657	15879	14885	747
B4C 119 KM2 600Denier 30 ply 7in.	12254	11431	12441	12726	12735	11494	13584	12792	13273	14598	14340	14225	12991	1047
Alum Plate KM2 600Denier 30 ply 7in.														
CF42 KM2 600Denier 30 ply 7in.	738	721	716	752	765	778	832	743	778	743	774	801	762	33
HS KM2 600Denier 30 ply 7in.	1125	1156	1214	1192	1192	1183	1188	1210	1197	1272	1330	1272	1211	56
TP half KM2 600Denier 30 ply 7in.	5733	6672	7455	6850	7757	8086	6325	7415	7562	7855	6908	7611	7186	697
TP full KM2 600Denier 30 ply 7in.	1632	1512	1708	1744	1748	1797	1824	1913	1668	1815	1846	1970	1765	125
PUR KM2 600Denier 30 ply 7in.	5733	6672	7455	6850	7757	8086	6325	7415	7562	7855	6908	7611	7186	697
Plate CF42 KM2 600Denier 30 ply 7in.		716	814	805	756	787	783	823	805	810	734	716	777	40
Plate HS KM2 600Denier 30 ply 7in.	1334	1294	1170	1263	1241	1094	1223	1165	1201	1183	1303	1130	1217	73
Plate TP full KM2 600Denier 30 ply 7in.	1174	1085	1188	1352	1263	1116	1326	1201	1383	1219	1370	1268	1245	98
KM2 850Denier 22ply														
KM2 850Denier 22ply 7in.	15915	14371	16080	16022	16004	16386	15368	14910	16600	16382	14509	15577	15677	742
B4C 119 Plate KM2 850Denier 22ply 7in.	12548	11427	12477	13108	12374	12792	12321	12530	12179	13446	15016	12147	12697	887
Alum Plate KM2 850Denier 22ply 7in.	12548	11783	13660	13357	13411	13059	13611	11712	13851	12508	12846	11854	12850	768
BF KM2 850Denier 22ply 7in.	743	725	738	743	756	752	747	747	738	747	747	770	746	11
CF42 KM2 850Denier 22ply 7in.	721		890	743	796	792	770	721	729	743	765	743	765	49
HS KM2 850Denier 22ply 7in.	1130	1174	1272	1268	1165	1281	1272	1339	1343	1361	1321	1383	1276	82
TP half KM2 850Denier 22ply 7in.	7424	6183	7184	8042	7922	8109	7980	8651	9047	6623	6997	8109	7689	831
TP full KM2 850Denier 22ply 7in.														
PUR KM2 850Denier 22ply 7in.	12583	12352	15154	12957	15203	11071	13691	13073	13424	14073			13358	1262
PLATE BF KM2 850Denier 22ply 7in.	992	983	1036	1090	1081	1139	1094	1014	1054	1045	916	1050	1041	59
PLATE CF-42 KM2 850Denier 22ply 7in.	721	805	890	863	801	836	747	796	752	787	698	729	785	59
PLATE HS KM2 850Denier 22ply 7in.	1245	1210	1179	1317	1357	1343	1352	1237					1280	70
PLATE TP full KM2 850Denier 22ply 7in.	947	1165	1085	1281	1170	1148	1183	1090	1245	1317	1165	1343	1178	110
K29 700Denier 18ply														
K29 700Denier 18ply 7in.	13126	14016	11769	12895	12775	14754	12014	12018			12975	12414	12876	932
B4C 119 Plate K29 700Denier 18ply 7in.	11080	11925	11907	11930	11930	10257	9323	9781	11818	9964	10564	11222	10975	965
B4C 83 Plate K29 700Denier 18ply 7in.	14736	13451	13633	11978	13918	14171	12543	11387	12259	11845			12992	1134
Alum Plate K29 700Denier 18ply 7in.	12027	11907	13268	11053	11356	11271	11311	12419	10568	12521	11147	11476	11694	757
CF42 K29 700Denier 18ply 7in.	939	925	996	943	934	979	961	1001	979				962	28
HS K29 700Denier 18ply 7in.	1281	1321	1414	1379	1392	1419	1472	1281	1526	1352	1374	1503	1393	80
TP half K29 700Denier 18ply 7in.	5431	4519	5244	5805	5693	5600	5769	5965	5511	6018	5965	5791	5609	414
TP full K29 700Denier 18ply 7in.	1886	1712	1850	1815	1890	1828	2002	1939	1930	1975	1966	2117	1909	104
PUR K29 700Denier 18ply 7in.														
Plate CF42 K29 700Denier 18ply 7in.	721	738	725	770	756	814	743	832	770	787	850	850	780	47
Plate HS K29 700Denier 18ply 7in.	1339	1357	1250	1379	1326	1366	1339	1330	1330	1374	1357	1339	1340	34
Plate TP full K29 700Denier 18ply 7in.	1508	1125	1099	1112	1156	1174	1139	1317	1032	1139	1090	1103	1166	127
K29 1000 Denier 13ply														
K29 1000Denier 13ply 7in.	15190	16431	17352	16391	15959	15564	16796	16484	16306	16204	16231	15283	16183	617
B4C 119 Plate K29 1000Denier 13ply 7in.	13580	13246	12530	13553	13268	14990	12045	12045	13126	10133	14674	14674	13155	1360
Alum Plate K29 1000Denier 13ply 7in.														
CF 42 K29 1000Denier 13ply 7in.	836	845	876	903	867	890	943	952	970	952	952	943	911	47
HS K29 1000Denier 13ply 7in.	1379	1552	1477	1597	1490	1499	1557	1557	1583	1664	1592	1646	1549	79
TP half K29 1000Denier 13ply 7in.	6761	6886	6917	6903	7628	7241	7152	7651	7646	7495	7357	7326	7247	323
TP full K29 1000Denier 13ply 7in.	1735	1859	1877	1926	1979	1846	2033	2055	2037	2024	2068	2153	1966	119
PUR K29 1000Denier 13ply 7in.														
Plate CF42 K29 1000Denier 13ply 7in.	752	787	818	810	814	845	867	858	934	894	885	854	843	50
Plate HS K29 1000Denier 13ply 7in.	1401	1406	1388	1397	1477	1357	1450	1495	1437	1468	1339		1419	50
Plate TP full K29 1000Denier 13ply 7in.	1036	890	1139	1139	1072	1148	1214	1068	1116	1183	1272	1281	1130	108



	Force (N)													
Material (Impact at 4 J)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
K29 1500 Denier 11ply														
K29 1500Denier 11ply 7in.	15808	14714	16155	15248	15506	15515	15466	16111	15910	15279	15145	16471	15611	497
Plate K29 1500Denier 11ply 7in.	13242	11378	13589	13184	7237	12557	12557	12841	14251	11378	14323	12615	12429	1880
Alum Plate K29 1500Denier 11ply 7in.														
CF42 K29 1500Denier 11ply 7in.	934	983	996	1099	1050	1076	1156	1063	1076	1112	1072	1112	1061	62
HS K29 1500Denier 11ply 7in.	1241	1388	1388	1495	1503	1517	1601	1557	1517	1530	1543	1588	1489	102
TP half K29 1500Denier 11ply 7in.	6338	7063	7228	7722	7757	7232	7406	7188	7619	7206	7299	6467	7211	438
TP full K29 1500Denier 11ply 7in.	1917	2037	1948	1895	2051	2077	2064	2002	1939	2099	2197	2046	2023	87
PUR K29 1500Denier 11ply 7in.														
Plate CF42 K29 1500Denier 11ply 7in.	841	907	836	854	841	956	881	992	903	956	1005	956	911	61
Plate HS K29 1500Denier 11ply 7in.	1454	1392	1450	1486	1374	1397	1388	1450	1392	1366	1419	1339	1409	43
Plate TP full K29 1500Denier 11ply 7in.	1125	1116	1059	1059	1156	1063	1143	1041	983	1179	1059	1152	1095	59
Zylon 500 Denier (35 x 35) 62ply														
Zylon 500 Denier (35 x 35) 62ply 7in.	11916	10622	8758	8758	10991	9007	8171	12001	8122	10066	11044		9951	1451
Plate Zylon 500 Denier (35 x 35) 62ply 7in.	9012	10502	5026	9821	10595	10391	9772	6561	10093	8389	8816	8669	8971	1691
Alum Plate Zylon 500 Denier (35 x 35) 62ply 7in.	8122	8500	7584	9261	5462	8122	8362	8158	8602	8705	7143	9461	8124	1052
CF42 Zylon 500 Denier (35 x 35) 62ply 7in.	689	898	818	694	729	712	694	752	787	778	770	756	757	61
HS Zylon 500 Denier (35 x 35) 62ply 7in.	1010	1050	1032	1072	1036	1054	1099	1094	1090	1103	1099	1103	1070	33
TP half Zylon 500 Denier (35 x 35) 62ply 7in.	3816	4034	3750	4297	4323	4252	3509	3425	3563	4319	3483	3416	3849	376
TP full Zylon 500 Denier (35 x 35) 62ply 7in.	1223	1285	1303	1303	1379	1463	1392	1388	1446	1432	1503	1468	1382	87
PUR Zylon 500 Denier (35 x 35) 62ply 7in.		6000	6570	7842	7281	6716	6112	6245	6361	6103	6814	6668	6610	557
Plate CF42 Zylon 500 Denier (35 x 35) 62ply 7in.	810	747	756	890	765	805	792	725	796	810	827	787	792	43
Plate HS Zylon 500 Denier (35 x 35) 62ply 7in.	1321	1250	1197	1285	1308	1308	1277	1268	1326	1285	1268	1281	1281	35
Plate TP full Zylon 500 Denier (35 x 35) 62ply 7in.	1183	1090	1228	1277	1152	1197	1188	1197	1254	1121	1085	1223	1183	61
Zylon 500 Denier (35 x 35) 32 ply														
Zylon 500 Denier 32ply 7in	13015	12726	12917	12601	12646	14038	13046	12610	13931	12508	12939	13090	13006	497
Zylon 500 Denier 32ply 7in Test 2	15470	15399	14527	13571	13633	13709	13833	14194	13633	12837	14011	13486	14025	775
B4C 119 Plate Zylon 500 Denier 32ply 7in	11703	13944	10364	10938	12419	13580	11418	14105	11387	12859	11667	11098	12123	1242
Alum Plate Zylon 500 Denier 32ply V3 7in.	8767	12317	11787	11267	13002	10786	12997	9345	11685	11627	15212	11053	11654	1697
B4C 83 Zylon 500 Denier 32ply V3 7in	13424	12975	11391	15065	12259	12067	14754	10159		8714	12499	10800	12192	1894
BF Zylon 500 Denier 32ply V3 7in	818	823	805		952	939	939		992	1005	867		904	77
BF Zylon 500 Denier 32ply 7in UNDAMAGED	738	707	721	694	734	729	725	738	716	729	725	694	721	15
CF 42 Zylon 500 Denier 32ply V3 7in	1953	1899	1882										1911	37
HS Zylon 500 Denier 32ply V3 7in	787		1374	1477	1530	1517	1570	1472	1503	1735	1592	1624	1471	245
B4C BF Zylon 500 Denier 32ply 7in	1072	987	979	1068	1059	0	979	1054	939	778	1045	898	987	90

Foam Testing (4 J)	**Force (N)**													
Material	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
HS Foam (18 x 18 cm^2)	1148	1214	1143	1152	1223	1250	1406	1210	1161	1383	1303	1179	1231	90
HS Foam (9 x 7.6 cm^2)	1401	1668	1997	1619	1570	1779	1655	2122	1753	2148	2233	1797	1812	259
CF-47 Firm Green	721	774		698	752	747	672	810	738	787	778	827	755	47
CF-45 Medium Blue	770	765	805	752	747	805	823	774	823	805	841	823	794	31
CF 42 Soft Pink	912	1027	885	827	947	961	916	872	925	952	956	867	921	53
Low Density Polyurethane	16409	18873											17641	1742
Tempur Pedic half thickness	11649	12067	10786	12205	11890	10898	11338	12041	11236	11854	12188	11743	11658	487
Tempur Pedic full thickness	2913	3558	4101	3563	3469	3536	3701	3701	3772	3799	3928	4065	3676	315
BF (Blue Firm) DAMAGED	1156	1152	1410	1045	1108	1197	1352	1294	1205	1174	1454	1432	1248	136
BF (Blue Firm) UNDAMAGED	729	729	747	725	698	729	725	729	738	721	738	765	731	16

DETERMINING HEIGHTS FOR ENERGY LEVELS TO REACH 4 AND 9 kN PEAK FORCES

Drop heights are indicated in english units next to the materials

For 4 kN Ballistic Fabric

Material	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
KM2 850D CF42 1ft	3550	3238	3527	3509	3185	3305	3216	3661	3763	2989	3025		3361	257
KM2 850D HS 13in.	3332	3447	3225	3452	3674	3825	3625	3888	3523	3736	2953		3516	276
KM2 850D CF45 1ft. 8in	3647	3994	4328	4025	4186	3901	4315	4404	4310	4390	4871	5160	4294	410
CONT. KM2 850D CF45 1ft. 8in	5160	6441	6592	6854	6845	8082	7771	7708	8109	9083			7264	1108
KM2 850D BF 1ft. 8in. DAMAGED	2375	2220	2469	1997	2162	2126	2228	2224	2384	2242	2251		2243	130
KM2 850D BF 1ft. 10.5in. DAMAGED	3683	4212	3799	3634	3745	3638	3723	3389	3456	4003	4052		3758	249
NEW BF SAMPLE														
KM2 400 D 2ft	2237	1984	2077	2139	2135	2202	2166	2260	2233	2300	2340	2340	2201	107
KM2 400 D 2ft 8 in.	3029	3100	3416	3403	3389	3492	3714	3509	3936	3919	3985	3950	3570	330
Zylon 500 D 2ft. 3 in	2847	2789	3158	3140	3234	3380	3541	3638	3443	3505	4119	4248	3420	442
Zylon 62 ply														
Zylon CF42 1ft 5in.	3683	3523	3305	3923	3572	3759		3981	4008	4217	4475		3844	348
Zylon HS	3443	3207	3754	3567	3425	3474	3923	4057	3803	4266	4177		3736	343
Zylon CF45 1ft. 10.5in	4208	3790	4297										4098	271
Zylon BF 2ft.	3848	3527		3705	3994	3625	3759	4190	3968	3968	3843	4399	3893	251
Zylon 32 ply														
Zylon HS 1ft. 3.5 in.	2887	2931	2789	3034	2896	3118	3354	3198	2842	3283	3145	3487	3080	221
Zylon BF 2ft.	3630	3928	4662	4955	4955	4248	4537	4590					4438	473
2Continued Zylon BF 2ft.	3554	4226	4306	4515	4808	5151	5440		5235	5311	5315	5698	4869	649
Contiunation Zylon BF 2ft.	6476	7130		7001	7206	7259	7740	8344	7682	8313	9043	9123	7756	856
KM2 400D HS	2695	2397	2584	2664	3007	3163	3082	2918	2793	2953	3038	3136	2869	241
KM2 400D BF 1ft. 10.5 in.	2802	3038	3002	3069	3158	3274	3545	3349	3474	3830			3254	304

For 9 kN Ballistic Fabric

Material	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
Zylon HS 2ft	7428	8029	7575	7989	7797	8660	8958	9532	9474	8967	9230	10435	8673	923
KM2 400D HS 2ft	6338	7722	7602	7081	7197	7895	8153	8269	8015	8006	7886	7882	7671	549
KM2 400D BF UNDAMAGED 3FT 9IN	7442	8189	8238	8238	8567	7957	9310	10253	12299	12468	12383	12526	9822	2042

For 4 kN with B4C Plate 119 ply Spectra

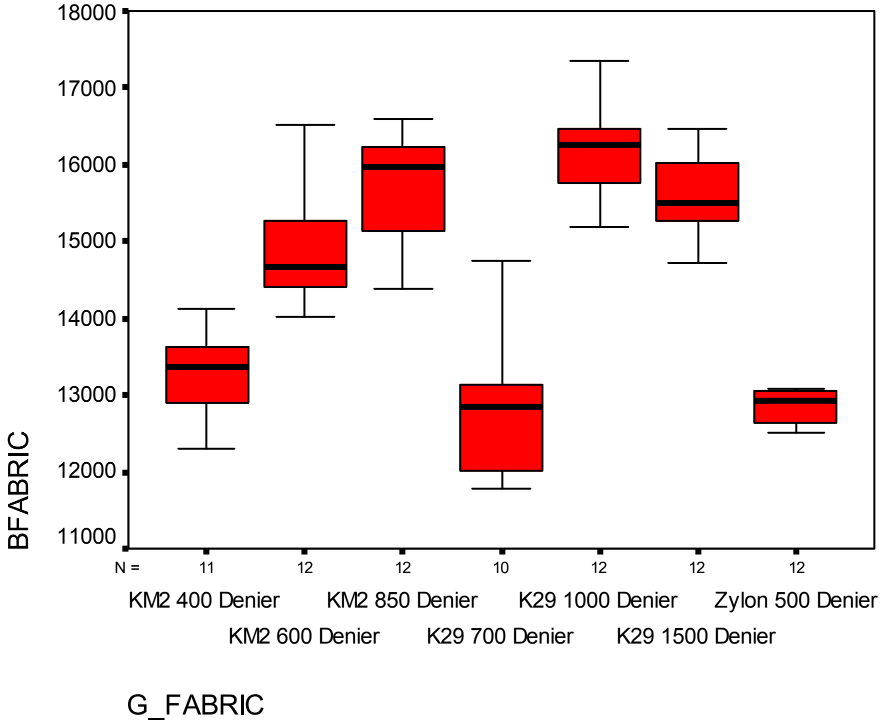
Material	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
KM2 850D BF 3ft.	3136	3367	3234	3283	3238	3385	3251	3234	3714	3394	3380	3710	3360	182
Zylon BF 3ft 3in.	3678	3905	4181		3954	3661	4079	4199	4141	4315	4172		4029	223
Zylon BF 3ft.	2802	2945	2891										2879	72
KM2 400D BF 3ft. 3in.	3140	4017	3910	3892	4146		4359	4639	4937	5084	5155	4911	4381	628
Continuation KM2 400D BF 3ft. 3in.	4639	4937	5084	5155	4911								4945	199
KM2 400D BF UNDAMAGED 3ft.5in.	3096	3300	3354	3354	3416	3558	3518	3625	3630	3616	3652	3692	3484	181

For 9 kN with B4C Plate119 ply Spectra

Material	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test12	Mean	Std.Dev
KM2 850D BF 5ft.	8140	8505	8718	10155	9674	9434	9483	9826	10066				9333	715
KM2 400D BF 5ft. 6in UNDAMAGED	5600	5991	6383	6601	6770	6712	6659	7055	7308	7406	7499		6564	519

12 APPENDIX E Statistical Analysis in SPSS

Ballistic Fabric Statistical Analysis (4 J)



Robust Tests of Equality of Means

BFABRIC

	Statistic(a)	df1	df2	Sig.
Brown-Forsythe	45.744	6	58.986	.000

a Asymptotically F distributed.

Tukey's HSD Multiple Comparisons

Multiple Comparisons

Dependent Variable: BFABRIC

			Mean Difference			95% Confidence Interval	
	(I) G_FABRIC	(J) G_FABRIC	(I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	KM2 400 Denier	KM2 600 Denier	-1537.0379*	288.40132	.000	-2411.1612	-662.9146
		KM2 850 Denier	-2329.4545*	288.40132	.000	-3203.5778	-1455.3313
		K29 700 Denier	471.9455	301.87949	.706	-443.0291	1386.9200
		K29 1000 Denier	-2835.0379*	288.40132	.000	-3709.1612	-1960.9146
		K29 1500 Denier	-2263.1212*	288.40132	.000	-3137.2445	-1388.9979
		Zylon 500 Denier	341.9621	288.40132	.897	-532.1612	1216.0854
	KM2 600 Denier	KM2 400 Denier	1537.0379*	288.40132	.000	662.9146	2411.1612
		KM2 850 Denier	-792.4167	282.06206	.087	-1647.3261	62.4928
		K29 700 Denier	2008.9833*	295.82918	.000	1112.3468	2905.6199
		K29 1000 Denier	-1298.0000*	282.06206	.000	-2152.9094	-443.0906
		K29 1500 Denier	-726.0833	282.06206	.149	-1580.9928	128.8261
		Zylon 500 Denier	1879.0000*	282.06206	.000	1024.0906	2733.9094
	KM2 850 Denier	KM2 400 Denier	2329.4545*	288.40132	.000	1455.3313	3203.5778
		KM2 600 Denier	792.4167	282.06206	.087	-62.4928	1647.3261
		K29 700 Denier	2801.4000*	295.82918	.000	1904.7634	3698.0366
		K29 1000 Denier	-505.5833	282.06206	.557	-1360.4928	349.3261
		K29 1500 Denier	66.3333	282.06206	1.000	-788.5761	921.2428
		Zylon 500 Denier	2671.4167*	282.06206	.000	1816.5072	3526.3261
	K29 700 Denier	KM2 400 Denier	-471.9455	301.87949	.706	-1386.9200	443.0291
		KM2 600 Denier	-2008.9833*	295.82918	.000	-2905.6199	-1112.3468
		KM2 850 Denier	-2801.4000*	295.82918	.000	-3698.0366	-1904.7634
		K29 1000 Denier	-3306.9833*	295.82918	.000	-4203.6199	-2410.3468
		K29 1500 Denier	-2735.0667*	295.82918	.000	-3631.7032	-1838.4301
		Zylon 500 Denier	-129.9833	295.82918	.999	-1026.6199	766.6532
	K29 1000 Denier	KM2 400 Denier	2835.0379*	288.40132	.000	1960.9146	3709.1612
		KM2 600 Denier	1298.0000*	282.06206	.000	443.0906	2152.9094
		KM2 850 Denier	505.5833	282.06206	.557	-349.3261	1360.4928
		K29 700 Denier	3306.9833*	295.82918	.000	2410.3468	4203.6199
		K29 1500 Denier	571.9167	282.06206	.407	-282.9928	1426.8261
		Zylon 500 Denier	3177.0000*	282.06206	.000	2322.0906	4031.9094
	K29 1500 Denier	KM2 400 Denier	2263.1212*	288.40132	.000	1388.9979	3137.2445
		KM2 600 Denier	726.0833	282.06206	.149	-128.8261	1580.9928
		KM2 850 Denier	-66.3333	282.06206	1.000	-921.2428	788.5761
		K29 700 Denier	2735.0667*	295.82918	.000	1838.4301	3631.7032
		K29 1000 Denier	-571.9167	282.06206	.407	-1426.8261	282.9928
		Zylon 500 Denier	2605.0833*	282.06206	.000	1750.1739	3459.9928
	Zylon 500 Denier	KM2 400 Denier	-341.9621	288.40132	.897	-1216.0854	532.1612
		KM2 600 Denier	-1879.0000*	282.06206	.000	-2733.9094	-1024.0906
		KM2 850 Denier	-2671.4167*	282.06206	.000	-3526.3261	-1816.5072
		K29 700 Denier	129.9833	295.82918	.999	-766.6532	1026.6199
		K29 1000 Denier	-3177.0000*	282.06206	.000	-4031.9094	-2322.0906
		K29 1500 Denier	-2605.0833*	282.06206	.000	-3459.9928	-1750.1739

*. The mean difference is significant at the .05 level.

B_4C 119 ssp/Ballistic Fabric (4J)